The Development of a Resource Allocation Methodology to Support System Design

by

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ABSTRACT

The objective of this thesis is first to present the development and application of a method to implement projects that support the axiomatic system design within an organization whose investment resources are constrained. The method presented is a new approach that leads to the selection of projects that axiomatically have the greatest benefit to the manufacturing system. The second objective of this thesis is to understand the organizational dynamics present during the adoption of an axiomatic design within an organization.

Axiomatic Design has proven to be a valuable means to understand and improve complex systems. Decomposing a system with the help of this method shows a path for implementation. The Manufacturing System Design Decomposition (MSDD) developed at MIT shows systematic linkages within a manufacturing system, and the design for an ideal manufacturing system.

With this knowledge "an ideal system" can be implemented if enough financial resources are available. In reality however, the budget is always tight and stakeholders need to understand where limited resources should be deployed to have the greatest impact upon the manufacturing system. The resource allocation methodology focuses upon how limited resources should be allocated to best meet the requirements of an ideal system.

Implementation of an axiomatic design such as the MSDD within an organization may require changes to the manufacturing environment. Existing literature has documented the dynamics apparent during a change initiative. However, organizations still struggle to adopt and implement a systematic manufacturing system. This thesis uses System Dynamics to study the adoption process within a manufacturing plant and compares it to behaviors presented in the literature.

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CHAPTER 1: INTRODUCTION

1.1 Motivation

The System Design Approach has been established as a valid methodology for the design of manufacturing systems [Cochran 1999, Zhao 2002, Won 2002, Cochran and Won 2002, Cochran and Dobbs 2000]. In existing organizations, the implementation of the System Design method is contingent upon economically justifying changes to the existing manufacturing system, and the organizational adoption of the System Design (SD) Approach.

The design of manufacturing systems is ordered by the SD Approach into a top-down structure. Customer needs are first established as the intention of the manufacturing system and their requirements are captured as functional requirements (FRs). The means to meet customer requirements are then described through design parameters (DPs). Functional requirements and design parameters are then decomposed until implementable design parameters become apparent. System Design requirements can best be achieved through an uncoupled or path dependent decomposition.

In existing organizations, to implement the SD Approach and its associated manufacturing system design decomposition generally requires changes to the present manufacturing system. Projects to change the manufacturing system need to be developed and evaluated according to their monetary benefit to the organization. The benefit of allocating resources to a project needs to be evaluated not only on the basis of the scarcity of the resource, but also on the impact a resource has towards achieving System Design objectives. The systematic allocation of resources enables organizations to identify and select projects that best meet the System Design requirements within any resource constraints.

As part of an organization's choice to adopt the System Design Approach, the organization may also need to change its manufacturing environment and associated organizational processes. Whilst the dynamics associated with organizational change have been documented within the literature, organizations have generally struggled to replicate the culture of systematic manufacturing system such as the Toyota Production System. Hence there is a need to understand the dynamics that reinforce or inhibit the adoption of the approach and the Manufacturing System Design Decomposition (MSDD).

This thesis first aims to develop an economic basis to allocate resources into projects that are capable of implementing the System Design Approach within an organization with limited resources. Second, this thesis attempts to capture the organizational dynamics within a manufacturing plant as the plant adopts the SD Approach and implements the MSDD.

1.2 Thesis Outline

This thesis is comprised of three main chapters. Chapter Two provides a general review of manufacturing system development throughout time and its resource allocation structures. Chapter Three develops a resource allocation methodology to implement System Design projects within a brown-field manufacturing environment and links the methodology into traditional project development and evaluation techniques. Chapter Four uses system dynamics as tool to capture and analyze the adoption of the SD Approach of the different stakeholders within a manufacturing plant.

Chapter Two serves as a general review of the evolution of manufacturing systems and as an introduction to the MSDD and Axiomatic Design. The evolution of manufacturing systems from the first industrial revolution through to the twentieth century is reviewed. The review demonstrates how manufacturing resources were initially constrained by capital and technology, and how over time these constraints have eroded. As resource constraints have changed, new production systems have evolved to capitalize on resource allocation structures. The Axiomatic Design approach and the MSDD are introduced and discussed in detail. Axiomatic Design and the MSDD provide the underlying foundation to the resource allocation methodology developed later in this thesis.

Chapter Three discusses in depth the development of transition projects to further implement the System Design within an organization. The scope of this chapter focuses on three elements. First, to develop a resource allocation method to link manufacturing System Design objectives to other organizational projects. Second, to link resource allocation to projects whose purpose is to implement the System Design. Finally, to extract the maximum benefits and economic value from these projects to the organization using traditional project development and evaluation tools.

Chapter Four uses a case study at an automotive parts supplier plant to analyze the organizational dynamics surrounding the adoption of a new SD Approach. A System Dynamics model is developed to capture and analyze the dynamics that occur as part of the implementation of the MSDD and the System Design Approach. The key dynamics that drove adoption at Plant N are compared to those in the literature. Inhibitors to adoption at Plant N are also examined and compared to the literature. Corporate policy recommendations are then concluded from the System Dynamics model.

CHAPTER 2: MANUFACTURING SYSTEMS AND RESOURCE ALLOCATION

2.1 The Evolution of Manufacturing Systems

Manufacturing systems have evolved as the result of technological advancement and the shifts that have occurred in needs and wants of customers for manufactured products. The industrial revolutions brought technological developments that advanced the scope and scale of manufacturing operations. Later, visionaries (Sloan, Ford and Ohno) developed systems to allocate manufacturing resources to meet the needs, wants and desires of their customers.

2.1.1 Manufacturing Prior to the Industrial Revolutions

Prior to the first industrial revolution, the size and scope of production was limited with labor being the key constituent. Manufacturing was cared out either domestically or through a craft guide. Within the domestic system, work was "put out" by merchants to homes where different stages of the manufacturing process were undertaken. In the craft guides, work in progress was passed from one shop to another. Both the domestic and the craft guides created a market for each of the different work in progress stages. Resources in the manufacturing system were dispersed and were centered on labor (e.g. in the form of skilled craftspeople). Work was undertaken with people working from home and selling their wares back to merchants or through crafts people who then on sold their products to other crafts people to process further.

2.1.2 The First Industrial Revolution

The first industrial revolution was centered in England during the mid eighteenth century, and was driven by technological change. This revolution brought numerous machines and manufacturing methods, improved productivity, and increased the range of goods that could be manufactured [Hopp 2001]. Watt, Arkwright, Kay and Hargraves invented the steam engine, the water frame, the flying shuttle and the spinning jenny respectively [Hopp 2001]. These technological changes in England enabled capital to replace labor resources, and the consolidation of manufacturing resources into centralized production (factories) with economies of scale.

America adopted the English industrial revolution, and went further towards consolidating manufacturing resources through vertical integration. Vertical integration became popular in American manufacturing plants due to two reasons:

- America did not have the strong tradition of craft guilds as in England. American production primarily operated on the domestic system, where the skills in production were dispersed and there were no formal organized constituencies to block integration. This enabled vertical integration to take place more easily than England.

- America's reliance on waterpower in 18^{th} and 19^{th} centuries (the steam engine invented by Watt was not popular till after the Civil war) created a manufacturing system constraint. Manufacturing plants had to be built close to a water wheel, which sent energy to the plant via a spinning shaft. This constraint lead to plants putting all their machines close to the water wheel leading to the consolidation of manufacturing processes.

The American industrial revolution also reintroduced the concept of interchangeable parts. Eli Whitney and Simeon North were contracted to produce 10,000 muskets for the US government [Hopp and Spearman 2000] and proved that interchangeable parts was a viable manufacturing strategy. Boorstein [1958] described interchangeable parts as "the greatest saving in human innovation in human history". Interchangeable parts reduced the need for highly skilled artisans and enabled production of different parts to be performed at different locations. This enabled manufacturing resources to become specialized in a particular part rather than a complete product.

2.1.3 Second Industrial Revolution

The second industrial revolution was pioneered by the development of the railroads in the United States [Hopp and Spearman 2000]. The railroads brought about two key differences in the allocation of resources:

- The reliance upon external capital. The railroads were considerably capital intensive. Capital and resources had to be raised from shareholders that would not directly manage the railroad. The creation of external capital enabled firms to vertically and horizontally integrate.

- The railroads created a market for mass produced products e.g. iron rails, wheels and spikes. This provided a catalyst for railroad suppliers to produce in mass.

- The introduction of accounting based performance metrics. The railroads focused on ton per mile costs. Mass retailers focused on gross margins and Marshall Field was tracking stock turns [Johnson and Kaplan 1987, Chandler, 1977].

With the creation of the railroads, the scale of manufacturing operations grew considerably. The steel industry was one of the first industries to move towards large-scale production. Carnegie brought the steel industry to unprecedented levels of vertical integration and efficiency. The goal of Carnegie's Edgar Thompson plant was "a large and regular output". This goal drove Carnegie to relentlessly exploit scale advantages and through increasing the velocity of throughput, Carnegie eventually became the most efficient steel producer in the world.

2.1.4 The Ford Production System and The Diversified Corporation of General Motors

Henry Ford and Alfred Sloan played a significant role in the development of manufacturing corporations. Henry Ford was a pioneer of high-speed vertically integrated manufacturing. Ford is recognized as the founding father of mass production and Sloan is credited for the design of the diversified corporation.

Ford had strong views on the requirements and design of the production system including just in time manufacturing, the value stream methodology, error proofing and zero defects, continuous improvement and worker involvement, and work place cleanliness [Ford 1926]. Ford is best remembered for his achievements in vertical integration, using standardized interchangeable parts for the automobile, the concept of the moving assembly line and the division of labor (the original pioneer of scientific management and the division of labor being Frederick Taylor). Ford's "mass" production system evolved around unit cost reduction through reducing the number of products and their variability, standardization and simplifying operations. Reducing the number of product variations enabled the production system to continue the same production pattern for long periods of time at high speed without the need for frequent changeover. The simplification of worker tasks enabled workers to assimilate their tasks rapidly. Ford raised efficiency by breaking down the assembly sequence into simple repetitive tasks and distributing those tasks along a moving production line [Womack et al 1990].

Ford's initial moving assembly lines moved automobiles through the assembly process at a defined rate to bring the work to the operators at defined time intervals, enabling the division of labor, where operators completed only a single task in the assembly sequence and could thereby specialize in a task or operation. In comparison, previous automobile plants were craft shops where individual workers would put together entire sub-assemblies such as engines, by themselves. In this way, complex sub-assembling skills and artisans became unnecessary. Production speed could be increased and the unit cost was reduced.

The mass-type production was generally implemented with manufacturing resources consolidated into departments, where departments had very specialized resources that emphasized economies of scale. Figure 2-1 and Figure 2-2 demonstrate typical high-speed assembly department (line) and departmental machining typical of the Ford production system.

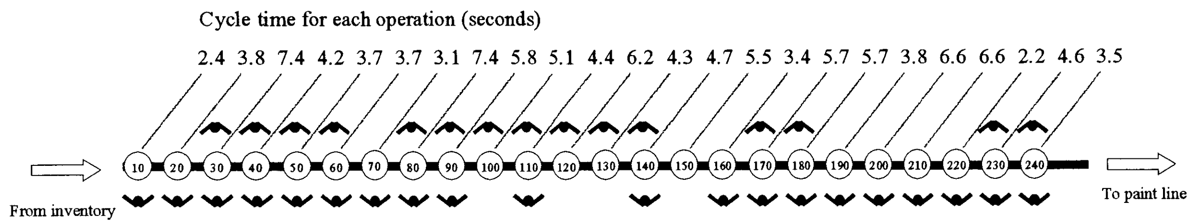


Figure 2-1:Schematic of a typical high-speed line layout of assembly-type manufacturing system [Low 2001].

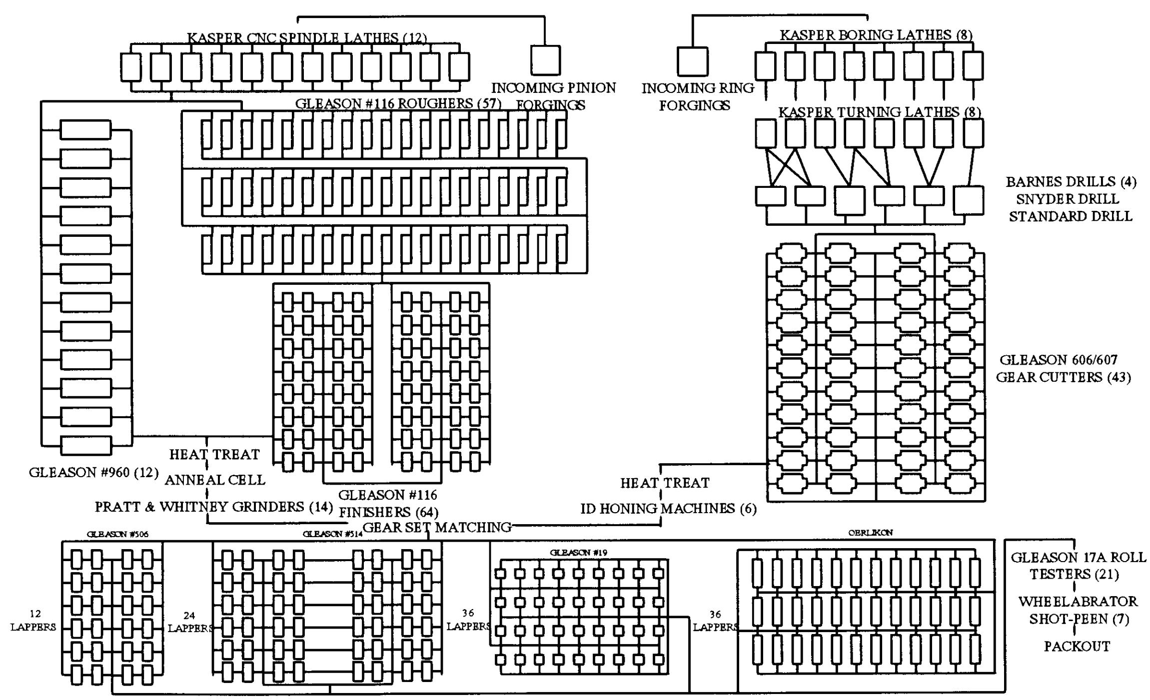


Figure 2-2: Schematic of a typical departmental layout of machining-type manufacturing system [Cochran 2001].

The results of Ford's "mass" production system enabled Ford to able to produce and sell cars at approximately less than 40% of his competitors and double the wages of his workers. Resources were merged together further, as Ford vertically integrated the complete production processes of an automobile at his River Rouge facility. In 1926, it took Ford just 81 hours to turn raw materials such as iron ore and coal and transform them into an automobile [Ford 1926].

As Ford consolidated his company's resources and focused on complete vertical integration, Alfred Sloan had pioneered the paradigm of the organization, which he termed *federal decentralization* [Cray 1979]. The concept was to create a central staff that was responsible for strategy, whilst division leaders were responsible for operational decisions.

Sloan proposed that the resources of a company should be structured as a set of autonomous operating divisions, which are coordinated through a strong corporate office. Sloan's general office implemented the return on investment (ROI) concept from DuPont and developed new techniques for demand forecasting, inventory tracking, and market share estimation. Each division was tailored to operate and serve a particular market segment in line with Sloan's belief of, "A car for every purse and purpose." [Cray 1979].

This strategy enabled General Motors (GM) to achieve greater flexibility and customer satisfaction. GM was able to become the largest car manufacturer in America with 32.3% market share in 1929 [Hopp and Spearman 2001].

2.1.5 The Toyota Production System (TPS)

The evolution of components of the Toyota Production System initially evolved over a considerable time period. The structural development of TPS arose out of a crisis. The crisis for Toyota was the decline of the Japanese economy after the Second World War.

Initially the 1902 invention by Sakichi Toyoda for an automatic loom that would cease operation if any of the threads snapped [Ohno 1988] was the first example of TPS. This loom accomplished two objectives. Firstly it separated the operators from the work, and secondly the automatic stopping mechanism was a form of error proofing. As a result of Toyoda's automatic loom, operators were now able to control numerous looms, and defects and scrap were reduced through the automatic strop mechanism. This loom formed the entry for Toyota into designing machines that could stop and call immediately for attention if problems or errors occurred [Ohno 1988]. As Toyota diversified and entered the automobile business, Kiichiro Toyoda was sent to study the Ford production system

The economic circumstances of post war Japan however forced Toyota to shift away from the Ford production system and develop a production system suited to their own local economic conditions. Toyota did not have the resources to develop specialized equipment for each model and were not able to stock large inventories of stock at each stage of production [Womack et al 1996]. The low volume and the high mix of the post war Japanese auto-market required Toyota to develop general-purpose machinery that could be utilized on different vehicle model types [Womack et al 1996]. Toyota also needed to develop a system that would ensure reliable supplies of parts without a large inventory [Womack et al 1996].

Ohno in 1956 visited the United States to observe US automobile plants. However, it was the US supermarkets that captivated Ohno [Ohno 1988]. Ohno understood the similarities between supermarkets and his own work at Toyota. Ohno described a supermarket as a place where a customer could get what they wanted, at the time needed, and the amount needed [Ohno 1988]. As people purchase according to their needs, supermarket operators must make sure that customers are able to buy what they want at any time [Ohno 1988]. The speed and accuracy in which supermarket shelves were replenished became the backbone for information flow in the Toyota Production System, or what is commonly referred to as "pull" production.

Pull production enabled Toyota to divide manufacturing resources into components for a family of products (e.g. manufacturing cells for a product family) and link together these components through the information flow Ohno witnessed in the supermarket. Ohno developed a number of tools to implement the supermarket system at Toyota, including Kanban as the primary means for communicating production information on the shop floor, and production leveling to reduce the impact of sudden swings in demand. Figure 2.3 is an example of a production sequencing board that levels production.

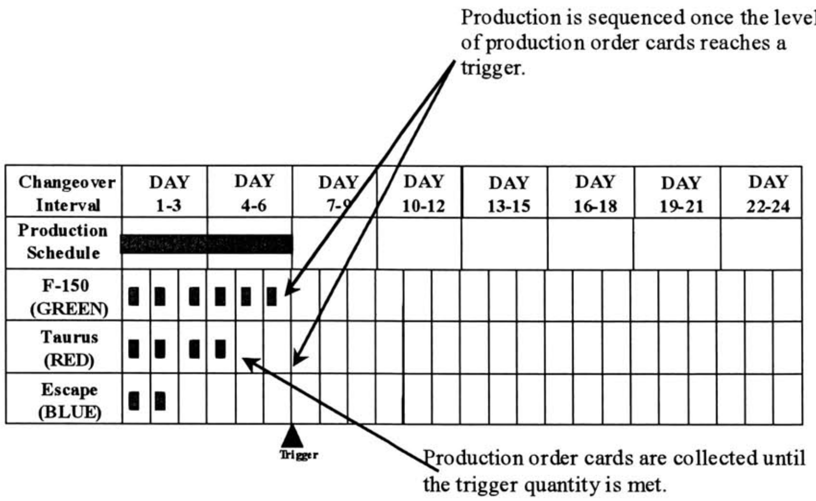


Figure 2-3: Production Sequencing Board.

2.2 Manufacturing System Design Framework

2.2.1 Systematic Approach towards Manufacturing System Design

The evolution of manufacturing described in the previous section was initially driven by technological change, but later driven by economic and resource allocation parameters. Initially, the development of these manufacturing systems was centered on the scientific management approach, pioneered by Fredrick Taylor. The scientific approach was to break up the system into small understandable components, and then find solutions for each of these components in terms of operating practices and resources. For simple systems this approach was valid.

However, as manufacturing systems became more complex, the interrelationships between different sub-systems begin to govern the performance of the overall system. To overcome the deficiencies that arise through scientific management, a systematic approach needed to be established. The Manufacturing System Design Decomposition (MSDD) is a systematic approach for the design of manufacturing systems. The MSDD uses an axiomatic design approach, and starts with a top-down approach to meet the needs firstly of the overall manufacturing system, and secondly to meet the needs of each of components within the manufacturing system.

2.2.2 Axiomatic Design

Axiomatic design establishes a scientific basis for system design. Despite the rise of the rapid technological growth in manufacturing that was considered above, there still remains many technological and societal problems that have been created through poor design practice [Suh 2001]. These problems arise as we continue to design empirically on a trial and error basis where:

- The merits between competing design options are not evaluated systematically. Design has evolved around intuitive and innate reasoning rather than scientific study [Suh 2001] and hence is not evaluated systematically.

- Design is currently viewed as being a non-structured process. Designers are not currently trained to view design as a structured process. Instead design is taught to be a subject that is not amenable to scientific rigor [Suh 2001].

Axiomatic design is a methodology to add structure and rigor to the design process, and ultimately establish a scientific basis for design. Axiomatic design is based upon two fundamental axioms that lead to a successful design [Suh 2001]:

- Axiom 1. The *Independence* Axiom. When there are two or more functional requirements, the design solutions must be chosen so that each functional requirement is satisfied in a predictable way.

- Axiom 2. The *Information* Axiom. The specified design solutions chosen should have the highest probability of requirement achievement.

Axiomatic design defines the design as 'an interplay between what we want to achieve and how we want to achieve it.' [Suh, 2001] 'What we want to achieve' will come from the customer needs. The methodology identifies three basic domains as illustrated in Figure 2-4. The internal and external customer requirements can be captured in the *customer* domain. These requirements can then be translated into a set of objectives or functional requirements (FRs) in the *functional* domain. FRs are defined as the minimum set of independent requirements, which completely characterize the functional needs of the customer. Depending on the FRs, design parameters (DPs) are designed to meet the FRs in the *physical* domain. Design parameters are the key solutions that logically satisfy the specified set of FRs.

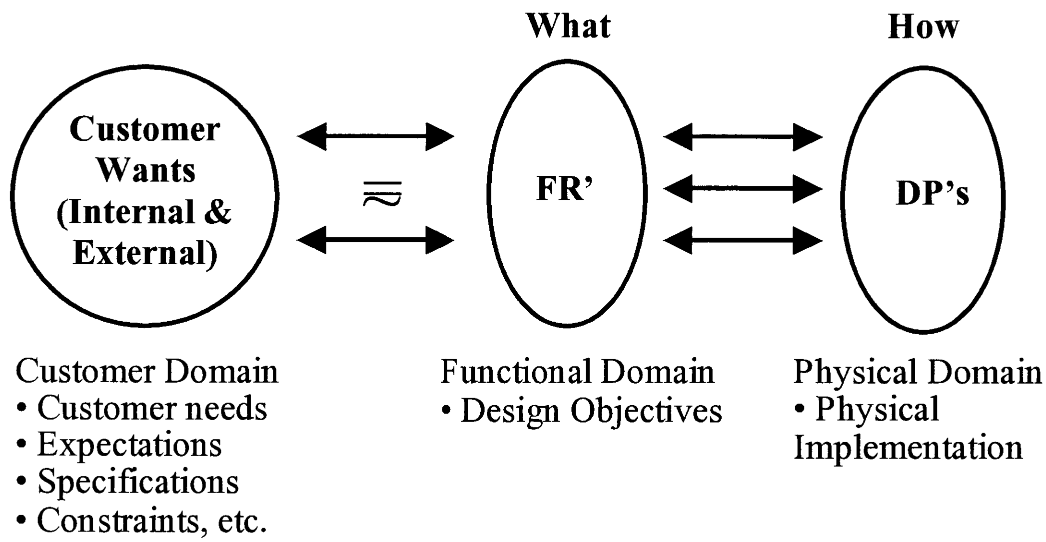


Figure 2-4:Mapping between customer domain, functional domain and physical domain [Modified from Suh 1990]

The axiomatic decomposition process is shown in Figure 2.6 below. Higher-level FR-DP relationships can be decomposed until physically **implementable** DPs have been achieved.

It is highlighted that the system functional requirements are equal to customer needs. Customer needs are usually phrased in a non-scientific way with ambiguity and overlapping [Zhao, 2002]. The designer should define a set of unambiguous and independent specifications to be design FRs.

In most cases, the DPs designed for system FRs are not physically implementable. DPs could either be subsystems that need to be decomposed further in detail or just general design directions that need to be further decomposed into physically implementable solutions.

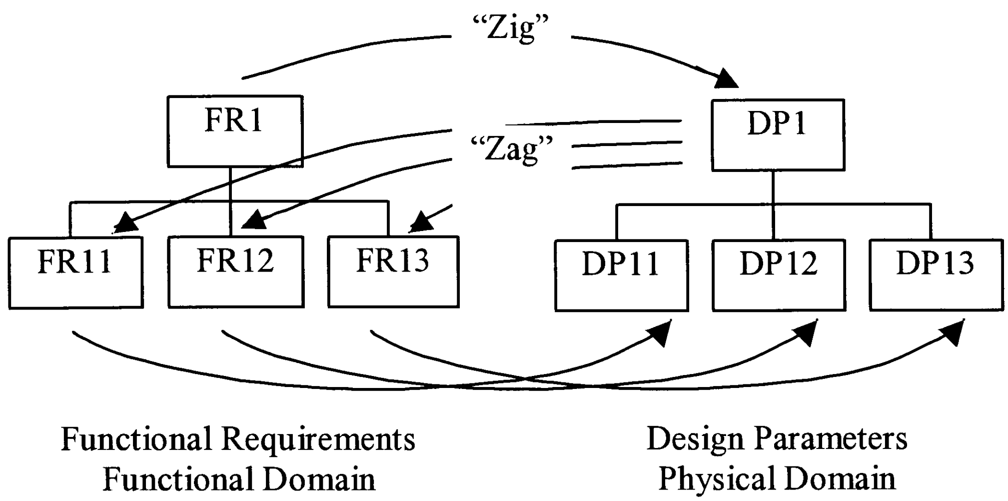


Figure 2-5:Zigzagging process of multi-level design decomposition [Modified from Suh 1990].

To decompose the high level FRs and DP pairs, zigzagging between the functional and physical domain is required. The design starts from the highest-level functional requirement FR1. FR1 is satisfied by DP1. However, DP1 is not physically implementable, so the design process returns to the functional domain and FR1 is decomposed to FR11, FR12 and FR13. The composition of these lower-level FRs will depend upon the composition of FR1 and the choice of DP1 (choosing a different DP1 would lead to different lower level FRs). Once FR11, FR12 and FR13 have been defined, the design returns to the physical domain and DP11, DP12 and DP13 are selected. This zigzagging continues until all the DPs are physically implementable. DPs that are physically implementable are referred to as leaf level DPs.

At a given level of a design hierarchy, the set of FRs that defines the specific design goals constitutes the {FR} vector in the functional domain. Similarly, the set of DPs in the physical domain that has been chosen to satisfy the FRs constitutes the {DP} vector. The relationship between these two vectors can be written as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 2-1:Design Matrix relating FRs to DPs.

2.2.2.1.1 Types of Design

When the number of DPs is equal to the number of FRs, axiomatic design identifies three main types of designs: uncoupled, path dependent (partially coupled), and coupled. Other designs where the number of DPs is not equal to the number of FRs, Suh [Suh 2001] has proved the design becomes either redundant or coupled.

To satisfy the Independence Axiom so that a design is predictable, the design must be either uncoupled or path dependent. An uncoupled design results when each FR can be satisfied independently by the means of only one DP, resulting in a diagonal matrix (see Equation 2-2). This design is the most robust. In the design matrix an 'X' signifies that a DP_j affects FR_i.

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

Equation 2-2:An Uncoupled Design.

The second type of design is the path dependent design. This design results in a triangular matrix (see Equation 2-3) and the independence of FRs can be guaranteed if the DPs are implemented in the proper (path dependent) sequence.

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

Equation 2-3: A Path Dependent Design.

Any other form of the design matrix is called a full matrix and results in a coupled design (see Equation 2-4). 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 optimization problem [Suh 2001].

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

Equation 2-4 A Coupled Design.

Table 2-1 Representations of Different Types of Design [Linch 2001].

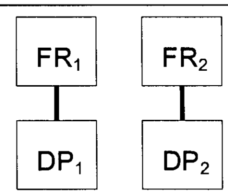
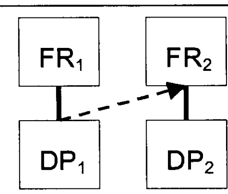
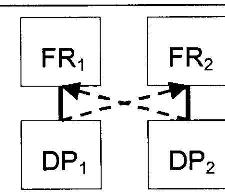
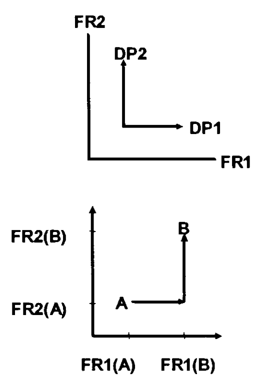
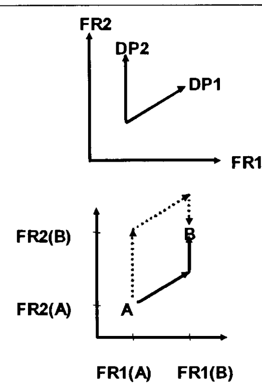
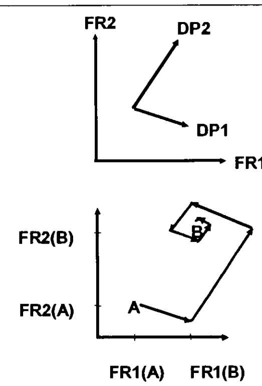
	Uncoupled design	Partially coupled design	Coupled design
Mathematical representation	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \bullet \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$	$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X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

Table 2-1 provides a summary of the differences between the three types of design, their graphical representation and an illustration of how their path dependency affects the design [Linck 2001].

2.2.3 Manufacturing System Design Decomposition

Cochran and his group at MIT have used axiomatic design to create a framework called the Manufacturing System Design Decomposition (MSDD). The MSDD represents a logical map of the ***design*** for a stable manufacturing system that operates with the fewest resources [Cochran et al 2000]. The MSDD represents a system design in its entirety.

Various other attempts have been made to capture in a systematic manner the complex interrelationships and tradeoffs that arise when designing or improving a manufacturing system. However, some of these attempts have failed to be comprehensive [Cochran et al 2000], by either failing to communicate how lower level requirements affect the overall system [Hayes and Wheelright 1979], failing to identify the means to achieve higher level requirements [Hopp and Spearman 2000], or failing to separate the means from the requirements [Monden 1998].

The objective for axiomatic design and the MSDD is for every FR must be achieved, for the design to be complete. W. Edwards Deming, stated, 'Management objectives cannot be met by unstable systems' [Demming 2000]. Cochran defines the six requirements (R) for system stability as:

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

R2. Produce the customer-consumed quantity every shift (time interval).

R3. Produce the customer-consumed mix every shift (time interval).

R4. Deliver perfect-quality products to the customer every shift (time interval).

R5. Do R2 – R4 in spite of operation variation.

R6. When a problem occurs in accomplishing R2 – R4, identify the problem condition immediately and respond in a standardized (pre-defined) way.

These attributes for a successful manufacturing system are discussed in a variety of writings [Cochran et al 2000] [Monden 1998] [Schonberger 1996] [Spear 1999]. The MSDD is an axiomatic design based framework that clearly separates the system FR and design DPs. The MSDD decomposes the highest level FR for the *manufacturing system* into multiple levels until the FR-DP pairs become implementable. This ensures that all DPs are consistent with the higher level FRs. The MSDD presents a partially coupled design that provides a framework to achieve the six requirements of manufacturing system stability.

Starting from the highest-level system FR/DPs, MSDD decomposes them to multiple levels of FR/DP pairs until all DPs become implementable. The decomposition therefore ensures all detail DPs are consistent with higher-level system level FRs. The MSDD presents a decoupled design and provides a path towards FR achievement in a systematic manner.

FR1 is the highest level FR in the system, and should present the goal of the manufacturing system. The goal is defined by Hopp and Spearman [1996] as being 'the fundamental objective of a manufacturing firm is to increase the well being of its stakeholders by making a good return on investment in the long term '. *FR 1* of the MSDD is hence defined as being 'maximize the long-term return on investment' and its DP, *DP1* is 'Manufacturing System Design'.

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

Equation 2-5: Goal of a Manufacturing System

The second level of the MSDD is derived from the ROI formula (Equation 2.6). *FR1* is influenced by three factors, the revenue produced from the manufacturing system, the costs involved in generating the revenue, and the investment required. These three factors can be translated into *FR-11 Maximize sales revenue*, *FR-12 Minimize production costs*, *FR-12 Minimize investment over the production system life cycle*. Their associated design parameters *DP-11 Production to maximize customer satisfaction*, *DP-12 Elimination of non-value adding sources of cost*, and *DP-13 Investment based on a long term system strategy*. The design matrix for *FR-1n* is partially coupled with *DP-12* affects *FR-11* and *FR-12*, and *DP-13* affects *FR-11*, *FR-12* and *FR-13* and can be expressed as follows:

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

Equation 2-6: First Level MSDD Design Matrix

The MSDD decomposition beneath FR-1n can be divided into six branches: quality, identifying and resolving problems, predictable outputs, delay reduction, operational cost, and investment. Figure 2.6 shows how these 6 branches relate to the six requirements of a manufacturing system.

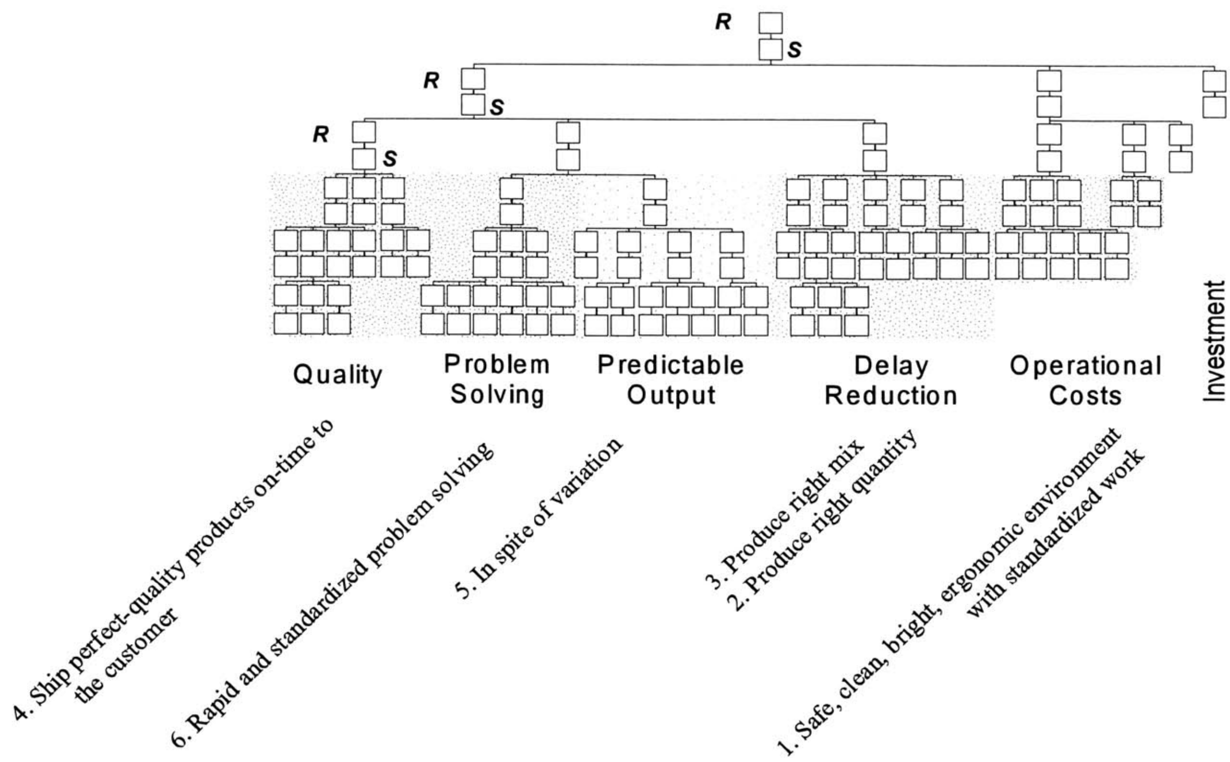


Figure 2-6: MSDD Decomposition

Figure 2-7 explicitly shows the relationship between MSDD branches and high-level FR-DP pairs. *FR-DP11* is further decomposed into the first four branches; *FR-DP12* is decomposed further in the fifth branch, and *FR-DP13* is further decomposed in the sixth branch. The following discussion is based on each of the six branches.

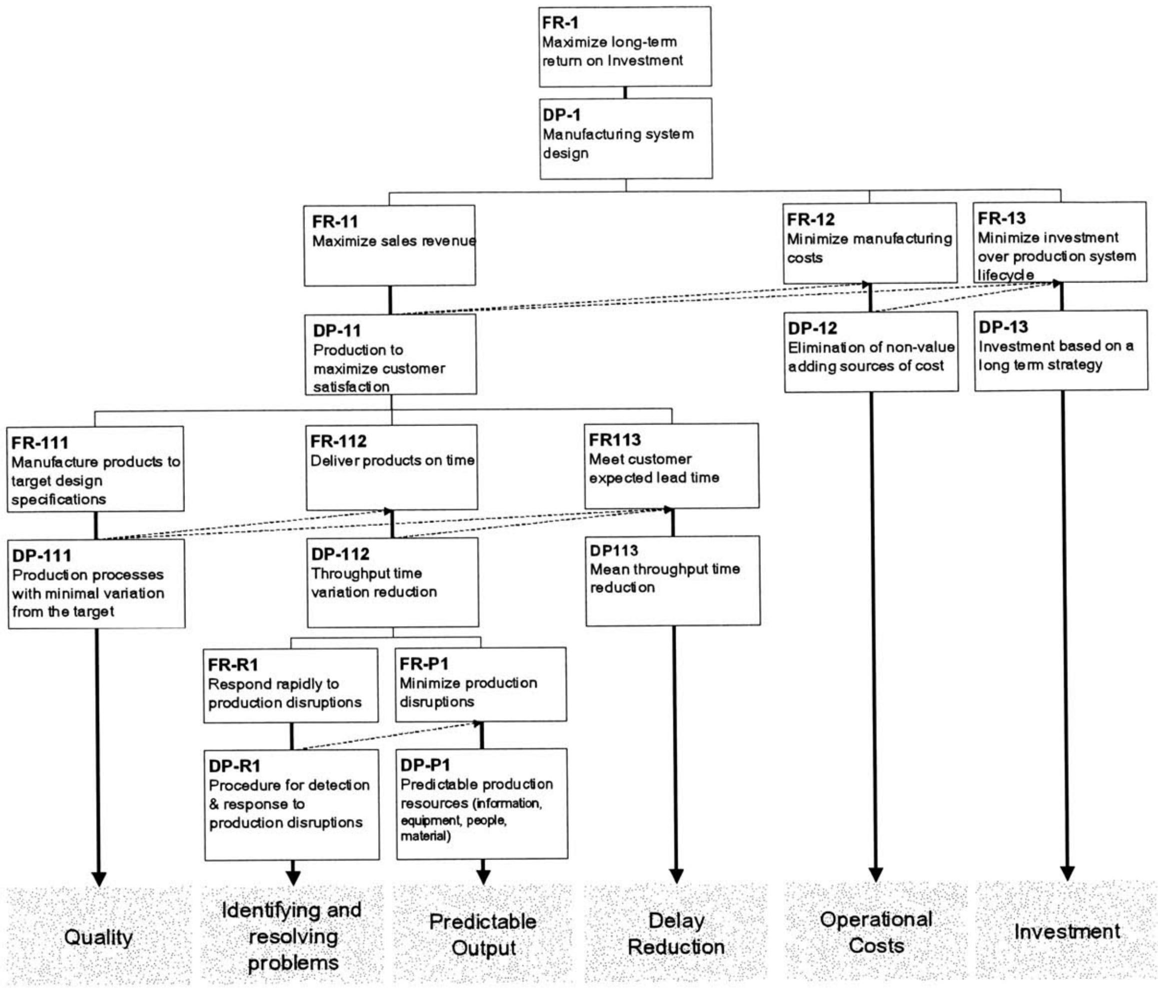


Figure 2-7: MSDD structure [Linck 2001]

2.2.3.1 MSDD Quality Branch

FR111 Manufacture products to target design specifications forms the start of the quality branch and is chosen as one of three FRs to meet *DP-11 Production to maximize customer satisfaction*. The quality branch is primarily concerned with quality in terms of firstly achieving the control limits of the process, secondly setting the target mean to the desired level and thirdly to reduce the process variation. *DP111 Production processes with minimal variation from the target* is selected to satisfy *FR-111*. *FR-DP pair FR-111* is decomposed further into three lower-level FR-DP pairs. *FR-Q1 Operate processes within control limits, FR-Q2 Center process mean on the target* and *FR-Q3 Reduce variation in process output*. Three DPs are chosen to address these FRs, they are *DP-Q1 Elimination of assignable causes of variation, DP-Q2 Process parameter adjustment, and DP-Q3 Reduction of process noise.*

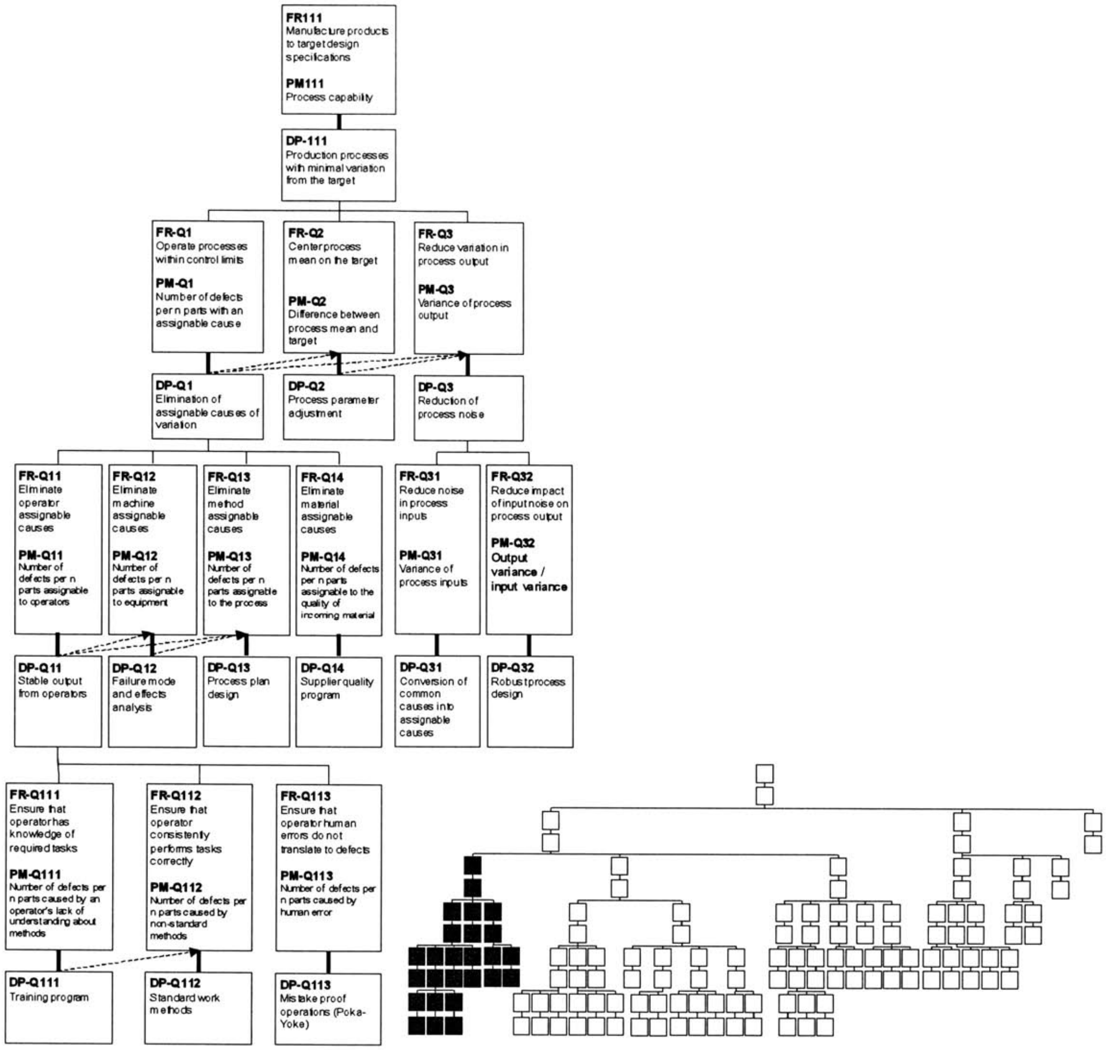


Figure 2-8: Quality branch of MSDD [Zhao 2002]

Implementing *DP-Q1 Eliminating all sources of assignable variation*, requires the consideration to of all of the sources of variation. These sources of variation can be broken into four contributory factors, operators, machines, operations and materials. Operator related variation requires standardization in order to be reduced. Figure 2-8 shows the full decomposition of the quality branch of the MSDD.

Standardization can come from operator training programs (*FR-DP -Q111*), standard work - methods (*FR-DP-Q112*), and applying mistake-proofing devices or Poke-Yoke (*FR-DP-Q113*).

Machine assignable causes of variation can be understood from failure mode and effects analysis (FMEA), where the root cause of the variation can be identified and procedures developed to prevent them from happening again (*FR-DP-Q12*).

Operations based assignable causes of variation can be addressed with a carefully designed process plan (*FR-DP-Q12*).

Materials based assignable causes of variation can be reduced through a supplier quality program (*FR-DP-Q14*).

2.2.3.2 MSDD Problem Identifying and Resolving Branch

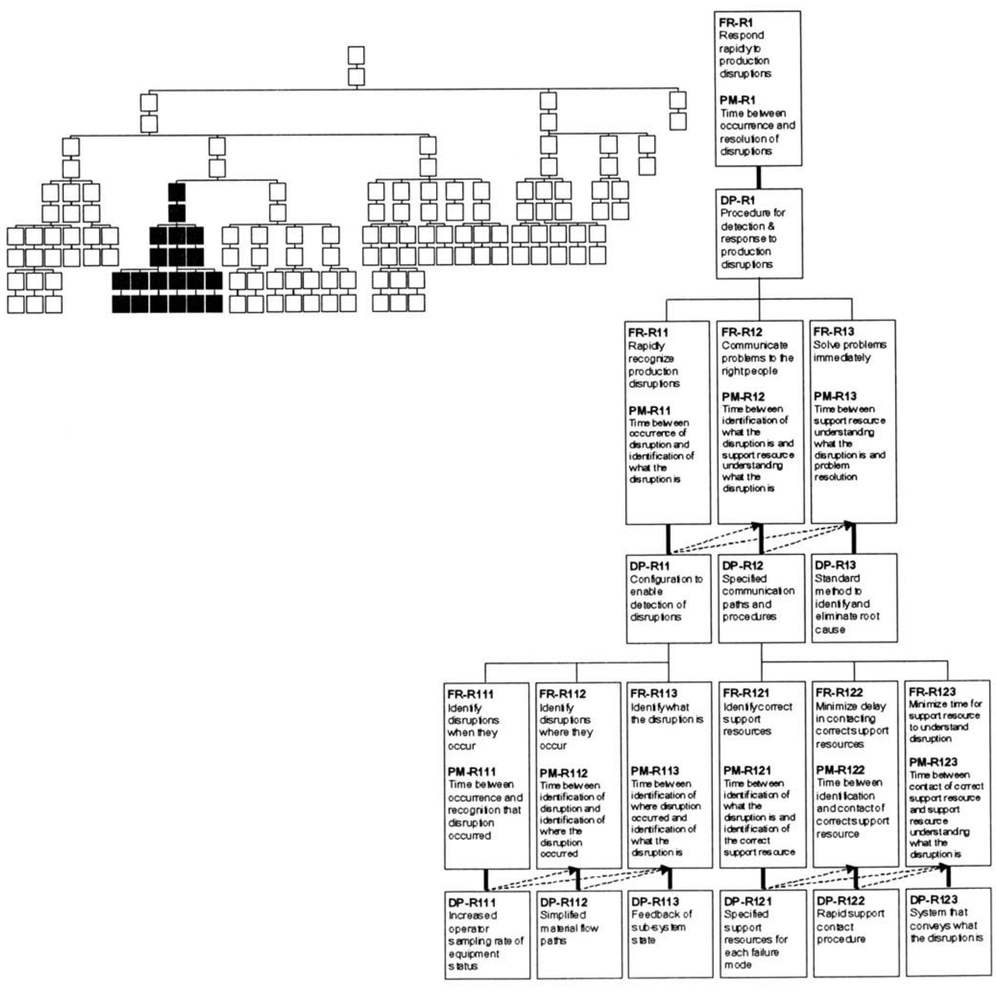


Figure 2-9: Problem identifying and resolving branch of MSDD [Zhao 2002]

The second branch of the MSDD, identifying and resolving problems in a predefined manner, addresses R6 and is shown as *FR-DP-R1*. Identifying and resolving problems in a rapid predefined manner, evolves around three processes, firstly recognizing production disruptions as they occur (*FR-R11*), secondly communicating the problems to predefined organizational members who are able to respond to the problem (*FR-R12*) and thirdly the application of measures to solve the problem rapidly (*FR-R13*). The full decomposition the problem identifying and resolving branch is shown in Figure 2-9.

FR-R11 Identify disruptions as they occur, is addressed by DP-R11, which states that the configuration of the manufacturing system should be able to detect disruptions. The requirement to communicate problems to predefined individuals (*FR-R12*) is solved by *DP-R12* and *DP-R11*, and is the combination of ensuring the system is able to detect disruptions, and by having paths of communication that are clear and effective. *FR-R13* requires the achievement of *DP-R11*, *DP-R12* and *DP-R13*. Hence, the system needs to be configured to detect disruptions, there should be clear communication channels, and procedures should be predefined so that problem can be resolved in as short a period as possible. Further zigzagging is accomplished to further decompose these FR relationships until they are leaf level DPs (Figure 2-9 shows the complete decomposition of the problem identification and delay reduction branch of the MSDD).

2.2.3.3 Predictable Output

The predictable output branch is the third branch of the MSDD, and begins by addressing *DP1* with *FR-P1 Minimize production disruptions* and its corresponding DP, *DP-P1 Predictable production resources*. *DP-P1* is achieved by ensuring the availability of relevant product information (*FR-P11*), ensuring predictable worker output (*FR-P12*), ensuring predictable equipment output (*FR-P13*), and ensuring material availability even in the presence of fallout (*FR-P14*). These lower level FRs are decomposed further until leaf level physically implementable DPs are derived (see Figure 2-10 for the fully decomposition).

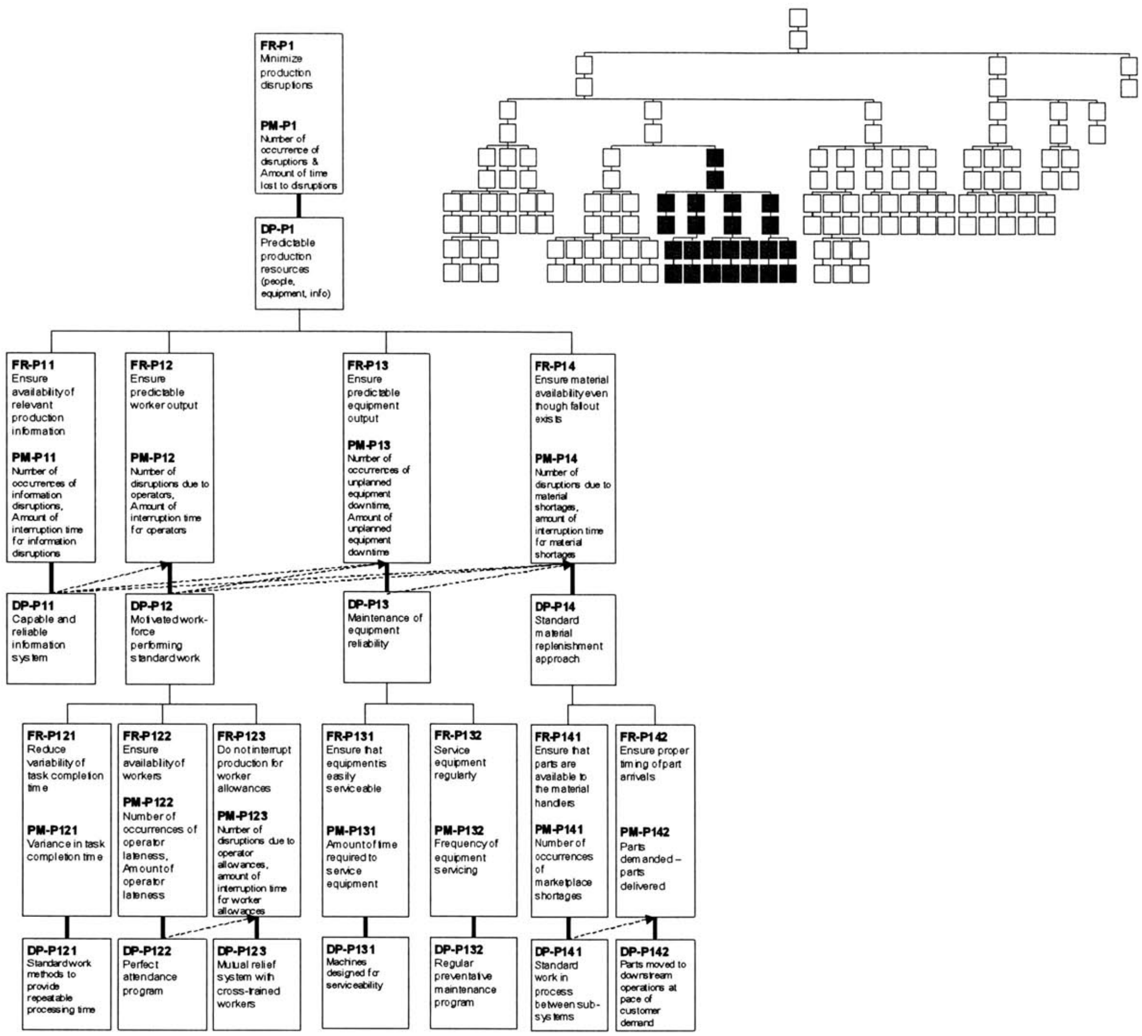


Figure 2-10: Predictable output branch of MSDD [Zhao 2002]

2.2.3.4 Delay Reduction

The delay reduction branch is the fourth branch of the MSDD and it branches out from *FR-T1-3*. The branch decomposes delay into five categories of delay, lot delay, process delay, run size delay, transportation delays and operational delays. Eliminating these delays will lead to improving mean throughput time (*DP-T-13*).

Lot delay is defined as when products are transferred between processes in large batch sizes. Individual parts must wait until all of the parts in their batch are processed before being able to move to the next process. Decreasing lot time delay is achieved through *DP-T1 Transfer batch reduction (single piece flow)*.

Process delay occurs as a result of machine processing time being greater than the rate at which parts arrive. Producing to customer takt eliminates process delay. In order to produce to customer takt, takt firstly must be defined (*FR-T21*), secondly the production cycle time must be equal to the defined takt time (*FR-T22*), and finally upstream parts arrive at the defined service rate (FR-T23). The corresponding DPs to achieve these FRs are: *DP-T21 Definition or grouping of customer to achieve takt times with an ideal range*, *DP-T22 Subsystem enabled to meet the desired takt time (design and operation)* and *DP-T23 Arrival of parts at downstream operations according to pace of customer demand*.

Run size delay is the result of the manufacturing system not being able to produce the customer required product mix. Products wait in the inventory area until the all of the customer required product types have been produced. The ability to manufacture the customer desired mix at every demand interval requires customer demand information be transferred to each process in the system (*FR-T31*) and the production run size be reduced to be sufficiently small (*FR-T32*). These FRs are achieved through the information flow design (*DP-T31*) and change over time reduction (*DP-T32*).

In order to reduce operational delays (*FR-T5*), the system should be designed to avoid production disruptions (*DP-T5*). This would entail ensuring that support resources do not interfere with its production resources (*FR-T51),* production resources do not interfere with each other (*FR-T52*) and that support resources do not interfere with each other (*FR-T53*). These three requirements are met by *DP-T51 Subsystems and equipment configured to separate support and production access requirements, DP-T52 Ensure coordination and separation of production work patterns* and *DP-T53 Ensure coordination and separation of support work patterns*, in a partially coupled manner.

The complete decomposition of the delay reduction branch is shown in Figure 2-11.

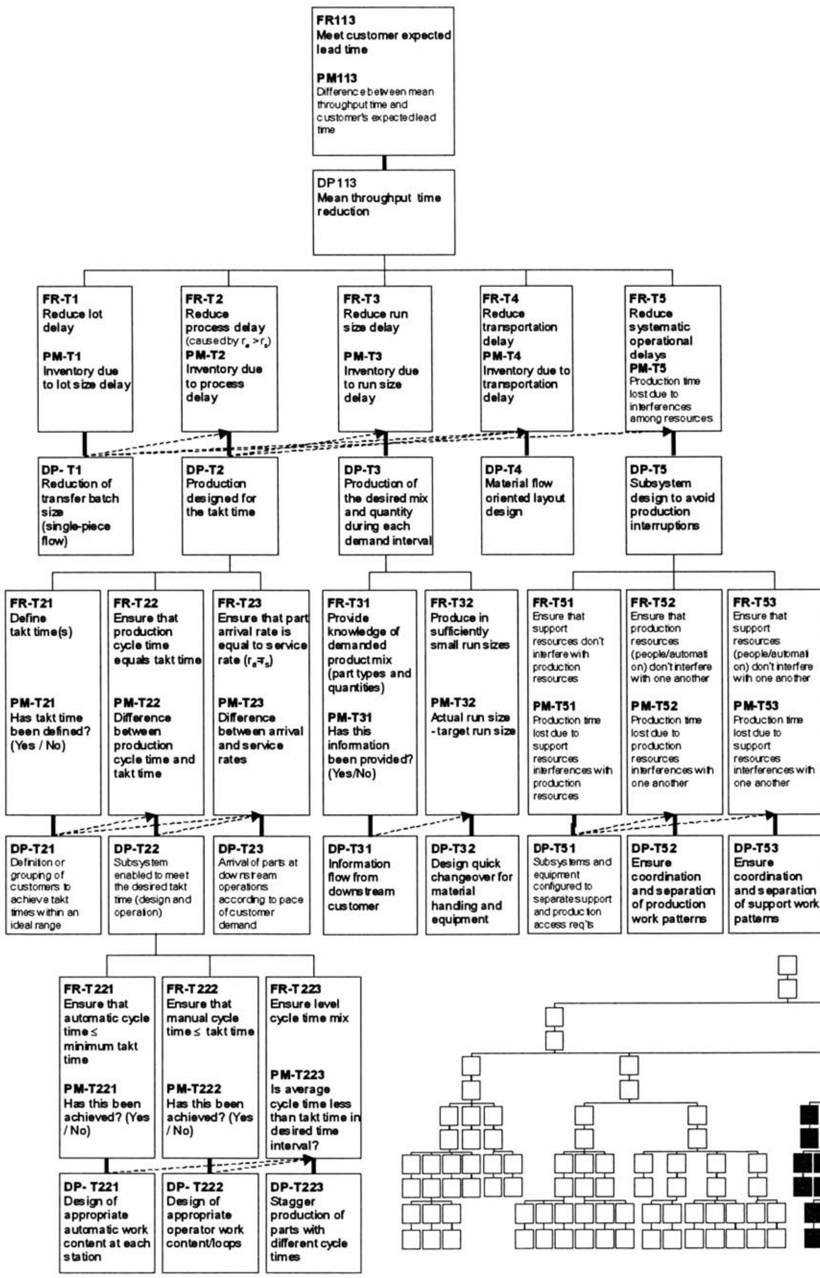


Figure 2-11: Delay reduction branch of MSDD [Zhao 2002].

2.2.3.5 Operational Cost

The operational cost branch of the MSDD, is decomposed into three branch level FRs, firstly the requirement to reduce direct labor (*FR-121*), secondly the reduction or indirect labor cost (*FR-122*) and thirdly the reduction of facilities cost (*FR-123*).

Non-value adding activities of direct labor are decomposed into eliminating operators' waiting on machines (*FR-D1*), eliminating wasted motion of operators (*FR-D2*) and eliminating operators' waiting on other operators (*FR-D3*). Separating humans from the machines *(DP-D1)* achieves *FR-D1 Operators waiting for machines*. *FR-D2* eliminating the wasted motions of operator is achieved through *DP-D1* and designing workstations and work loops to facilitate operator motion to achieve their tasks (*DP-D2*). *FR-D3* is accomplished by designing balanced work loops to ensure all operators have the same cycle time (*DP-D3*).

Reducing the waste in the indirect labor of the manufacturing system (*FR-122*) can be decomposed into two components, firstly to improve the effectiveness of the production managers (*FR-I1*), and secondly to eliminate information disruptions (*FR-I2*). Achievement of *FR-I1* is through the creation of self-directed work teams (horizontal organization) (*DP-I1*). *FR-I2* is accomplished through seamless information flow in the manufacturing system (i.e. visual factory) (*DP-I2*).

The full decomposition of operation cost branch is shown in Figure 2-12.

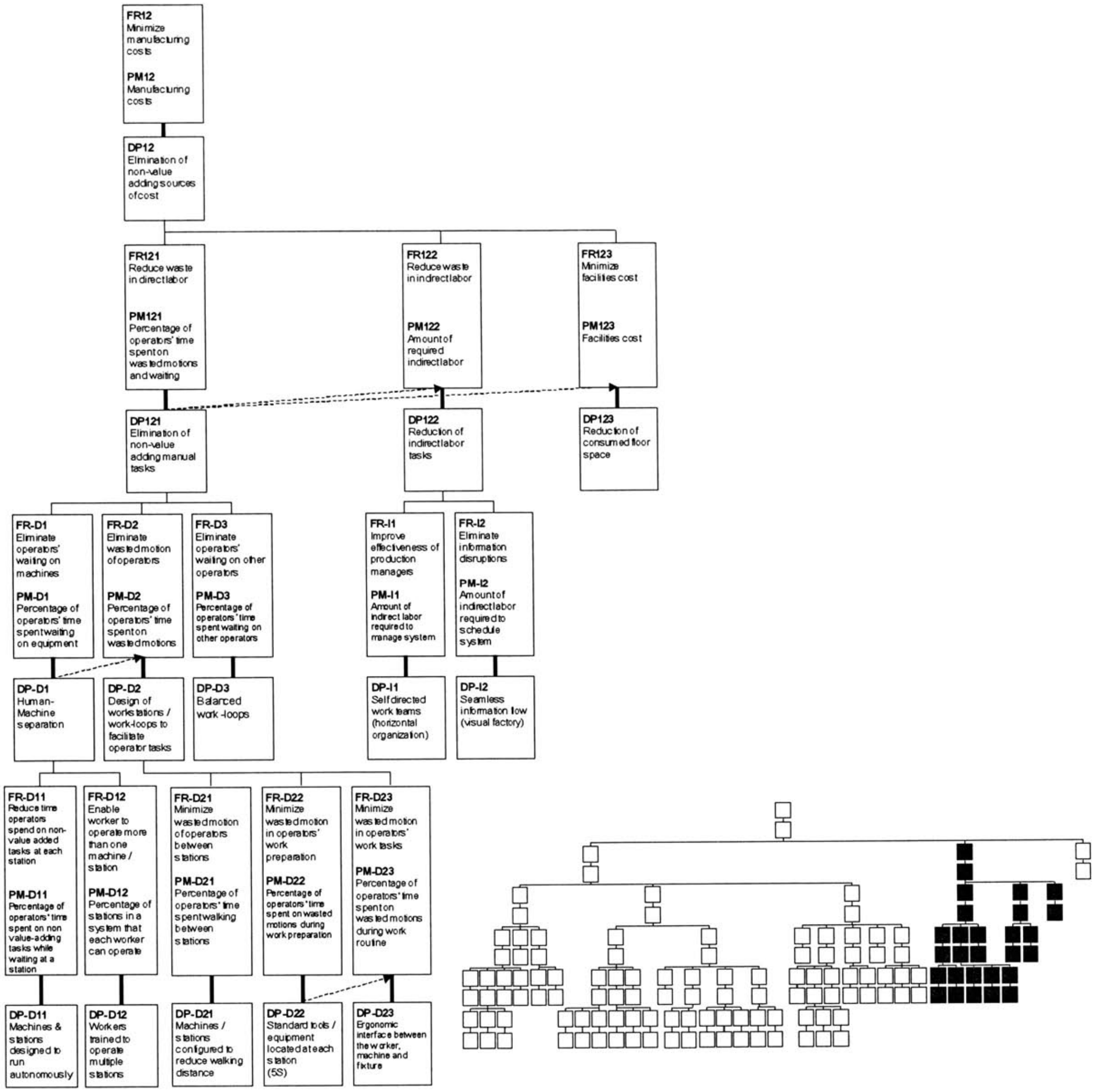


Figure 2-12:The operation cost branch of MSDD [Zhao 2002].

2.2.3.6 Investment

The MSDD does not give out a detailed decomposition of investment, as investment is very case specific, and is influenced by a host of factors that are outside the realm of the manufacturing system [Szentivanyi 2002]. However, general comments can be drawn from the investment branch in the MSDD. The objective of the MSDD is to achieve the System

Design, and ideally investment should not be a constraint to achieving System Design. The position of the investment branch in MSDD is shown in Figure 2.14.

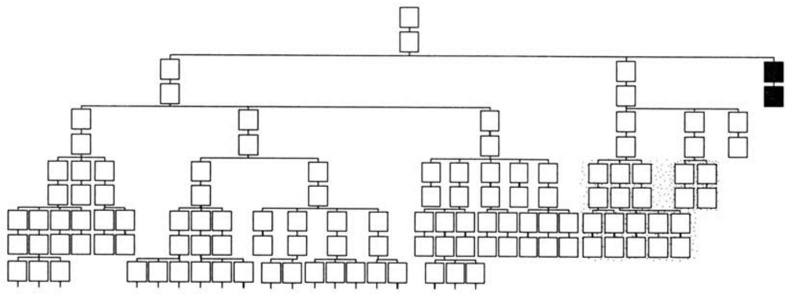


Figure 2-13: The investment branch of MSDD

However in reality, investment constraints do exist. Investment constraints affect the level of resources available to achieve the System Design. One of the aims of this thesis is to develop an investment approach for organizations that are investment and resource constrained.

CHAPTER 3: THE ALIGNMENT OF MANUFACTURING SYSTEM DEVELOPMENT AND RESOURCE ALLOCATION

"WATCH THE COSTS, AND THE PROFITS WILL TAKE CARE OF THEMSELVES" ANDREW CARNEGIE

3.1 Introduction

Industry struggles to achieve the six requirements of system stability resulting in higher manufacturing costs [Johnson and Broms 2000; Cochran 2000]. As a consequence, firms must choose to allocate investment and resources to develop their manufacturing system further towards achieving the six requirements of system stability in order to reduce their true manufacturing costs. Through improvement projects the performance of the manufacturing system can be improved. The management of investment and resource allocation is paramount to ensure an organization's survival and prosperity within their evolving business environments [Bryan et al 1998, Agrawal et al 1996, Adams 1998]. However many organizations fail to utilize their capital resources effectively or to their full potential as demonstrated by the analysis of Agrawal et al 1996, Carter et al 1996, Koss 1996 and Kenward 1993. The consequences of failing to manage and utilize their resources adequately can lead to companies becoming entrapped in a 'Capital Doom Loop' [Koyoma and van Tassel 1998]. Companies who do not understand the linkage between investment and system design over invest and unknowingly and inevitably have much higher costs resulting from system instability (e.g. fighting fires, expediting, holding 'what-can-we-make-today meetings,' making defective products, etc.).

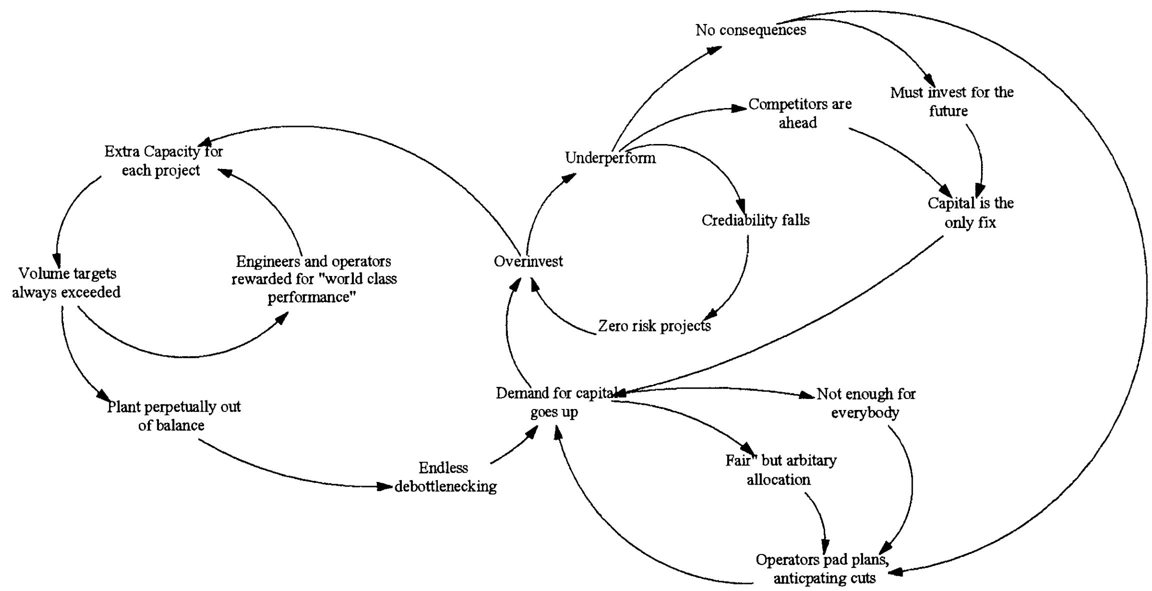


Figure 3-1: Capital Doom Loop [Extracted from Koyama and van Tassel 1998 page 144].

Escape from the 'Capital Doom Loop' is not impossible; by focusing both on the greater organizational system and within each project, resources can be allocated systematically towards DP implementation to achieve FR requirements. System improvement and investment performance is achieved through addressing the organization's resource allocation methodology, resource and project design and the physical implementation strategy. There are numerous techniques in the literature to improve investment productivity ranging from industry specific techniques and software packages [Carter et al 1996, Poulton 1996, Lessen 1996, Lougeay 1993] to industry wide analyses such as Clean Sheet Capital Redesign Technique [Carter et al 1996]. This thesis proposes that the impact an investment project has upon an organization is linked to its System Design. Hence an organization's resource allocation strategy should be linked to its System Design (for manufacturing organizations, this would be the MSDD).

3.2 Resource Allocation Strategy

In order for a project to maximize its economic value to an organization and its impact upon the enterprise system, its resource strategy should be based upon creating value and be measured in terms of performance related to business objectives from an organizational and systematic viewpoint. However, traditionally this has been difficult to achieve, as projects were not defined in terms of clear organizational business objectives, but rather as a function of their individual project benefits [Unknown 1998]. It is paramount that a paradigm shift occurs, from building big projects to great systems and in turn great businesses. This would enable a focus shift from building assets to evaluating the System Design requirements.

3.2.1 Project Linkage To Organizational Requirements

Defining the need of a resource or investment project in terms of the overall business needs will ensure that the most value is created from the project [Shaked & Leroy 1998]. For a manufacturing firm, Cochran [Cochran et al 2000] defined the goal of the manufacturing system within the enterprise as being to fully achieve the System Design requirements as stated in the MSDD. Upon establishing a genuine business need, a project's form should be developed to fulfill the need in the enterprise system, support the company's corporate strategy and enhance its competitive position. Alternative forms to the traditional view of building more assets to achieving organizational goals should be considered, as they are areas of existing latent value in the organization. Within manufacturing plants, capacity can be increased by repairing equipment, removing bottlenecks or poke-yoke.

The economic value created by improving an existing plant with little or no capital expenditure is cited in Narjarian's 1992 study of manufacturing plants. The study found that re-configuration of existing manufacturing plants could improve a company's competitive advantage and production capacity. This was achieved through developing smoother and more rapid work flow and achieving the just-in-time benefits of increased capacity, faster cycle time, lower work in progress inventory, reduced set up time and smaller lot sizes [Narjarian 1992].

3.2.2 Organizational Synergy

In order for a project to add economic value above the company's investment on a project, it must provide synergistic benefits to the organization [Shaker et al 1997]. The MSDD provides detailed map of the relationships between different branches within a manufacturing system. These path dependent relationships can then be used as basis for estimating the synergistic benefits of a project within a manufacturing organization.

Synergy particularly becomes important when considering and developing projects that individually do not utilize capital productively but collectively benefit the organization. Scenarios where this can occur include the development of a marginally viable plant in a network, the trial of new technology or the improvement of a manufacturing system.

The development of a marginally viable plant in a network is often considered when organizational sentiment and the interests of all stakeholders outweigh the initial economic conditions of the project. For example, an automotive parts manufacturer may economically wish to dispose of its non-profitable plants, however removing these plants would lead to labor disputes in its remaining plants. In these cases, Koyama and van Tassel believe that linking the capital investment with business performance is currently the best industry practice. Establishing such a clear link promotes companies to make the painful transition from the dogma that capital is free to the knowledge that they must earn the right to spend. Doing so will make both the plant viable and optimize the total network.

While linking business performance to capital expenditure is suitable for plants in a network, in many cases it is still not enough to promote the viability of adopting new technology or the start of a continuous improvement process. These initiatives have a learning curve for staff and bring a wide range of potential tangible and intangible benefits for both the project and the organization in the long term. The synergistic benefits of technology need to be assessed beyond traditional boundaries [Noaker 1994, Dhavale 1995, Kenward 1993]. Noaker and Dhavale suggest that instead of evaluating the immediate capital productivity from adopting a new form of technology or continuous improvement initiative, management should evaluate the potential long-term loss in capital productivity should they not adopt.

3.2.3 Axiomatic Approach to Project Development and Selection

The MSDD provides a scientific basis to identify projects to support an organization's system design. The 'health' of an existing manufacturing system design can be evaluated with a questionnaire based on the MSDD [Linck 2001]. This enables management to prioritize and select improvement projects based on their sensitivity with respect to FR achievement.

As a foundation for an investment and resource allocation methodology, the FRs and DPs are related to measurable monetary units. Investment (IV) in a DP results in benefits (BF) from achievement of the FRs (see Figure 3-2).

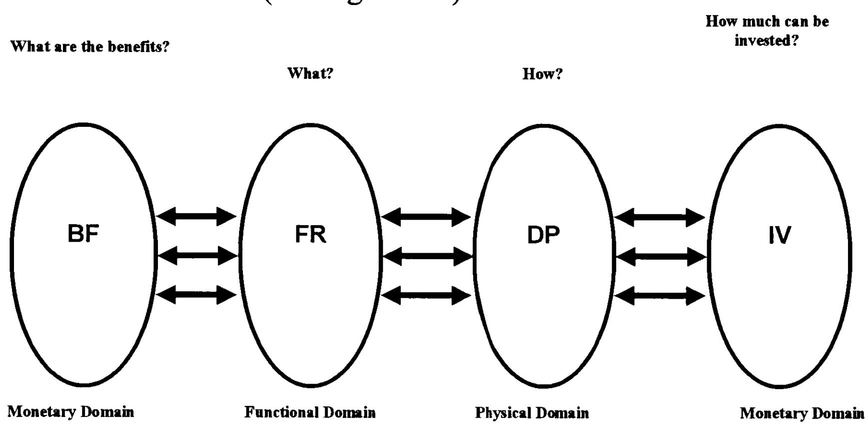


Figure 3-2: Conversion process from monetary investment to monetary benefits

The current state of each FR must be known and full achievement of each FR is the goal [Cochran et al 2000]. Higher FR achievement will result in benefits that can be monetarily quantified. Improvement in FR achievement requires investment towards its path dependent DPs. Comparing estimated benefits to the required investment enables effective utilization of limited resources.

In order to quantify the relationships between FRs and DPs, performance measures for both are a preliminary necessity. FR achievement can be quantified by the performance metrics defined in the MSDD.

A new cost matrix [R] is derived (see Equation 3.1) to quantify the benefits (BF) resulting from investments (IV). R_{ij} is an expression in monetary units of the sensitivity of benefit resulting from the increase in FR_i achievement caused by investment in DP_j (i.e. return on investment from investing in DP_j).

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \boxed{\frac{\partial FR_i}{\partial DP_j}} * \frac{\partial DP_j}{\partial IV_j} = \frac{\partial BF_i}{\partial IV_j}$$

$$\underbrace{\frac{\partial FR_i}{\partial DP_j}}_{A_{ij}}$$

Equation 3-1: Differential Form of Cost Matrix Element R_{ij}

3.2.3.1 Simplified model – Single FR-DP Pair

For a linear design, the design matrix elements (A_{ij}) are constants; for a nonlinear design, A_{ij} are functions of the DPs [Suh 2001]. It is believed that most A_{ij} are not constant over the range of implementation, but vary in shape. In practice, companies will be able to use any baseline cost curves they have developed, and as they undertake a continuous portfolio of projects, they will be able to establish cost curves for each FR. For simplicity in model development, the A_{ij} functions have been assumed to take the shape of normal cost curves.

The following model is based on two assumptions:

1. In order to simplify the model, one DP only affects one FR (Section 3.2.3.1 only).

2. The occurrence of investment and benefit are at the same point in time. In reality the benefits will be realized at a later point in time and discounted.

The formula of the R-element is partitioned (see Equation 3-2).

Benefit received by achieving FRi caused by improving one DPj

$$R_{ij} = \boxed{\frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j}} * \boxed{\frac{\partial DP_j}{\partial IV_j}}$$

Improvement in one DPj caused by investment in DPj

Equation 3-2: Partitioned [R] element

Figure 3-3 below depicts the sensitivities of the two components in R_{ij}. To express both components with the monetary term in the numerator, the second component ($\partial DPj / \partial IVj$) was inversed. This graph is based on the assertion that investment in a DP can only become prohibitive once the FR has been fully achieved in the eyes of the internal and external customers. Therefore, the point of intersection represents the absolute full FR achievement. In other words, an additional dollar should be invested in DP_j as long as the benefits are greater than the investment at any point in time.

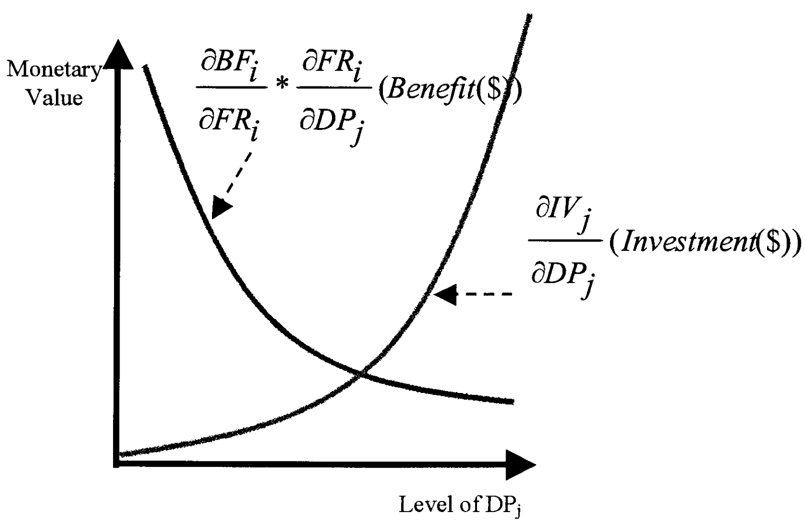


Figure 3-3: Sensitivity of Benefit to Investment

The curves in Figure 3-3 are based on the following assumptions:

1. The amount of further benefits to be gained from higher FR_i achievement declines with increasing levels of DP_j implementation.

2. The amount of investment required to improve DP_j increases with higher levels of DP_j implementation.

Incremental investment in a DP is profitable in the region to the left of the point of intersection in Figure 3-3. The mathematical expression for this statement is:

$$\frac{\partial IV_j}{\partial DP_j} \leq \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j}$$

Equation 3-3: Investment Performance Sensitivity

or restated:

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j} * \frac{\partial DP_j}{\partial IV_j} \geq 1$$

Equation 3-4: Investment Performance Sensitivity

3.2.3.2 Complete Model – Multiple FR-DP Relationships

Assumption #1 in Section 3.2.3.1 is now retracted. As seen in Chapter 2, the implmenetation of *DP-Q111* (Training program) is path dependent. *DP-Q111* (Training program) does not only affect *FR-Q111 Ensure that operator has knowledge of required tasks*, but also *FR-Q112 Ensure that operator consistently performs tasks correctly* (see Figure 3-4).

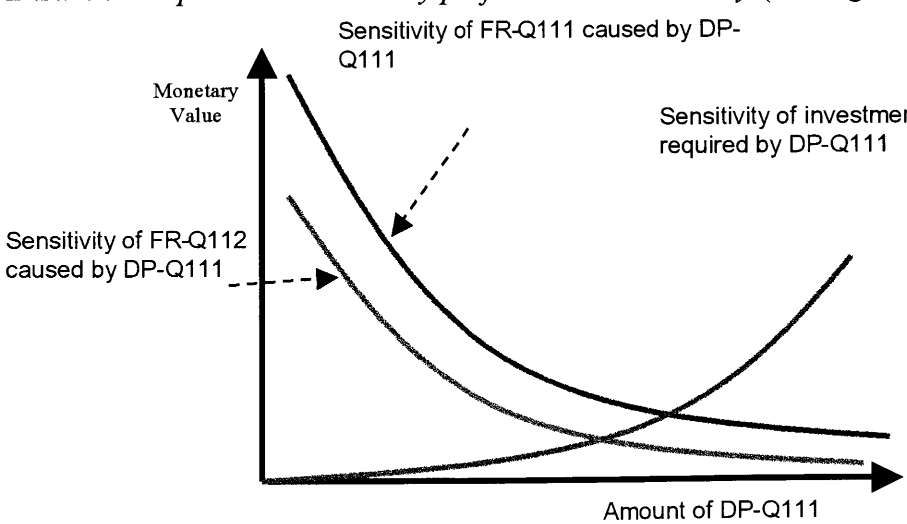


Figure 3-4: Sensitivity of Benefit to Investment – Multiple FR Case

The benefit from *FR-Q112* is smaller than the benefit from *FR-Q111*, because *FR-Q112* is mainly influenced by *DP-Q112*. The total benefit caused by further implementing a single DP is the sum of the individual benefits gained from better achievement of all path dependent FRs (see Figure 3-5).

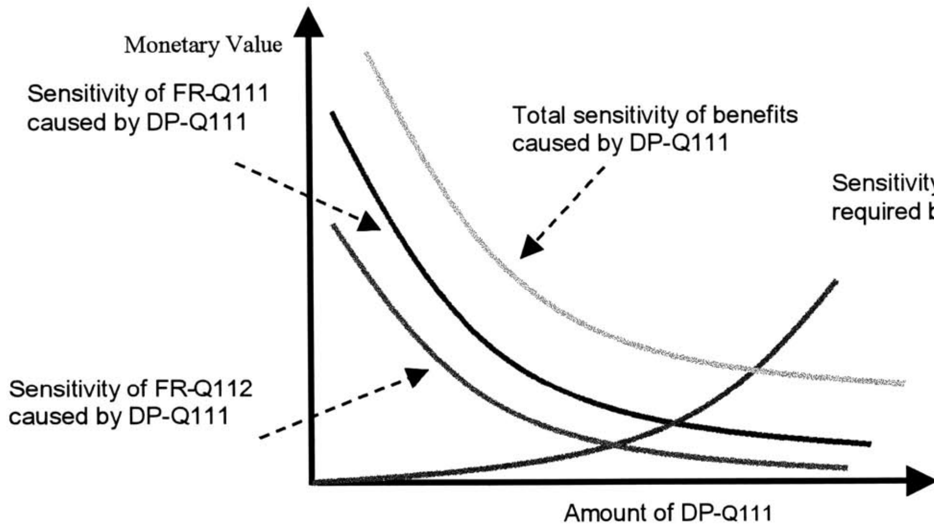


Figure 3-5: Total of sensitivity implementing DP-Q121

Mathematically, the allowable investment in *DP-Q111* (from Figure 3-5) can be expressed as follows:

$$\frac{\partial IV(Q111)}{\partial DP(Q111)} \leq \frac{\partial BF(Q111)}{\partial FR(Q111)} * \frac{\partial FR(Q111)}{\partial DP(Q111)} + \frac{\partial BF(Q112)}{\partial FR(Q112)} * \frac{\partial FR(Q112)}{\partial DP(Q111)}$$

Equation 3-5: Investment Performance Sensitivity – Multi FR Case

This equation states that investment in DP(Q111) has a positive benefits to its path dependent FRs (FR(Q111) and FR(Q112)). Hence, investment in DP(Q111) should consider the benefits that arise in FR(Q111) and FR(Q112). For an investment in a DP that has path dependent FR benefits, the sum of the multiple benefits should be greater than the investment in the DP (see Equation 3-6).

$$IV(DP_j) \leq \sum_{i=1}^{n} BF(FR_i)$$

Equation 3-6: DP Investment Decision Equation

Equation 3-5 can be restated as:

$$1 \leq \frac{\partial BF(Q111)}{\partial FR(Q111)} * \frac{\partial FR(Q111)}{\partial DP(Q111)} * \frac{\partial DP(Q111)}{\partial IV(Q111)} + \frac{\partial BF(Q112)}{\partial FR(Q112)} * \frac{\partial FR(Q112)}{\partial DP(Q111)} * \frac{\partial DP(Q111)}{\partial IV(Q111)}$$

Equation 3-7: Investment Performance Sensitivity – Multi FR Case

Equation 3-7 can be expressed as:

$$1 \leq R_{BF(Q111),IV(Q111)} + R_{BF(Q112),IV(Q111)}$$

Equation 3-8: Investment Performance Sensitivity – Multi FR Case

Hence an investment should be considered as long as the sum of the sensitivities from all path dependent FRs is greater than one.

Or as a general expression:

$$1 \leq \sum_{i=1}^{n} R_{BF(FR_i),IV(DP_j)}$$

Equation 3-9: Investment Performance Sensitivity – Multi FR Case

Once the benefit sensitivities are summed for each DP_j, improvement projects (DPs) can then be prioritized based on the summed benefit sensitivities [R_j] from the greatest to least, with 1.0 serving as the lower limit for improvement projects. This will ensure the most effective allocation of constrained company resources.

3.2.4 Organizational Flexibility

The demands on a project to deliver a variety of results dependant on the flexible demands of the organization can add a price premium to the project design and engineering stages of the project and incur non-necessary operating expenditure. The traditional strategy in the past has been to design for the maximum possible peak capacity the project is required to deliver [Carter et al 1996]. However to achieve a more beneficial solution can be achieved by considering when and where the peak capacity occurs and developing project goals to align with the level of flexibility required by the company in its competitive environment. Thus to achieve an organization's capital productivity objective, senior management and the project team must achieve a balance between meeting changing market and organizational needs with a project that is economically viable throughout its useful life to the organization.

3.2.5 Development Timing

The timing of commencement will have an immense impact on the overall cost of undertaking the project and on the projects operating conditions during the influential early stages of the project's life. The timing of commencement should consider the possibility of deferring the project, the possibility of changes in the market and technology and the economic operating conditions should also be considered to maximize capital productivity.

Deferring a project gives an organization the option value of acquiring more information to increase the certainty of return on their investment. In many cases the influence of project deferral according to Koyama and van Tassel on business for large capital expenditure projects has little impact on business; in fact deferring a project can increase capacity utilization during a projects early years and thus enhance returns [Koyama and van Tassel 1998].

In axiomatic terms, there are certain conditions that can affect the rate of FR achievement. For a non path-dependent system, the rate of achievement for a single FR is correspondent to the current level of DP implementation and the current state of FR achievement. In a path dependent or coupled system, the rate of FR achievement for a single FR is a function of the level of its direct DP implementation and the implementation of all other path dependent DPs. Hence in a path dependent or coupled system, the ability to sequence and time DP implementation can increase the rate of FR achievement. Individual DPs may now become easier to implement as other DPs work towards achieving a particular FR either directly or a result of it path dependent nature.

3.3 Resource and Project Design

The relationship between a physical resource and its investment into implementing a design parameter should be understood through the same axiomatic lens as design parameters are to functional requirements. Resource design focuses upon developing an optimal resource structure for a project to implement design parameters. This involves considering the type of assets that would best meet a project's goals and its interface with the rest of the organization.

Traditionally this has involved optimizing across organizational and project path dependencies, minimizing bottlenecks, and removing the incentive to build unsinkable 'gold plated' assets.

3.3.1 The Path Dependency of Resources

The influence a resource has in accomplishing a DP is a function of the current level of DP accomplishment. Hence, the path dependencies inherent between design parameters and functional requirements described in Chapter 2 can likewise be used to evaluate the selection of physical resources to be used within a manufacturing system improvement project. The path dependency of resources enables a project to be structured firstly in terms of resource impact and secondly in terms of resource sequencing. Aligning a project's resources with each other theoretically should bring direct benefits through a reduction in the operating costs and the total investment requirement.

The understanding between DP accomplishment and FR achievement through path dependency can be applied in the selection of resources to invest to accomplish a DP. Certain resources may have a greater impact through path dependency than considered on their primary DP relationship. The participation of these resources within a project can lead to the multiple implementations of DPs within a project to achieve a FR. Hence, selection of these resources should include their path dependent nature.

The path dependent nature of resources to DPs, and DPs to FRs also enables resources to be sequenced so that they can have the greatest impact upon DP implementation. Resources that don't require an initial high level of DP implementation to be effective can be applied early in the process to implement the DP before resources that do require a high initial level of DP accomplishment.

3.3.2 Removal of Gold-plating

Gold plating involves designing or using assets that are significantly above what is considered the extremes in operating conditions. Gold plating is essentially the allocation of resources to implement DPs where there is no marginal benefit from each additional unit of resource devoted. As a result, over-engineering can be a catastrophic impediment to achieving resource productivity. An over-engineered project will never attain the maximum possible ideal use of resources; no matter what improvements are realized further in the project evaluation stages of the project. In a global context, gold plating has been shown to be a leading obstacle to competitive advantage across a range of industries, and consequently the economic demise of some of the world's most powerful nations [Agrawal et al 1996].

To overcome the fallacy of over-engineering, project teams need to consider what emphasis should be placed on each incremental level of DP implementation. The 'bells and whistles' need to be carefully considered in relation to the basic objective to best meet the system design requirements with the available resources.

3.3.3 Risk Management

As a project nears the evaluation and possible implementation stage, there are usually still some uncertainties over the fundamental FR achievement derived through the allocation of resources. The sensitivity between resource to DP, and DP to FR can have a dramatic impact upon the selection and allocation of resources. Traditionally, cost is sacrificed and resources are allocated to cover every permutation of the possible relationship.

Traditional risk identification and mitigation techniques should be applied to reduce the underlying risk. In addition, the selection of resources to implement a DP should be based focused upon the resources that have the highest probability of success per unit of investment. These resources will have the highest likelihood of implementing the DP and would be in alignment with the second axiom i.e. support the lowest information required to implement a DP. This is analogous to selecting the DP design to have the lowest information content and hence the highest likelihood of success [Cochran et al 2000].

3.3.4 Minimizing Bottlenecks

The complete implementation of a DP may be caused by a constraint in one or more resources i.e. a bottleneck. A bottleneck can be defined as a critical limiting factor to achieving maximum FR achievement in a project. In physical systems, Goldratt [Goldratt 1984] proposes that bottlenecks can be found, understood and eliminated through the theory of constraints. The theory of constraints also provides an understanding into how a constraint/bottleneck can control the performance of the system, and furthermore become the center for feedback mechanisms for the other components in the system. Collectively the inter-relationships between resources and DPs can be viewed in a similar manner to the physical systems that have been studied.

The impact of resources to implement a DP can be hindered by a bottleneck, and the releasing of this constraint should be considered to improve the performance of the existing resources devoted to implementing the DP. Similarly, the feedback from the existing bottlenecks to implementing the DP should be feedback into future resource allocation decisions.

3.3.5 Extracting the Maximum Latent Value from a Resource

Koyama and van Tassel believe that too many companies stop looking for benefits once a project clears its hurdle rate. In addition companies whose policy is to go beyond the hurdle rate rather than to accept zero-return standards can boast a culture and system that enables the full benefit to be attained from every capital dollar. Latent value in a resource can be utilized by identifying the path dependency between resources, DPs and FRs. Once a resource's path dependency is known, efforts can be made to ensure that a resource makes a significant impact upon DP implementation.

3.4 Project Evaluation

The Project Evaluation stage of the resource and investment allocation process is primarily concerned with the evaluation of how effective a project is at achieving organizational objectives before physical implementation. Frequently, organizational requirements (FRs) can be achieved through a number of different projects, and the evaluation process method is used to compare the different benefits and risks of differing project options. It is regularly during the project evaluation process that the economic costs and returns are estimated and the productivity of a project can be calculated through a variety of techniques.

On the surface, the evaluation of a project's expected system performance can directly influence the investment productivity and economic value added by a project. A direct comparison of the project alternatives and the development of a project portfolio to best decide the stages of a project that would create the greatest economic added value for an organization and the most efficient use of resources can be concluded from the project evaluation process.

However a detailed understanding of the governing factors that drive the economic project evaluation process can provide the backbone and the numerical analysis to understand the impact of the resource allocation strategy and the project design of a project prior to implementation. Currently in industry, the most common economic project evaluation procedures are based on the concept of Discounted-Cash-Flows. The current industry best practice is Net Present Value [Koyama and van Tassel 1998] and the developing Real Options Valuation techniques are explored further.

3.4.1 Net Present Valuation

Net Present Value (and derivatives based upon it) is currently the industry best practice for evaluating economic viability of projects [Carter et al 1998]. Derivatives of the Net Present Value technique have been developed over the years to incorporate project risks and uncertainties and the flexibility to change a project path mid way through.

3.4.1.1 Net Present Value (NPV) Theory

Net Present Values are calculated on the principal of discounting the net cash flows of a project during a time period applicable to the project. This will vary depending on the nature of the industry the project is operating in. The Net Present value calculation is shown below:

$$NPV = \sum_{n=0} \frac{CF_n}{(1+r)^n}$$

Where : NPV = The net present value of the project.

CF=The Net Cashflows for the time period n.

r=Discount rate. The current industry best practice is to use the average weighted cost of capital.

n= period of evaluation, e.g year 1, year 2 etc

Equation 3-10: Net Present Value Calculation [Needles et al 1990].

3.4.1.2 NPV Levers to enhance Capital Productivity

Clearly from the NPV calculation in Equation 3-10 the two key influences to the economic return of a project are the timing of the net cash inflows and outflows. Due to the geometric progression of the discount rate, NPV suggests improvements to capital productivity through reducing the initial capital investment and encouraging cash inflows to occur as early as possible in the project's life.

3.4.1.3 NPV Flexibility and Risk

Risk has traditionally been incorporated into NPV calculations as a contribution to the discount factor, as shown in Equation 3.5. Flexibility in project options and stages however are not included in the formulation of the traditional NPV evaluation. Nevertheless many derivatives of NPV have been developed to incorporate flexibility and options into the evaluation process.

While applicable to certain projects, the conventional method of incorporating risk into the discount rate of a project is highly inaccurate for a number of other projects. Conventionally it is assumed that the level of risk increases with time, and thus the discount rate is an applicable medium to incorporate that risk as it progresses geometrically. However in a number of large resource intensive projects such as firm wide continuous improvement initiative, the level of risk decreases with time as a project develops. The techniques researched in the literature all suggests excluding the risk factor from the discount factor and applying separate risk factor to each stage of the project.

Flexibility and the option to stop a multistage project at a particular stage have never been the strong points in traditional NPV valuations, as they are not incorporated into the formula. Decision Trees and their derivatives of them have been developed to incorporate both a project's risk and flexibility more accurately. Decision Trees are computed by calculating the NPV for each option available to the company at the time, applying a risk factor for that stage and the perceived options in the future, and developing a tree of the projects NPV with time. The tree can then be used as a navigational tool in considering project options to enable the most optimal use of capital.

3.4.2 Real Option Valuation (ROV)

The Real Option Valuation (ROV) technique is a capital expenditure evaluation technique based on an adaptation of the Nobel Prize winning Black-Scholes model for calculating financial options. The Black-Scholes model was initially developed for financial options in 1973 by Fisher Black and Myron Scholes and later modified by Robert Merton.

Real Options Valuations provides an evaluation technique that is capable of accepting market and project uncertainties as well as multistage and multi-option projects, incorporating many of the elements of strategy and process redesign, and assigning a dollar value to them. These features make Real Option Valuation a valuable tool in assessing projects, and are a basis for improvements in capital productivity.

3.4.2.1 Options Theory

Modern Options theory is based around the Black-Scholes Option formula, as modified by Robert Merton. For financial options it is described in Equation 3-11 as:

$$TOV = Se^{-\delta t} \times \{N(d_1)\} - Xe^{-rt} \times \{N(d_2)\}$$

Where:

$$d_1 = \frac{\ln(S/X) + (r - \delta + \sigma^2/2)t}{\sigma\sqrt{t}}$$

$$d_2 = d_1 - \sigma\sqrt{t}$$

Where for financial options:

S= Stock Price

X=Exercise Price

δ=Dividends

r=risk free rate

σ=uncertainty

t=time to expiry

N(d)= Cumulative normal distribution function

Equation 3-11:Black Scholes Option Valuation Equation (Brailsford & Heaney page 698).

To apply the Black-Scholes Option formula to project evaluation, the levers of financial options need to be replaced with the options commonly available when evaluating a project.

Thus the symbols used in Equation 3-11 take on a new meaning and become:

S= Present value of cashflows when option is purchased

X=All fixed costs expected over the life of the investment

δ=cashflows lost to competitors who undertake and invest in the opportunity

r=risk free rate

σ=uncertainty

t=time to expiry

N(d)= Cumulative normal distribution function

[Leslie and Micheals 1997].

3.4.2.2 TYPES OF OPTIONS

A project may have many different types of options. Options firstly may occur naturally e.g., to defer, contract, shut down or abandon. Or options may be planned and built-in with extra cost e.g. to expand growth options, to default when investment is staged sequentially, or to switch between alternative inputs or outputs. Table 3.1 describes briefly the most common categories of real options.

Table 3-1:Types of Options

Category	Description	Important In	Analyzed by
Option to defer	Management holds a lease on (or an option to buy) valuable land or resources. It can wait (x years) to see if output prices justify constructing a building or plant, or developing a field.	**All natural resource extraction industries**; real estate development; farming; paper products	Tourinho; Titman; McDonald & Siegel; Smith; Ingersoll & Ross
Time to build option (staged investment)	Staging investment as a series of outlays creates the option to abandon the enterprise in midstream if new information is unfavorable. Each stage can be viewed as an option on the value of subsequent stages, and valued as a compound option.	All R&D intensive industries, especially pharmaceuticals; ***long-development capital-intensive projects, e.g., large-scale construction or energy-generating plants***; start-up ventures	Brennan & Schwartz; McDonald & Siegel; Trigeorgis & Mason; Pindyck
Option to alter operating scale (e.g., to expand; to contract; to shut down or restart)	If market conditions are more favorable than expected, the firm can expand the scale of production or accelerate resource utilization. Conversely, if conditions are less favorable than expected, it can reduce the scale of operations. In extreme cases, production may halt or start up again.	**Natural resource industries such as mine operations**; facilities planning and construction in cyclical industries; fashion apparel; consumer goods; commercial real estate.	Brennan & Schwartz; McDonald & Siegel; Trigeorgis & Mason; Pindyck
Option to abandon	If market conditions decline severely, management can abandon current operations permanently and realize the resale value of capital equipment and other assets in secondhand markets.	Capital-intensive industries, such as airlines and railroads; financial services; new product introductions in uncertain markets.	Myers & Majd
Option to switch (e.g., outputs or inputs)	If price or demand change, management can change the output mix of the facility ("product flexibility"). Alternatively, the same outputs can be produced using different types of inputs ("process flexibility")	Output shifts: Any good sought in small batches or subject to volatile demand, e.g., consumer electronics; toys; specialty paper; machine parts; autos; Input shifts: **All feedstock-dependent facilities, e.g., oil; electric**	Margrabe; Kensinger; Kutatilaka; Kutatilaka & Trigeorgis

		power; **chemicals**; crop switching; sourcing	
Growth option	As early investment (e.g., R&D, lease on undeveloped land or oil reserves, strategic acquisition, information network/infrastructure) is a prerequisite or link in a chain or interrelated projects, opening up future growth opportunities (e.g., new generation product or process, oil reserves, access to new market, strengthening of core capabilities). Like interproject compound options.	**All infrastructure-based or strategic industries,** especially high-tech, R&D, or industries with multiple product generations or applications (e.g. computers, pharmaceuticals); multinational operations; strategic acquisitions.	Myers; Brealey & Myers; Kester; Trigeogis; Pindyck; Chung & Charoenwong
Multiple interacting options	Real-life projects often involve a "collection" of various options, both upward-potential enhancing calls and downward-protection put options present in combination. Their combined option value may differ from the sum of separate option values, i.e., they interact. They may also interact with financial flexibility options.	Real-life projects in most industries discussed above.	Brennan & Schwartz; Trigeorgis; Kulatilaka

(Source: Wang unpublished. Lenos Trigeorgis, 1993. Real Options and Interactions with Financial Flexibility. Financial Management. Autumn.)

3.4.2.2 Real Options Levers of Influence

As a consequence of having six variables to be adjusted to, Real Options Valuation technique can be used as an opportunity to pro-actively lever the inherent flexibility in a project to achieve an optimal use of resources. This opportunity arises from the fact that in many real world project situations there are usually a limited number of players interacting with one another, each of which can influence the real-option levers and hence the option value. Leslie and Michael provide techniques on how to influence and shift option levers within a project to improve real-option value and capital productivity, a summary of which is shown in Figure 3-6.

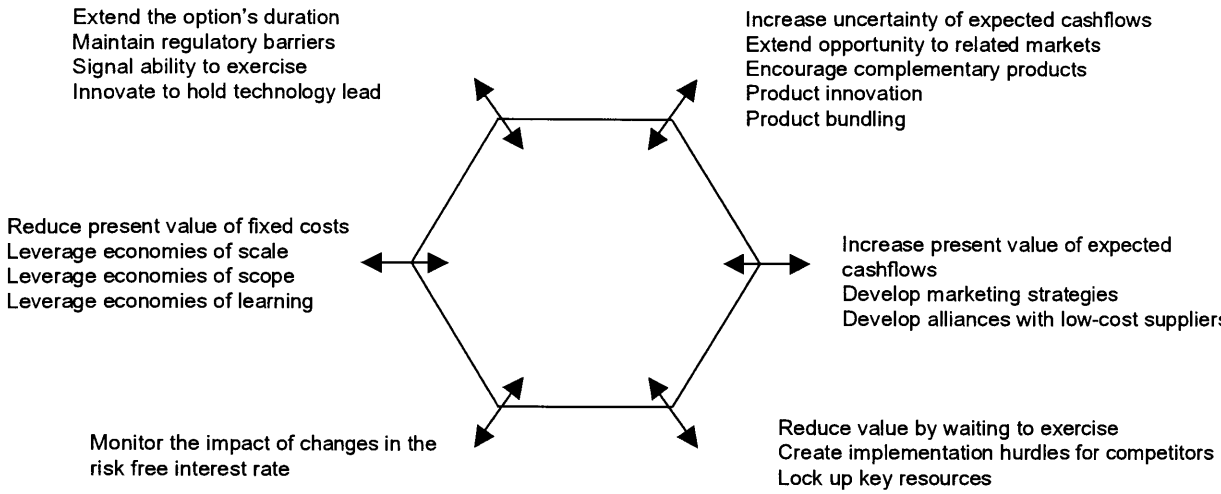


Figure 3-6: Managing real options proactively. Extracted from Leslie and Michaels 1997, page 12.

3.4.2.3 Real Options Risk

Risk is one region where ROV differs from conventional discounted cash-flow techniques and are areas where the ideas developed in financial options are highly advanced.

Risk in an ROV is incorporated through the "no arbitrage" principal, or law of one price. This simply states that two investment opportunities that produce the same (equally uncertain) payoffs must be worth the same; otherwise, arbitrageurs would buy the undervalued investment and sell the over priced investment and make a risk-free profit in the process.

3.4.2.4 Real Options Flexibility

Flexibility in a project evaluation technique is important as many projects have a wide range of options as the project develops and comes to fruition in our ever evolving and changing world. Real Options valuation use 'Rainbow', 'Compound' and 'Learning' options to allow for the inherent uncertainties and options available as a project is engineered, both of which are based on the concept of decision trees.

Learning options are primarily used to reduce a projects risk and as an exploratory measure to gain an appreciation of the project's potential. An example of a learning option is the piloting of the System Design Approach within a plant. Initially, the approach is only applied to value stream in the production system. As the value of System Design Approach is appreciated and the customization requirements understood, the approach can then applied throughout the plant. Finally, the approach can be applied throughout multiple plants in the organization and with suppliers.

Rainbow and compound options are used to present and model all the possible foreseeable options and outcomes in a project. Rainbow options use a decision tree style analysis to weight the potential costs and benefits of the options available to the company as the project progresses. The only major difference between a decision tree used with a NPV analysis and ROV is the discount rate. As an option is usually a leveraged position, thus its discount rate is significantly higher than the weighted cost of capital traditionally used for NPV.

3.5 Physical Implementation

Engineering a physical change to a manufacturing system is the final design stage prior to implementation. Charles Poulton and Koss believe the adequate management of this stage of a projects development is an important phase in aligning project outcomes with organizational goals. Capital productivity in this stage of a project is primarily achieved through tightening the screws on unnecessary costs. The design at this stage of a project should be focused on achieving an optimally low cost through aligning the design with the development of a project purchasing strategy [Chapman et al 1997]. In practical terms this, involves the utilization of a combination of fit for purpose components, the use of industry standard designs and the benchmarking of initial project designs with current advances in technology and managerial techniques.

3.5.1 Performance Measurement

The improvement of a manufacturing system is continuous and projects are usually developed over significant time frames and involve a large number of different resources at different project stages. In order to ensure the optimal use of resources, advances in modern technology and managerial philosophies that occur during the development of a project must be incorporated into the project's engineering design. Benchmarking provides a valuable tool to undertake this task. Through a firm grasp of the fundamental assumptions that underpin the design of the project, benchmarking is capable of comparing the existing design and technology with industry best practices to develop a design that best meets the fundamental project objectives.

3.5.2 Fit for Purpose Components

Designing fit-for-purpose components to improve capital productivity is based on the assumption that the minimum resources used to ensure organizational goals would ensure optimal resource productivity. This assumption is true for a wide range of project applications; however in highly complex and specialized projects the risks to time and cost in procuring true fit for purpose components should be considered.

To achieve true fit-for-purpose designed components; designers must reduce excess capacity in their designs, and question the assumptions and historical practices that underpin their design. The overall aim of these practices is to shift the designer's paradigm to focus on and scrutinize cost as the primary driver in the design.

3.5.3 Industry Standard Designs

The use of industry standard designs and specifications can be advantageous in many resource intensive projects to raise investment productivity projects, in comparison to custom specifications. Efficient resource allocation could be jeopardized in highly complex and specialized projects through custom specifications extending the capital cost of the project and the risk of lengthening the project procurement duration. These scenarios would occur, as contractors would need to modify existing plant and equipment and the possible need to purchase further equipment and non-industry standard materials to conform to custom specifications. Also, additional time and cost could be incurred as stakeholders learn to install and operate custom design plant.

3.6 Resource Allocation Case Study

The Production System Design (PSD) Laboratory worked with an aircraft manufacturing company (Aircraft Manufacturer Y) facing challenging cost targets and having limited available resources. This case study primarily focuses on the development or a resource allocation strategy for Aircraft Manufacturer Y based solely upon applying the axiomatic approach to project development and selection method that was developed in section 3.2.

Aircraft Manufacturer Y's management was seeking a scientific methodology to define their production system and guide their decision-making. Senior management at Aircraft Manufacturer Y evaluated their production system using the Product Delivery System framework and the manufacturing costs incurred from not meeting the six requirements for stability in a manufacturing system (refer to Chapter 2 for an in-depth discussion on the requirements for manufacturing stability). The project development and selection methodology was then applied to accurately estimate the potential for investment within each DP, and the sensitivity of investment in a DP towards achieving system design goals and the most effective use of available investment. Finally an implementation guide based upon the material developed in this chapter was developed to further promote efficient resource allocation at Aircraft Manufacturer Y.

3.6.1 Product Delivery System

The Production System Design Laboratory at MIT has used axiomatic design to create a framework called the Product Delivery System (PDS). The PDS is an extension of the MSDD framework and incorporates the impact of product design decisions on the manufacturing system. This is particularly important during the introduction of new product to be manufactured by the production system.

The PDS like the MSDD represents the **design** for a stable manufacturing system that operates with the fewest resources [Cochran et al 2000]. The PDS represents a syst em design in its entirety. **Every** FR must be achieved for the design to be complete. Below in Figure 3-7, the key branches of the PDS are shown with their relationship to the 6 requirements of a stable manufacturing system.

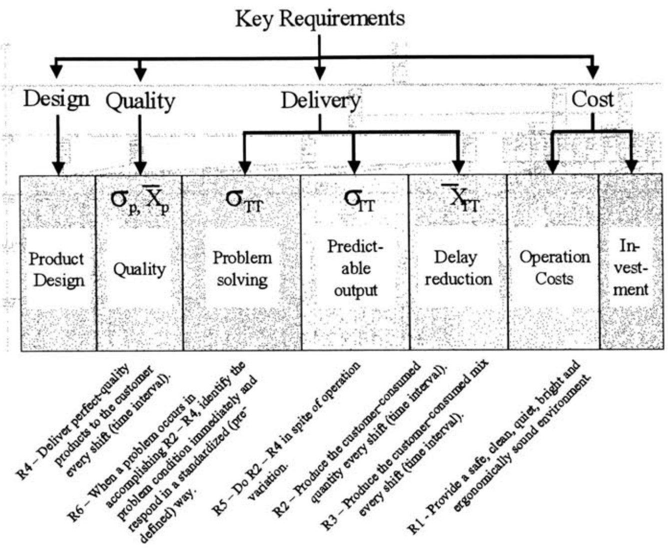


Figure 3-7: Product Delivery System (PDS) and the Six Requirements for System Stability

3.6.2 PDS Evaluation of Aircraft Manufacturer Y

Data was not readily available on the cost incurred from not fully achieving the PDS requirements. Management estimated this cost to be about one-half of the current assembly (direct labor) time per aircraft. To determine the cost of not achieving the requirements, the three most recent aircraft to complete production were used as a baseline.

Accurately quantifying the impact of each PDS requirement not being met was nearly impossible, but from program metrics and data available, only the following PDS requirements and solutions could be **estimated**.

Table 3-2: PDS Requirements Identified at Aircraft Manufacturer Y.

FR-111 'Design products that meeting program requirements'

DP-111 'Product Design Process'

FR-Q1 'Manufacture products within engineering requirements'

DP-Q1 'Elimination of assignable causes of variation'

(i.e. non-conformance work)

FR-P11 'Ensure availability of relevant production information'

DP-P11 'Capable and reliable information system'

(i.e. unavailable, late, incomplete, inadequate, or unclear work instructions)

FR-P12 'Ensure tools and supplies are available'

DP-P12 'Processes to ensure adequate supplies'

FR-P132 'Ensure availability of workers'

DP-P132 'Attendance policy enforcement'

(i.e. 'labor loss' - excessive, insufficient or untrained workforce compared to requirements)

FR-P15 'Ensure material availability even though fallout exists'

DP-P15 'Standard material replenishment approach'

(i.e. part shortages)

Figure 3-8 below shows the PDS with the quantified FR-DP pairs highlighted.

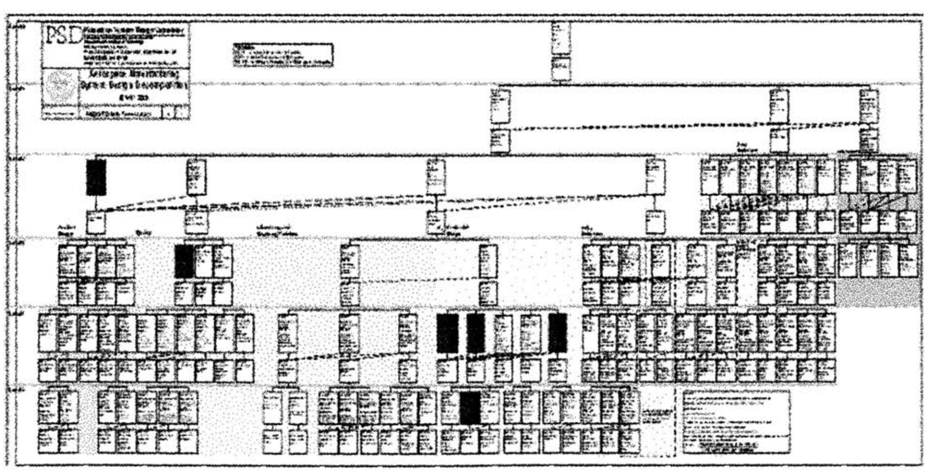


Figure 3-8: PDS Requirements Studied at Aircraft Manufacturer Y

3.6.3 Path Dependent Investment Potential for Aircraft Manufacturer Y

Direct labor cost per plane was estimated for each of the above requirements while indirect (non-assembly) cost per plane was only estimated for FR111, FR-Q1, FR-P12 and FR-P15. Total program cost was calculated by summing the direct and indirect costs.

The graph in Figure 3-9 below displays the total labor hours per plane incurred from not fully achieving six PDS requirements (not account for path dependency).

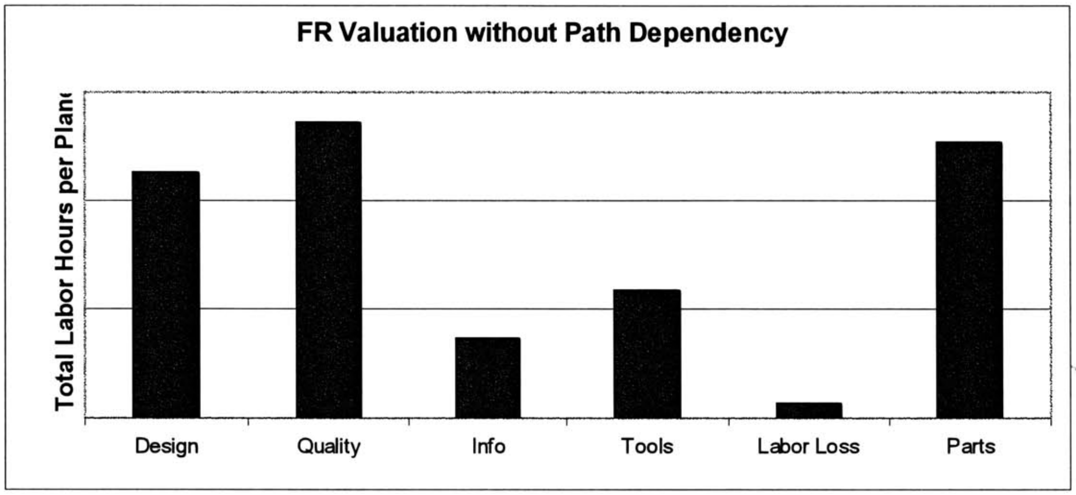


Figure 3-9: FR Valuation without Path Dependency at Aircraft Manufacturer Y.

3.6.4 System Design Resource Allocation at Aircraft Manufacturer Y

Because the PDS represents a path dependent design, investment in one DP will have a positive affect on multiple FRs. To more accurately estimate the allowable investment in each of the above DPs, the path dependency must be determined as shown in Equations 3-12 and 3-13.

$$\begin{Bmatrix} FR-111 \\ FR-Q1 \\ FR-P11 \\ FR-P12 \\ FR-P132 \\ FR-P15 \end{Bmatrix} = \begin{bmatrix} X & - & - & - & - & - \\ X & X & - & - & - & - \\ X & X & X & - & - & - \\ X & - & X & X & - & - \\ - & - & - & - & X & - \\ X & X & X & - & - & X \end{bmatrix} * \begin{Bmatrix} DP-111 \\ DP-Q1 \\ DP-P11 \\ DP-P12 \\ DP-P132 \\ DP-P15 \end{Bmatrix}$$

Equation 3-12: Path Dependency of Studied PDS Requirements at Aircraft Manufacturer Y

Management estimated the magnitude of the design matrix elements (see Equation 3-13). For example, 90% of the cost of not fully achieving FR-Q1 'Manufacture products within engineering requirements' was due to poor implementation of the direct DP, *DP-Q1 Manufacture products within engineering requirements*, and the other 10% of the cost was incurred from not fully implementing *DP-111 Design products that meeting program requirements*.

$$\begin{Bmatrix} FR-111 \\ FR-Q1 \\ FR-P11 \\ FR-P12 \\ FR-P132 \\ FR-P15 \end{Bmatrix} = \begin{bmatrix} 1.0 & - & - & - & - & - \\ 0.1 & 0.9 & - & - & - & - \\ .03 & .03 & .94 & - & - & - \\ 0.8 & - & .05 & .15 & - & - \\ - & - & - & - & 1.0 & - \\ .01 & .02 & .01 & - & - & .96 \end{bmatrix} * \begin{Bmatrix} DP-111 \\ DP-Q1 \\ DP-P11 \\ DP-P12 \\ DP-P132 \\ DP-P15 \end{Bmatrix}$$

Equation 3-13: Path Dependency Contribution at Aircraft Manufacturer Y

The previous bar chart (Figure 3-9) is then modified according to the degree of the path dependency indicated in Equation 3-13 (see Figure 3-10). Path dependency defines the relative contribution of a DP to the benefit arising from an FR. Understanding the path dependency in the system design allows one to more accurately estimate the value of a DP to achieving the system design FRs.

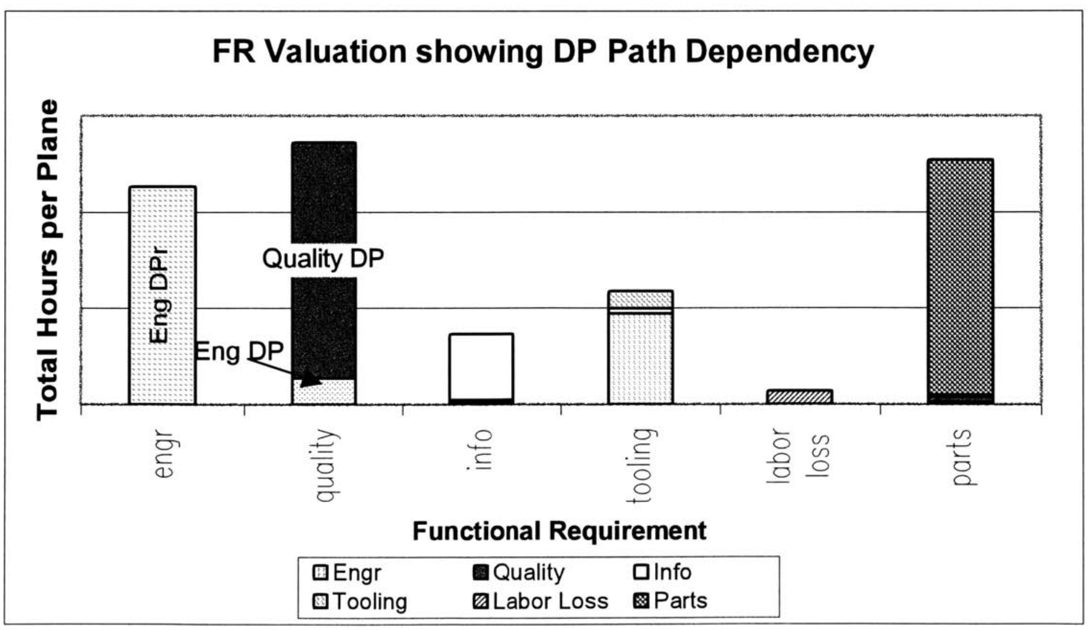


Figure 3-10: FR Valuation showing Path Dependency at Aircraft Manufacturer Y

For example, as seen in Figure 3-10, not fully implementing the engineering DP (DP-111) affects not only the achievement of its direct FR (FR-111), but also has significant effect on the achievement of quality (FR-Q1) and tooling (FR-P12) requirements. Figure 3-11 shows the total value of a DPs implementation. It is the summation of each DP's effect on its own direct FR and its path dependent FRs (i.e. depicted by summing the elements of each column in the design matrix [A] (shown in equation 3-13)).

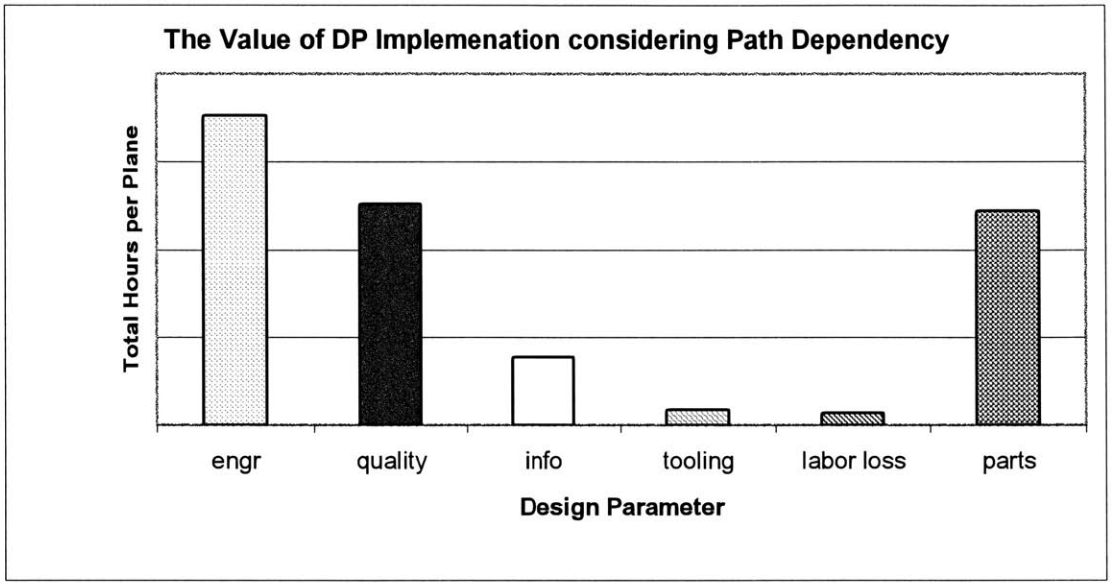


Figure 3-11: Allowable Investment in each DP

Accounting for path dependency yielded a more accurate estimate of the allowable investment in each of the DPs. Figure 3-11 shows that increased resources should be allocated towards implementing engineering (DP-111) and quality (DP-Q1).

The PDS represents a system design in its entirety. **Every** FR must be achieved for the design to be complete. However, given limited resources, the knowledge of the path dependent relationships provides a scientific basis for the allocation of resources.

3.6.5 Project Devleopment and Resource Allocation Implementation Steps

To fully implement the project development and resource allocation methodology developed in this chapter, it is recommended that Aircraft Manufacter Y undertake the following steps to implement this methodology:

1. **System design evaluation to identify the health of the current system.** This can be accomplished through a questionaire developed by Linck [Link 2001]. Linck [2001] developed a questionaire that enabled particpants in the production system to judge the achievement of their manufacturing system towards achieving the leaf level FRs in the MSDD.

2. **Valuation of FRs not fully achieved** - Estimate the potential benefits to be gained from each FR. If the benefit to an FR cannot be quantified, denote with a '+'.

3. **Evaluate organizational strategy** – Understand the inherent flexibility in the organization the options around project timing available to the organizaiton.

4. **DP contribution** - Understand the path dependency between valued FR to multiple DPs to derive the total contribution of a DP. This can be accomplished through the development of the [A] and [R] matrices.

5. **Creation of DP implementation project** – Projects should be created to further implement design parameters.

6. **Project redesign** – Projects should be further improved by considering the linkage to the design parameter and the greater enterprise system, and the required resources defined. Components of a project can be improved by careful selection of the types of resources required to implement a design parameter. Furthermore, the actual resources used to implement the project can be improved through local selection choice and comparison.

7. **Valuation** - NPV or ROV analysis of the expected benefits of achieving the FRs resulting from the investment in a DP, and most importantly the project's sensitivity

to investment levers. The NPV or ROV analysis can be used to identify possible areas of leverage to enhance the benefits achieved gained through achievement of the path dependent FRs.

3.7 *Conclusions from Project Development and Resource Allocation*

There currently is an understanding of the need to link resource allocation to the enterprise system to advert poor performance caused by system instability. The need to understand the enterprise's system is demonstrated throughout defining a resource allocation strategy for the company and a project, the resource and project design, and the options available to enhance the choice of resources utilized during physical implementation.

To define a project-based resource allocation strategy, the inherent flexibility of the organization, and the organizational synergy needs to be understood. The ability for the manufacturing system to meet the requirements of system stability is required to understand the sensitivity of different project options to achieve the System Design. Projects need to be centered on implementing DPs where there is considerable economic benefit to the manufacturing system. Once the sensitivities of a project's possible performance are understood, economic value can be created through further redesign of the project's type of resources and then its actual choice of resources.

The path dependency of resources, over-engineering, and risk management should be considered during the development and selection of resources to use within a project.

The physical implementation of a project should be aimed at reducing the overall procurement cost without undue risk. This can be achieved through the combination of designing fit for purpose components, using industry standards and benchmarking with industry best practices.

CHAPTER 4: SYSTEM DESIGN IMPLEMENTATION WITHIN A MANUFACTURING PLANT

4.1 Introduction

The resource and investment allocation methodology described in the previous chapter forms one component of the System Design (SD) Approach that has been developed by the PSD Laboratory. The MSDD described in Chapter 2 forms the backbone to the SD approach. The other components of the SD Approach are the 4+10 method for organizational improvement, and the application of physical modeling (Refer to Cochran et al 2001 and Cochran 2002 for a discussion on these components). Before the resources allocation methodology from Chapter 3 can be applied, the principles of the MSDD must be learnt and adopted by the organization. Key stakeholders and their constituent members in the organization have to learn and adopt the SD approach.

The PSD Laboratory's interaction with Plant N during the redevelopment of Plant N's manufacturing system is used as a case study for understanding the learning processes involved with adopting the SD Approach. A System Dynamics model was created to capture and understand the learning and adoption processes at Plant N (refer to Sterman 2000 for a through discussion on System Dynamics). The System Dynamics model assumes adoption and learning is a result of Plant N being a living enterprise. Key stakeholders are analyzed to identify and understand their interest in the SD Approach, and provide insight into their behavior. The dynamics of adoption are then analyzed and compared to models in the literature. Inhibitors to the adoption process are also then described and compared to the literature. Recommendations are then drawn from the structural nature of the model to accelerate and sustain the adoption of the SD Approach at Plant N and generically at other automotive plants.

4.2 Introduction to Plant N

Plant N is a tier one automotive components supplier whose purpose is to manufacturer a commodity component for an automobile. The long-term profitability and viability of Plant N is currently uncertain. Previously options were considered to either close the plant or sell it to a competitor. However, both the trade union and senior management have together agreed to try and turn the plant around and return it to profitability. Within the plant, local management and the local chapter of the union initiated the PSD Laboratory to assist in the redevelopment of Plant N's manufacturing system and provide System Design training.

4.2.1 Plant N as a Living System

For Plant N to firstly adopt the SD approach and secondly to implement these principles, Plant N is required to be a living entity that is capable of learning. If a company were merely "bundles of assets" they would be dead objects, and learning would be impossible for them [DeGeus 1997 pg 91]. 'Companies can learn because they are living beings' [DeGues 1997 pg. 91] and that the actions a living entity makes is a result of its learning processes. To define what is a living entity, DeGeus uses Stern's concept of a persona [DeGeus 1997 pg 85], with the key attributes of a persona being:

- The persona is goal oriented, with longevity as the goal.
- It is conscious of itself. The persona knows its own internal structures and also knows how it fits into other structures. It is part of a hierarchical structure.
- It is open to the outside world. The persona is an open system, where new tangible and intangible elements constantly enter and exit, and the persona interacts with the outside world.
- It is alive but has a finite lifespan. The persona is born, it lives and one day it will pass away.

SD Adoption arises only as a result of learning. Stern postulates that a living entity learns through the mechanism of introception [De Gus 1997]. Introception is the ability to be aware of one's own stance and its position in relation the rest of the world. Introception occurs at three levels, at a biological level (i.e. is it hot? Cold? Does the environment excite us?), at a direct experiences level (memories of positive experiences that occurred in the past), and at a values and beliefs level (where all our principles and beliefs are open to question in light of the values and attitudes of our environment) [DeGus 1997]. At Plant N, introception at a biological level occurs from external threat and stimuli such as materials supply, competitor action or customer changes. Introception from direct experiences could be from how the last crisis was solved the previously, or how the plant was able to improve earnings in the past. Introception from examining a corporation's values and beliefs arise through strategic rethinks about Plant N's purpose in the greater corporation.

As part of the SD Approach, Plant N is required to identify and react to changes in its manufacturing system. This requires Plant N to have a living manufacturing system. The concept of a living manufacturing system is mentioned widely in relation to the SD approach and the Toyota Production System. Ohno and Cochran have described the need for the identification and reaction to changes in the manufacturing system to derive from decision mechanisms that are similar to how the human body reacts to changes within its environment. Cochran commonly refers to the enterprise's need for a nervous system, and the different components of an enterprise system to be analogous to the types of flesh that performs various functions in the human body [Cochran 1994]. The nervous system would firstly, enable the constituents of the system to "feel" how the system is performing, and understand how individual actions contribute to the overall performance of the system. Secondly, when conditions in the system change (e.g. problem conditions), the constituents would be able to feel the problem arising and be able to react in a predefined manner. Ohno [Ohno 1988] describes a business organization as comparable to the human body. The autonomic production system through the use of kanban is similar in function to the autonomic nerves in the human body that work without regard to human wishes. Ohno postulates firstly that if every small change in the system required the brain to react, the business will be unable to avoid burns or injuries and be unable to capture new opportunities [Ohno 1998]. Secondly, the organizational strength that is required to adapt to internal and external changes is similar to the strength acrobats have in their spine in order to be flexible and perform acrobatic maneuvers.

4.3 Stakeholder Analysis

Within an organization, there are many stakeholders who can influence the direction and the speed of change. Stakeholders can include, Management, Shop Floor Employees, Trade Unions, Customers, Government Regulators and community groups (e.g. Environmental Groups, Trade Associations etc).

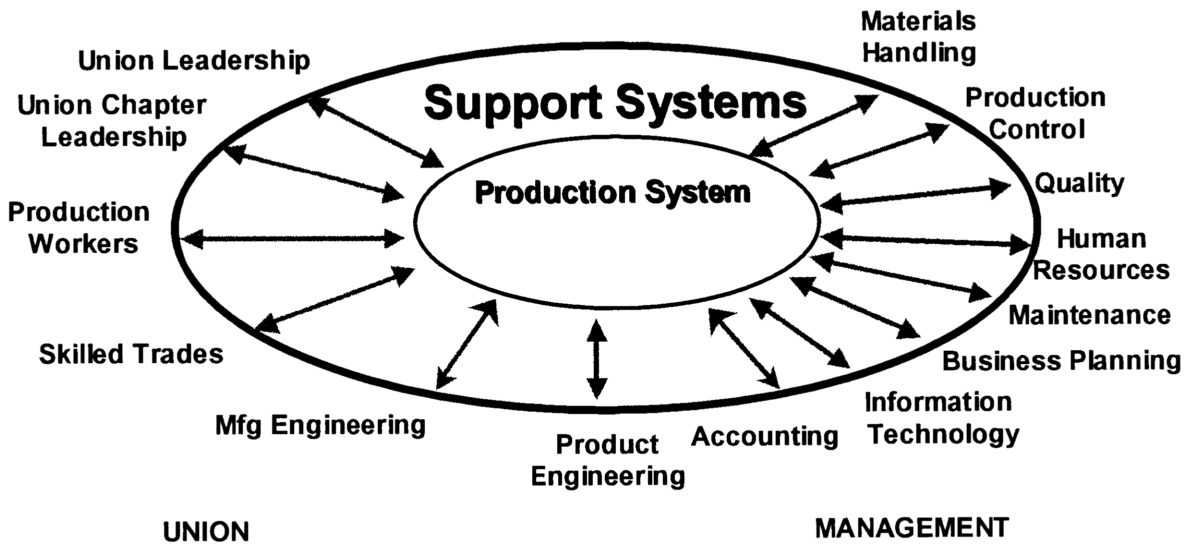


Figure 4-1: Change Initiative Stakeholder Composition.

To each of the stakeholders, a change to the policy in which company resources are allocated, can be viewed politically, strategically and culturally. Each stakeholder has his or her own interests towards the development and implementation of the SD Approach. The governance of Plant N comprised of a partnership between the Local Trade Union and Plant Management. Plant Management and the Local Trade Union are the key stakeholders affected, and have the ability to influence the adoption of the SD Approach within the plant. Other stakeholders cannot significantly influence the adoption, and are not directly affected by changes to the plant's operating system.

The interaction between different stakeholders can affect the overall adoption within the plant. Negativity by either the Local Trade Union or Plant Management could have a detrimental effect towards the plant adoption of the SD Approach (Section 4.4 describes the adoption dynamics in further detail). This was expressed through a common concern to change by shop floor employees, "Is management serious to commit to this change?" and managers were afraid that workers would reject any changes and demand concessions for any changes from the status quo. As a result, stakeholders referred to new initiatives as 'the plan' or 'somebody else's plan' and initiatives only became passing fads.

4.3.1 The Local Trade Union (LTU)

The Local Trade Union is a chapter of a national union that is very prominent in the automotive manufacturing industry. The parent union represents all workers (skilled and production) who work for the three largest US manufacturers in this industry. The union has a strong presence in the development of the industry. As part of further developing the industry, the union has been providing knowledge and advice on manufacturing systems improvement to local chapters and plant mangers.

4.3.1.1 LTU - Strategic Impact

The Local Trade Union's purpose is to provide a valuable service to its members, and represent its members' interests to other parts of the organization. At Plant N this can be interpreted strategically as firstly ensuring the long-term survival and viability of the plant (i.e. ensure that its members have a job to go to), and secondly, to maintain or improve the level of benefits (both monetary and non-monetary) received by its members. The SD Approach was expected to improve operational practices and overall plant profitability, and hence had a good strategic fit to meet the local trade union's first strategic goal. Combining the SD Approach ownership with workgroups enables the Local Trade Union to meet its second strategic goal.

Ownership of the SD Approach implementation can increase the contribution of the union to the plant and the greater organization. Union leadership and technical assistance can accelerate the rate of shop floor employee and management adoption of the SD Approach.

In conjunction with the SD Approach, the union has also championed the use of workgroups in the plant. Through workgroups and the SD principles, shop floor employees will have a greater control over the operation of the plant. This in turn increases the overall power the union has to ensure that the number of workers and their benefits remain at the status quo or improve.

4.3.1.2 LTU - Political Impact

Adopting the System Design principles politically affects all stakeholders. In the trade union, the relationships among the local chapter, the national union leadership and management are all affected by the adoption of the SD Approach at Plant N. The evolution of ownership from the PSD Laboratory to trade union leadership and then to the plant will dictate the overall political impact within the local trade union.

The local chapter of the trade union will face political pressure from within itself as it seeks to look after its own interests, corporate level union interests and the interests of its members at Plant N. The Local Trade Union could face political pressure from management, its own members, and union leadership could arise if the interests for all three parties are not aligned. The local chapter will have a greater role in the leadership of the plant as a result of the SD Approach and the workgroup structure. This could lead to political pressure from managers whose role changes as a result of the SD Approach and union members who are against the SD Approach. The local trade union chapter is also responsible for resolving any difference between local members and national union leadership. The political conflict between local union members and national union leaders is however unlikely, as the consequences of not changing are greater i.e. closing the plant down and possible redundancy.

At a corporate level, the adoption of the SD Approach at Plant N provides a new precedent for union leadership. Successful implementation at Plant N provides a strong argument to implement the System Design Approach at other plants and enhance the overall union leadership within the organization. This can create the issue of whether corporate wide success is more relevant than success at Plant N. The likelihood of this occurring however is small. Success at Plant N is required before the approach can be applied at other plants.

The final political issue is the ownership of the SD initiative at Plant N. The SD Approach was brought to Plant N by national union leadership external to the plant. This could lead to a political conflict between local members, union leaders and management. It however has been noticed that ownership of the approach has shifted as the local union chapter and management have adopted the System Design Approach. As local responsibility and ownership has increased, it is expected that individual workgroups and shop floor employees will eventually own the initiative.

4.3.1.3 LTU - Cultural Impact

Both Plant Management and the Local Trade Union leadership have described the SD Approach as a paradigm shift that would return the plant to viability and long-term sustainability. The intention for union leadership was to have both local union members and managers redesign their operating practices and manufacturing system, and then use the workers and their workgroups as a foundation for continuous improvement.

Local union members were however viewing the initiative with caution. The shop floor employees feared the initiative may be just another fad, and were uncertain about management's commitment to allocate resources to support the initiative.

To overcome the fears from local union members, both Plant Management and the Local Trade Union leadership has continually endorsed this initiative. Participation in pilot groups and educational seminars has also been used to communicate union and management leadership's intentions to local union members. The Plant Manager and Union Chapter Chairman have appeared throughout the pilot process, and made personal endorsements of the SD to overcome people's fears.

4.3.2 Management

The management stakeholder comprises of two groups, Plant Managers who are responsible for the plant, and Corporate Managers who are responsible for the greater corporation. The composition of the plant's management had been adjusted prior to the plant's involvement in the system design process. The plant's management now comprised of a mix of previous plant managers and specialist managers brought in from other parts of the organization. Members of the new management team were veterans in their manufacturing sector and were proactive towards encouraging SD adoption within the plant.

4.3.2.1 Management - Strategic Impact

Management had two strategic objectives, Corporate Managers were responsible for the long-term profitability and sustainability of the corporation, and Plant Managers were responsible for profitability of the plant. Adopting the SD Approach enabled Plant Managers to achieve the strategic goal of plant profitability, and provided corporate management an opportunity to incubate a new operating approach. Senior Plant Managers emphasized the strategic merit to all plant managers through a series of 'steering' committee meetings. However, there remained factions of management who were not aware or opposed to the strategic goals. Primarily it was mangers that would be required to change their day-to-day work practices that were the most opposed to the SD Approach.

Management's strategic objective in implementation and adoption of the SD Approach was to support the local union. The local union by itself did not have the resources to design and implement the initiative, which enabled management to actively participate in the customization of the SD Approach within Plant N.

4.3.2.2 Management - Political Impact

The adoption of the SD Approach had two political impacts on management. These impacts were firstly on management's responsibility for changes in the plant's operating practices and secondly on a strengthening of the union's leadership in the plant. The increase in union leadership could spread throughout the organization and is concern for both plant and corporate level managers.

The intent of management was to act as a partner and as a resource for the union to implement the SD Approach. This gave the union ownership of the process. It also made the union responsible for the resulting changes to the manufacturing system. This enabled management to avoid the traditional confrontational approach to management-union negotiations for changes to the manufacturing system.

The adoption of workgroups and the SD Approach increases the level of leadership the union has within the plant. As a result, the leadership role of plant management changes, and in some respects diminishes. If managers perceived that their political power within the plant was diminished, their only recourse to stop the erosion would be to prevent the adoption of the SD Approach within the plant. The consequences from not adopting would be detrimental to the plant, as the status quo was not sustainable in the long-term. Hence it is considered to be in the local Plant Management's political interest to allow the shifting of their political power in the plant to enable the long-term viability of the plant.

To Corporate Managers, the change at Plant N affects their political relationship with their union counterparts. This initiative provides a precedent for how other plants may operate if the initiative is successful. Corporate Management can be brought into the process by plant management to support the management's interests in SD Adoption.

4.3.2.3 Management - Cultural Impact

The culture for management in the plant changes with the adoption of the SD Approach. Plant Management's primary focus changes and union members become responsible for former management functions. The role of managers is redefined to leading and supporting system improvements in the plant rather than 'fighting fires'. Management control is shifted from responding to every problem to keep the status quo, to defining and implementing produces so that the manufacturing system automatically responds to problem conditions. This enables management to devote more resources towards overall system improvement and further implementation of DPs.

Plant N's SD adoption increases the role of the union in the plant's leadership. To a majority of management, this is an extension of the existing partnership between management and the trade union. However to dissidents within management, this initiative was originally viewed as a 'union encroachment' with certain middle managers acting in a hostile manner initially. However, the views of the initial dissidents changed, as they themselves learnt and adopted the SD Approach.

4.3.3 Stakeholder Analysis Results

The adoption and change model should draw upon the following conclusions:

- Shop floor adoption is different from management adoption. Shop floor adoption is driven by the commitment of both the union and management.

- Management has the additional resistance of 'losing control' in the plant.
- Both management and the union have external pressures on them to adopt and implement the change initiative.
- The internal resistance to both management and the union is low. The consequences for not adopting are too great.

4.4 System Dynamics Model of Plant N Adoption of The System Design Approach

A system dynamics model was developed to capture the actions of the two stakeholders at Plant N, as they adopted and implemented the SD Approach. Sterman 2000 provides a detailed introduction into the System Dynamics methodology. The results from the stakeholder analysis lead to a model that was structured into four components to capture the results from the stakeholder analysis:

1. The adoption process of the unionized workforce.
2. The adoption process of the plant management.
3. The amount of successful projects as a result of adoption.
4. The amount of change that has occurred within Plant N. This is defined as the cumulative sum of the amount of successful projects from adoption.

The basic causal structure of the model is shown below in Figure 4-2.

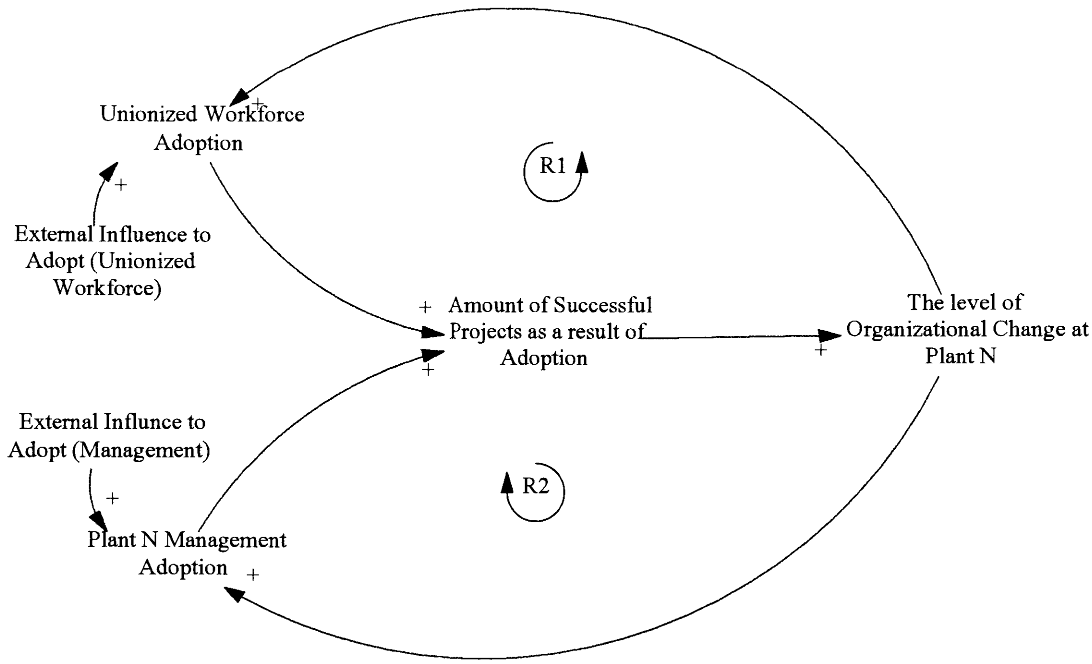


Figure 4-2: Simplified Causal Structure of Adoption at Plant N.

Within each of the basic adoption processes there is an exogenous variable, which is the external influence to be adopted. A Bass model is modified to capture the dynamics of adoption for the management and union at Plant N, with the learning process captured with people shifting from Potential Adopters, to Adopters, and to Champions of the Change. Reinforcing dynamics at Plant N that encourage adoption and learning are then added to the modified Bass model, and compared to models in the literature. The dynamics of inhibitors to adoption and the SD Approach are then presented and compared to the models proposed by Senge et al 1999 and others.

The complete stock and flow structure of the adoption process for the SD approach at Plant N is shown in Appendix 2.

4.4.1 The Bass Model for Diffusion and Adoption

The structure of the Bass model captured adoption process at Plant N. Both management's and the unionized workforce's adoption to the SD Approach was influenced by the existing level of adoption, and the power of an external influence to initiate the process and provide commitment to the Plant N.

The Bass model is a diffusion model developed by Frank Bass [Bass 1969]. It is one of the most popular models for new product growth and is widely used in marketing, strategy, management of technology, and other fields [Sterman, 2000]. The Bass model overcomes the initial problem associated with other simple adoption models such as the SI model for infection (S being the those who are susceptible, and I being those who are infectious), by assuming external information sources such as advertising or a consultant can alert potential adopters to the option of adopting.

Sterman [Sterman 2000] describes the Bass model's original introduction primarily was as a tool for forecasting sales of new products. Bass did not specify the nature of the feedback at the operational level, however Sterman described the feedback is interpreted usually as being word of mouth (social exposure and imitation) or external sources of awareness, and adoption is interpreted usually as the affects of advertising. Modifying the terminology of the Bass model to suit the introduction of the SD Approach at Plant N, the Bass model for each stakeholder (the union and management) is shown in Figure 4.3.

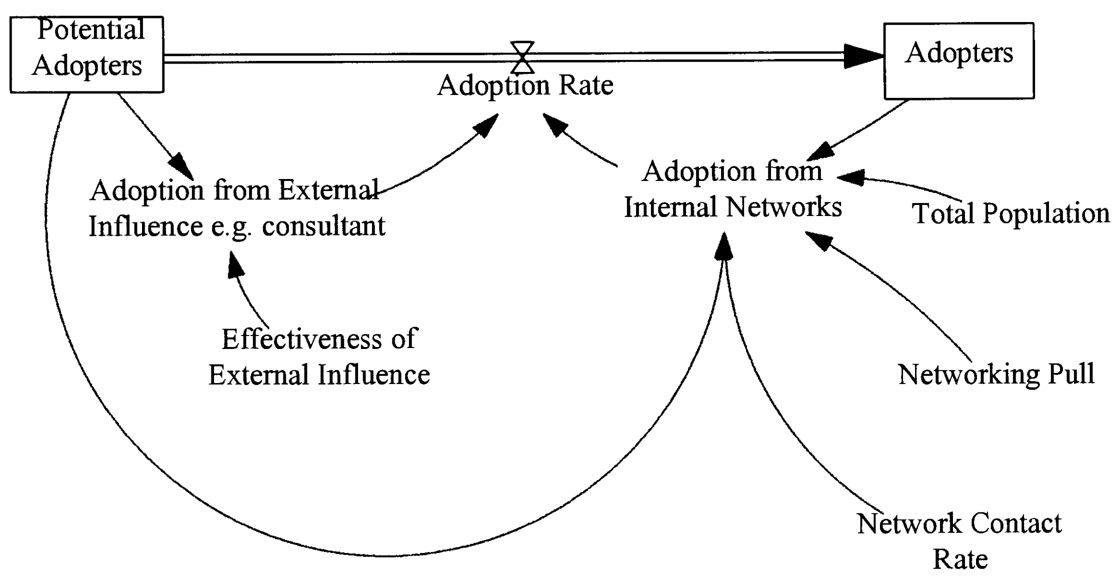


Figure 4-3: Bass Model for Adoption (from Sterman 2000) modified to describe adoption of the System Design initiative at Plant N for each stakeholder.

Figure 4-3 shows that the rate of change, or the total adoption rate is the sum of the adoptions from internal networks and the adoptions from external influences e.g. consultants. Initially when change is first introduced, the adopter population is zero, with promotion of adoption by external influences being the only path to adoption. This external influence is initially large and declines as the pool of potential adopters shrinks. Assuming that the Effectiveness or External Influences, the Network Contact Rate, and the Network Pull remain constant, the Adoption Rate (AR) for each stakeholder can be described as:

$$AdoptionRate = Adoption\ \ from\ \ External\ \ Influences + Adoption\ \ from\ \ Internal\ \ Networks$$

$$Adoption\ \ from\ \ External\ \ Influences = Effectiveness\ \ of\ \ External\ \ Sourcces \times \\ Potential\ \ Adopter\ Population$$

$$Adoption\ \ from\ \ Internal\ \ Network = \frac{Network\ \ Contact\ \ Rate \times Network\ \ Pull \times Potential\ \ Adopters}{Total\ \ Population}$$

Equation 4-1:Mathematical Representation of a modified Bass model for the adoption of the System Design Initiative at Plant N for each stakeholder.

Equation 4-1 can be expressed compactly as:

$$AdoptionRate = Effectiveness\ \ of\ \ External\ \ Sourcces \times Potential\ \ Adopter\ Population + \\ \frac{Network\ \ Contact\ \ Rate \times Network\ \ Pull \times Potential\ \ Adopters}{Total\ \ Population}$$

Equation 4-2:Compact Mathematical representation of the modified Bass model for the adoption of the System Design Initiative at Plant N for each stakeholder.

The modified Bass model above, currently does not account for any diminishing propensity by Adopters or the resistance to adoption felt by Potential Adopters and Adopters when considering the adoption or further mastery of System Design. Adopters never stop continuing to be Adopters, and their encouragement for Potential Adopters does not change over time. However, at Plant N the Adopters' enthusiasm and commitment for the System Design initiative can vary over time, both increasing and diminishing (previous initiatives have come to be known as fads). If Adopters have continued success from the SD Approach, they develop a mastery of SD Approach and may wish to promote and encourage more Potential Adopters to adopt. Eventually with further mastery, Adopters become Champions of the Change. Conversely Adopters' may no longer be inclined to promote the approach further to Potential Adopters and become Passive Adopters. Finally, Adopters may simply leave the organization/system for a number of reasons.

The Adopter population can be broken down into subsections that represent their degree of support for the SD Approach. In the model below (Figure 4.4), 'Former Adopters' have been characterized into four main groups, those who passively continue to employ the change initiative, those who are now masters or champions of change those who have stopped applying the change initiative, and those who have left the system. The rate at which Adopters change their habits has been assumed to be a first order decay.

Active Adopters and the Champions of Change are now the only influence Potential Adopters receive internally to adopt. These are Adopters who still fully endorse the change, and who are able to and wish to promote the change initiative further within the organization.

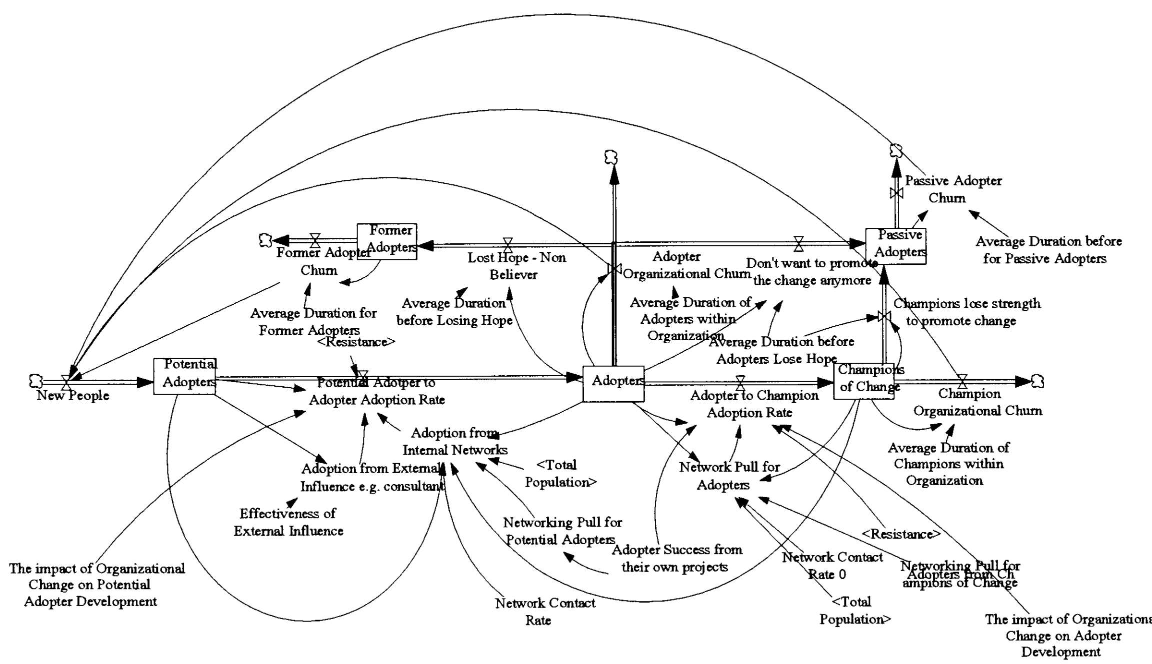


Figure 4-4: Modified Bass Model including changes in Adopter Behavior and increased complexity in the adoption process at Plant N for each stakeholder.

The behavior of the modified Bass model with the new additional phases (i.e. the stocks and their decision analysis) in the adoption process is shown in Figure 4-4. Sterman [Sterman 2000] showed that a modified bass model was analogous to a SIR epidemic model (Susceptible population, Infectious population and Recovered population). The tipping point for an epidemic to take place is similarly analogous to the point at which adoption is sustainable. In this model of Plant N, the tipping point at which enough momentum has gathered for adoption to be sustainable occurs when the adoption rate is greater than the total rate of Adopters and Champions of Change stop promoting adoption or leave the plant (i.e. leaving the organization, becoming passive and no longer wanting to promote the initiative, or losing hope and no longer believing in the initiative).

4.4.2 Reinforcing Change and Adoption

This reinforcing nature in the modified Bass model above (Figure 4-3) shows that adoption is partially driven by the ability for Adopters and Champions of Change to convince Potential Adopters to adopt. The rate at which Potential Adopters adopt is a function of the number of Adopters and Champions of Change, and the success that Adopters and Champions of Change have had with the SD Approach. This process continues to reinforce itself until there are no Potential Adopters remaining. For Potential Adopters, the reinforcing nature of adoption can be broken down into three types, firstly due to their individual success, secondly due to internal diffusion from other adopters, and thirdly due to overall positive results at Plant N.

4.4.2.1 Individual Success

As people at Plant N realized personal achievements from their use of the SD Approach, they are likely to reinforce their commitment and invest towards further success. This in turn would create further personal achievements and investment. In the stock and flow structure in Figure 4-5 this was represented by adopters creating successful projects. These successful projects in turn reinforces the merits of adoption, and give Adopters further incentive to use and master the SD Approach. This leads to Adopters becoming Champions of the SD approach at Plant N.

The rate at which successful projects are created and implemented is a function of the number of Adopters, and the availability of Champions to guide adopters through the development and implementation of their projects.

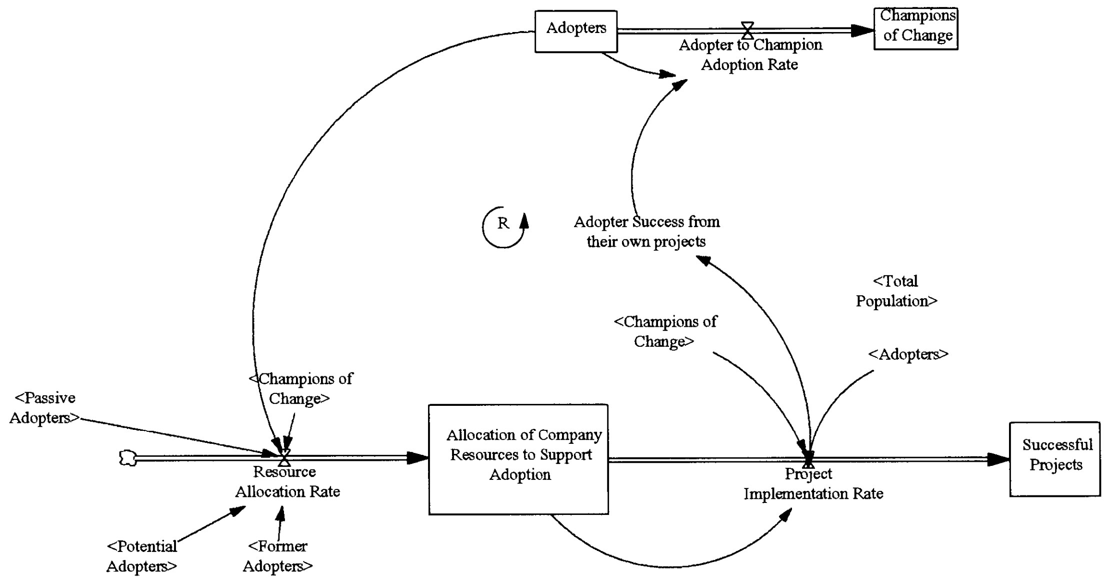


Figure 4-5: The Reinforcing Loop for Personal Results.

This pattern of behavior coincides with observations in the literature. People seek joy in work [Deming 2000], so people will continue to commit and invest in work that brings them joy. To describe this behavior, Senge et al 1999 proposed the 'Because it Matters (Personal Results)' growth loop (see Figure 4-6).

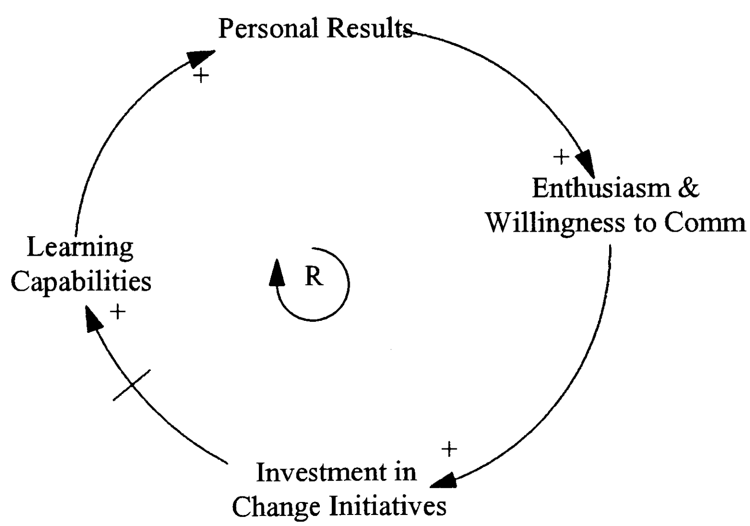


Figure 4-6: Senge et al 1999 'Because it Matters' Reinforcing Loop

Senge et al 1999 states that this growth loop will be 'balanced' or inhibited if people's personal and family lives are sacrificed. The inhibitors of the 'Because it Matters' loop are:

- Management. Management will need to recognize the difference between committed people and compliant people. People have their own ideas and passions, and management may loose control of the process.

- Over-zealousness. As the level of commitment people have to the initiative increases. Without defined boundaries, people may sacrifice their life outside the organization.

- Organizational creditability. Initial Adopters may be ineffective at convincing their peers to adopt, and their own credibility within the organization may be diminished in the process.

The overall result at Plant N was that individual success was enabled through external and internal change champions (PSD Laboratory and Union Experts) being involved to create the environment to adopt. As part of management adoption, Managers understood that their role in the plant was changing, and a reduction in control was part of their adoption. The credibility to adopt was expressed through Union and Management recognition and a number of open and candid forums where people could express their experience with the SD Approach. Plant Management and the Union Leadership limited burnout through ensuring the plant had sufficient resources to operate during the adoption period, and through the sequencing of the adoption process within the plant.

4.4.2.2 Internal Adoption through Diffusion

The reinforcing dynamic that drives adoption occurs through existing networks that include Adopters, Potential Adopters and Champions of Change. Adopters and Champions of Change are able to diffuse their knowledge and success from the SD approach with Potential Adopters, and Champions of Change can help Adopters gain experience and mastery. Within the proposed model of adoption at Plant N, the diffusion reinforcing process is captured in Figure 4.7 by both the influence of Adopters and the Champions of Change from both Management and the Unionized Workforce, and their ability to diffuse their experiences to Potential Adopters within Management and the Unionized Workforce.

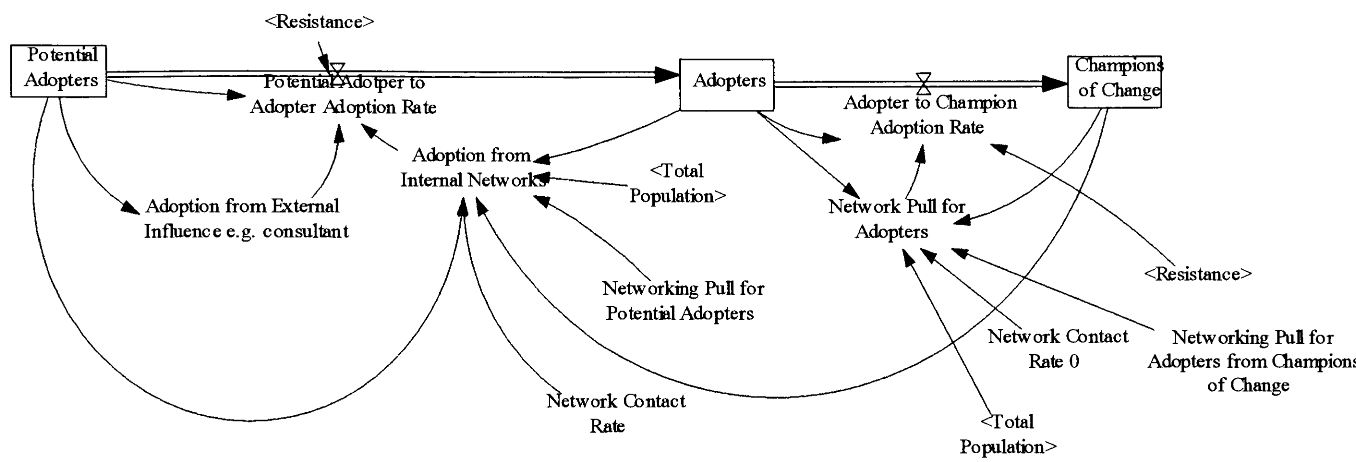


Figure 4-7: Stock and Flow Structure of Internal Diffusion at Plant N

In the literature, Senge et al 1999 proposes a reinforcing loop 'because my colleges take it seriously', which shows for a generic organization how a change initiative can be diffused through the internal networks present within the organization. In this model (see Figure 4-7), networking and diffusion creates enthusiasm for change, which then leads to increased investment and people being involved with the initiative. This behavior can however be attributed to another condition, i.e. people are not prepared to join the initiative until they see personal or business results being achieved by those who have adopted (refer to the following discussion on business results).

These informal networks however, Senge et al 1999 describes a very powerful pathway to transmit change through an organization for the following reasons:

- These networks already exist in organizations, and spreading change initiatives through them is a natural extension.
- Information that passes through these networks has credibility. Potential Adopters believe the information and results Adopters achieve through the change initiative.
- These initiatives provide a safe environment for Potential Adopters to experiment and apply the change initiative to their area within the organization without any pressures form above.

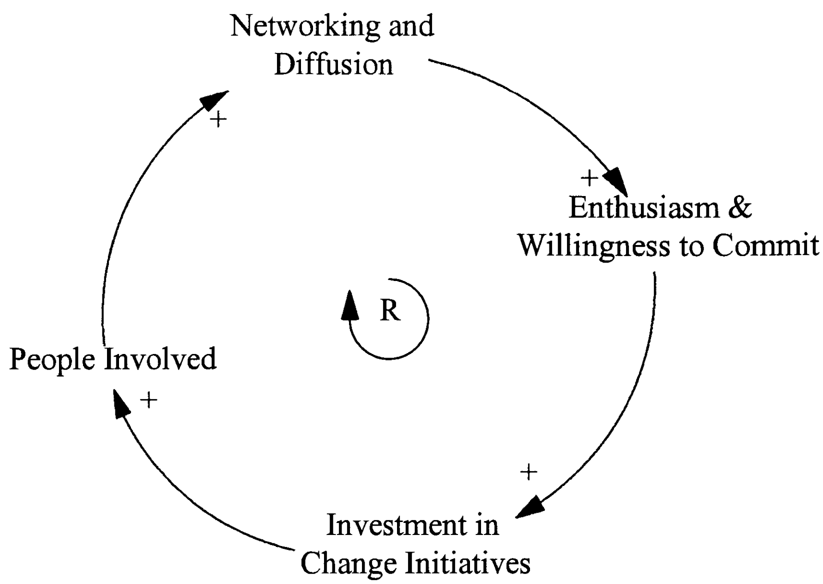


Figure 4-8: Senge et al 1999'Because my colleagues take it seriously' Reinforcing Loop.

At plant N, this reinforcing dynamic was enhanced through the creation of a number or forums. These forums comprised of existing networks within the plant, and brought together board cross sections of the plant that could share their experiences and learn from each other informally.

4.4.2.3 Achievement of Business Results

At Plant N, the goal of the SD Approach was to improve business results and ensure the long-term viability of the plant. As Management and the Unionized Workforce began to adopt, improvements to the business results became apparent. This improvement in business results reinforced the application of the SD Approach and was one factor to encourage Potential Adopters to adopt. This reinforcing behavior is captured in the stock and flow structure in Figure 4-9.

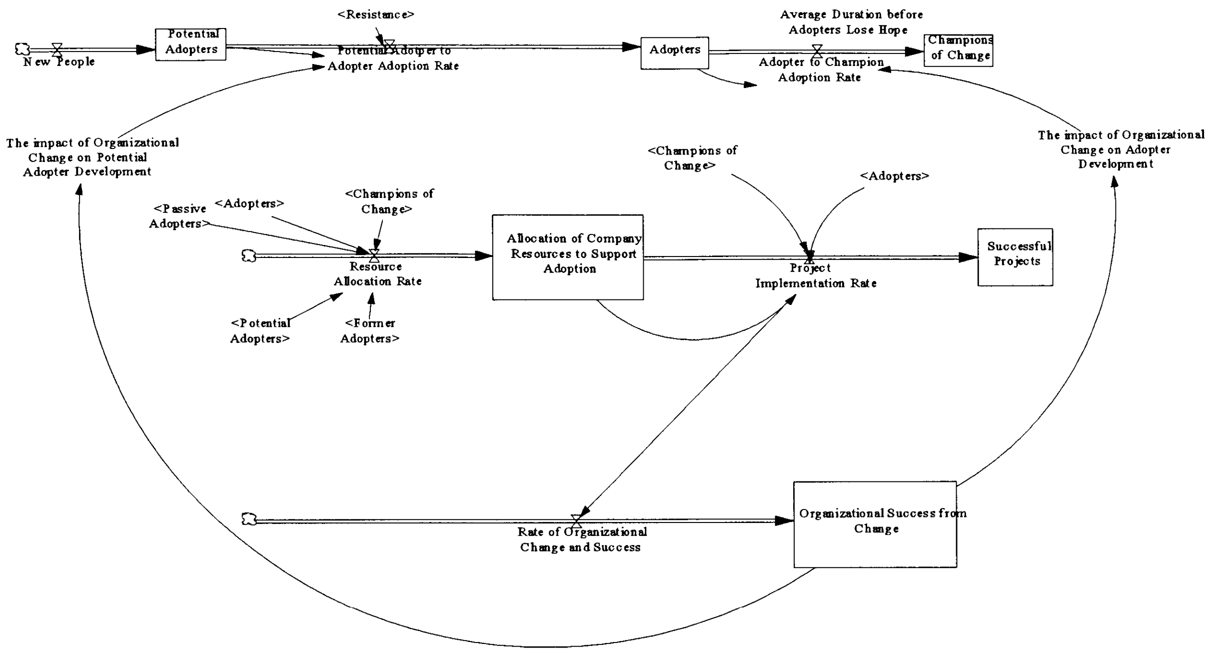


Figure 4-9: Stock and Flow Structure of Adoption from Achieving Business Results.

In the literature, Senge et al 1999 describes improving business results as being one of the goals of change. Senge proposes that a change initiative would lead to new capabilities and business practices. These new business practices would then lead to new successful projects, which would enhance the credibility of the change initiative. Enhanced credibility would lead to increased investment and greater enthusiasm to adopt, which would further create new business practices. This reinforcing loop is shown in Figure 4-10.

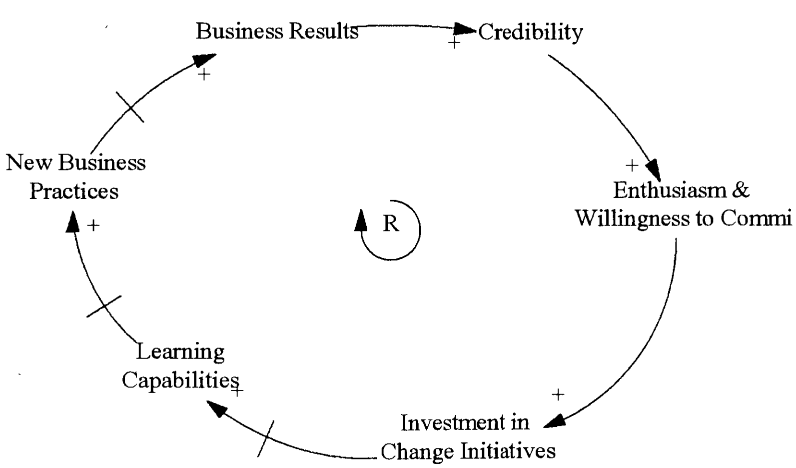


Figure 4-10: Senge et al 1999 'Because it works' Reinforcing loop

Senge 1999, however also identified problems with this causal relationship. These problems are summarized as:

- It is often difficult to quantify the improvement in business results.
- Mixed results that may occur as a result of experimentation and teething problems during adoption may tarnish the image of the change initiative leading to improvement.
- There are significant delays between adopting the change initiative and the fruition of improvements to business results.

At Plant N, the current Plant Operating System was closely monitored. Through resource allocation the time delay between action and result was not severe, and through monitoring the impacts of various improvements could be easily identified and quantified.

4.5 Inhibitors to Change

Plant N's commitment required to develop and implement the SD Approach must comprise firstly to learning and teaching the System Design Approach, and secondly to overcome the inhibitors to adoption. Inhibitors to adoption modeled by Senge et al 1999 have been included directly into the adoption model at Plant N if present, or collected under the generic variable resistance if they were not observed.

4.5.1 Infrastructure to Support Adoption

The level of support to adopt available is one factor that governs the speed at which people can learn or 'adopt', and implement successful projects. Stern [2000], Senge [1999] and Ohno [1988] recognized that the difference in the level of support required and the level of support given to a change initiative can inhibit the rate at which an organization changes.

At Plant N, support is received from external influences, Champions of Change, and the Adopter population. Champions of Change and External Influences provide support for Adopters to develop mastery of the initiative. Potential Adopters received support from Champions of Change, External Influences and the Adopter population (see Figure 4.10).

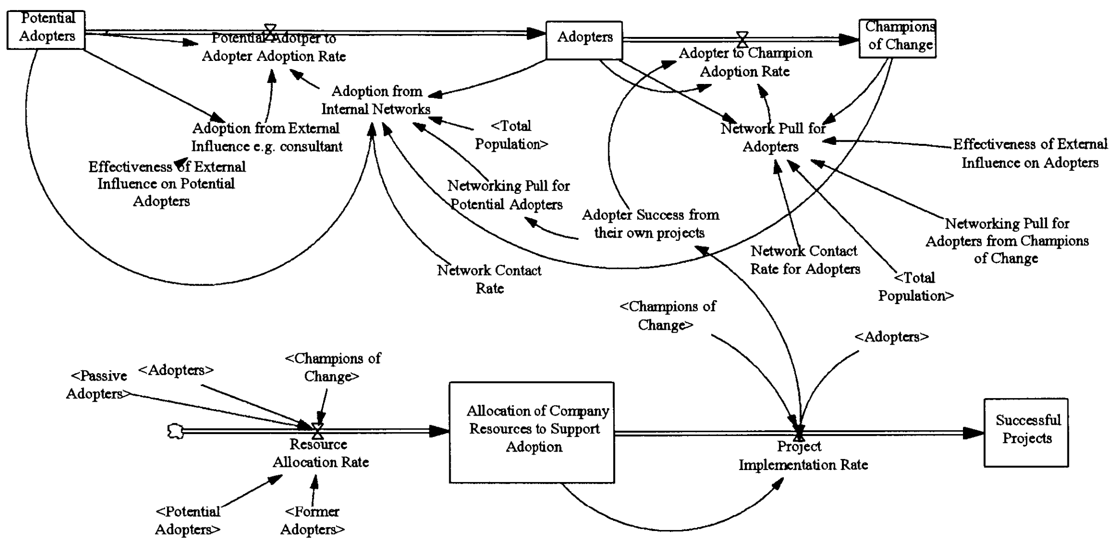


Figure 4-11: The Impact of Coaching available at Plant N

Figure 4-11 also shows that the impact of Champions of Change and the Influence of External Consultants has upon the rate at which resources are allocated successfully, and the rate at which individual projects are completed. The PSD Laboratory and Union Experts provided the infrastructure to initiate the System Design method at Plant N, and then were available to 'Train the Trainers' and create Adopters and Champions of Change within the plant.

4.5.2 Relevance

The ability for people to relate the SD Approach to their daily work is a fundamental factor for adoption to occur. People need to understand firstly that adoption in their work area is important for the plant, and secondly how their adoption can be implemented in their work area. Stern described the importance of linking the change initiative (in the case of Stewart Stern being EVA®) to the people involved and how remuneration could be linked to the initiative. Senge et al [1999] modeled this inhibitor as a gap between the commitment required, and the level of personal connection. This gap would then inhibit the enthusiasm and willingness of people to the change initiative.

Cochran has been able to develop a methodology to overcome a possible lack of relevance at Plant N, and link the SD Approach with the work that participants are involved with. Cochran has developed tools such as the Physical Modeling to capture relevance. Physical Modeling has enabled participants to see the linkage between their own work and the rest of the enterprise, and how their actions affect the enterprise as a whole. Physical modeling also provides an opportunity to see how changes to an individual's work practice can change the performance of the enterprise system [Cochran et al 2001].

As a result of Cochran's work at conveying the relevance of the SD approach to participants, non-relevance has only been modeled implicitly within the adoption model of Plant N. Relevance is assumed to be a function of the contact rate of Potential Adopters to Adopters and Change champions. As Adopters and Change Champions grow within the system, and the rate of successful implementation projects increases, Potential Adopters are assumed to learn the relevance of the change initiative through their own internal network, as shown in Figure 4-11.

4.5.3 Commitment to Change

Individual commitment for each stakeholder requires the support and trust from within the plant, and personal reflection upon the impact the adoption will have upon the individual. At Plant N, a degree of trust was lacking between management and union initially. This lack of trust is captured in the two quotes below:

"A lot of projects have started, implemented, run for a short time, and then dropped" Shop Floor Employee at Plant N.

"We will not implement this initiative without the support of the workers." Senior Manager at Plant N.

Both Management and the Unionized Workforce required personal reflection, as the SD Approach affected fundamental work practices for both groups. Unionized Workgroups would become responsible for their own work practices and improvement upon them.

Management's role would be redefined to helping sustain system improvements rather than the current daily 'fire fighting' to ensure the status quo.

The development of pilot workgroups provided an opportunity for the SD Approach to be discussed openly and freely between Management and the Unionized Workforce. The Unionized Workforce and Plant Managers were able to address each other's concerns and state their commitment to each other verbally. Physical simulation was used as a tool to allow both stakeholders to reflect upon their individual work practices and how their operations would be affected. Together through physical simulation and the open forums, management and the union could instill "trust" to the members of both stakeholder groups.

Senge et al (1999) modeled the commitment to change as a gap in personal reflection, and a gap in trust. The gap in personal reflection is the difference between the personal reflection required, and the safety for reflection and dialogue. This leads to inhibit the enthusiasm and willingness to commit in the organization. The gap in trust is a result of the difference between the clarity and credibility of management values and aims, and the trust in management required. This inhibits the credibility of the change process.

In the proposed adoption model at Plant N, the adoption process of management and union are separate. The influence that management has on shop floor employee adoption and vice versa is captured by the rate at which successful projects are being accomplished (see Figure 4-2 for simplified model of adoption).

Within the model, personal reflection is only captured implicitly through the constraints in internal diffusion and personal success. The time required to reflect is assume to be a first order delay. Not all potential adopters commit to adoption immediately; instead the contact rate and the levels of success they see from the SD Approach govern the rate of adoption.

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4.5.4 Performance Measurement

The expected and the actual performance of the SD Approach can differ throughout the implementation phase. The scorecard at which the impacts of change are judged, and expectations that the organization places upon the initiative can thus become an inhibitor to the System Design Approach's adoption and implementation.

The expected performance is generally a function of linear thought, whilst the actual performance is reinforcing and is exponential in effect. Consider the Toyota Production System (TPS) described in Chapter 2. TPS evolved over a considerable time period, and could be considered to have begun in the early 20th century with Toyoda Sakichi's autonomous weaving machine. It was not until after the second world war, that Ohno visited the US and the other principles of the TPS system developed further [Ohno 1988]. It was not until the 1970's that TPS's impact was recognized universally in terms of production, and earning per car produced.

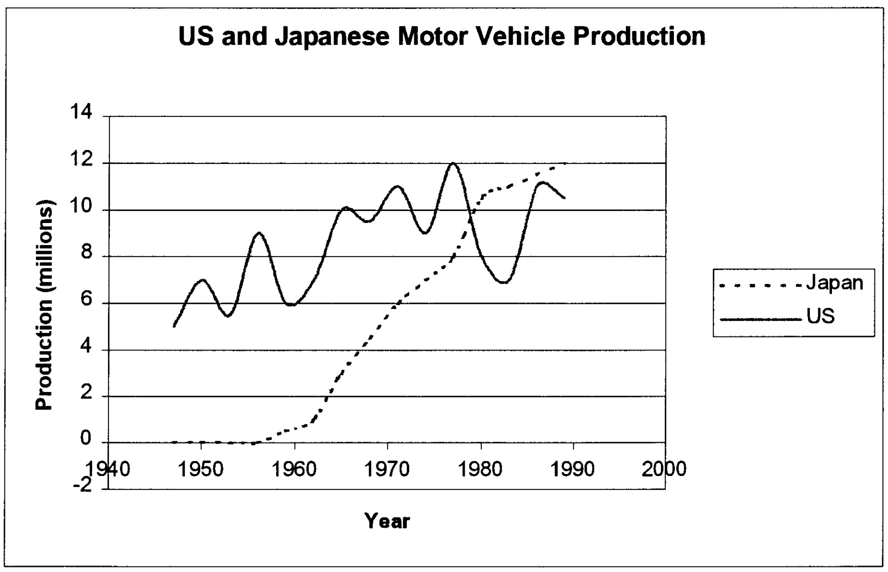

Figure 4-12: Comparison of US and Japanese automotive production between 1947 and 1989 [Womack et al 1990].

The early gap between the lineal expectation and the exponential performance is compounded further due to the delays inherent in the system before the value of the approach becomes apparent. This gap can put pressure on the adoption and learning process, and inhibit the rate of adoption and mastery.

Johnson [Johnson et al, 2001] however argues that information from performance measurements should not be used to guide day-to-day decisions about operations. Instead, decision-making should be guided by a deeply ingrained awareness and sensitivity to the workflow. If an organization followed Johnson's idea, this inhibitor would no longer exist.

This inhibitor can be overcome through a firm understanding of the time periods required before the results of the SD Approach can be quantified. The initial selection of projects that provide the fastest and greatest improvement to the system (refer to Chapter 3 for a discussion on project development and resource allocation to achieve rapid results) can also reduce the impact of this inhibitor.

4.5.5 Governance

As an organization becomes alive and begins to learn, control within the organization changes [DeGues 1997, Senge et al 1999, Ohno 1988]. Resistance will arise from Management who has been identified as needing to give up control to enable change (refer to stakeholder analysis for further explanation). This behavior, Senge et al 1999 describes as a gap between the controls imposed by Management, and the progress of the change initiative. The gap leads to a reduction in the enthusiasm and willingness for change for the plant.

The controls that Management place to inhibit the change process, is however believed to be a function of management's own adoption of the change initiative. As Managers adopt the SD Approach, they are prepared for change in the governance structure of the plant required to achieve plant adoption. This behavior is captured in the proposed adoption model of Plant N, by viewing the adoption of Management separately from Unionized workforce. The rate of Unionized Workforce adoption is linked to Management by the rate of successful projects the plant completes, as Management has control over the number projects implemented.

4.5.6 General resistance to Change

Time constraints and fear and anxiety are further constraints Senge et al 1999 that inhibit adoption. At Plant N, these constraints however did not appear to be apparent. To allow for the Plant N model to be valid for other plants, these factors were included in the model as, general resistance to change (as seen in Figure 4-13).

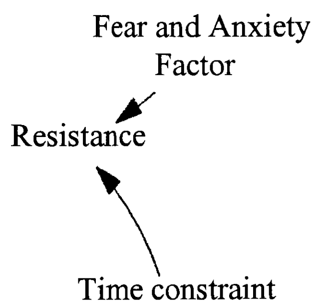

Figure 4-13: General Resistance to Adoption

4.6 Chapter Conclusions

The case-study of the SD Adoption at Plant N provided an insight into the key drivers for SD Adoption at Plant N.

First, to sustain the System Design initiative over the long-term, the plant must develop a carrying capacity for the approach. The carrying capacity is a core foundation of people who have adopted (or are teachers or champions of the initiative) and believe in the approach. This core group may evolve with members either joining or leaving, however it must be greater than a minimum size for the approach to spread throughout the plant. The minimum size of this core group is dependent on the success members have with the SD Approach and their ability to influence other members within the plant. The carrying capacity forms a solid foundation for the SD Approach to be continually implemented and refined within the plant.

Second, the different stakeholders play an important role in implementing the SD Approach. Without the support from all stakeholders, the initiative faces considerable resistance, as people in the plant would be unable to examine their underlying beliefs and learn through introception. The support of both Management and Union is required to provide leadership to the entire workforce and endorse the initiative, and to create a sense of ownership of the SD Approach for all members of the plant.

Third, the rate of SD Adoption and refinement is a function of the personal success people have with the initiative, their ability to coach their colleagues, and their ability to create visible business success as a result of the SD Approach. During the early stages of the initiative, the speed at which adoption takes place is highly dependent on the level of outside support to teach people the SD Approach as there are few internal champions to coach their colleagues, and because the benefits of adoption have a time delay before they become visible.

Fourth, the application of the SD Approach can be inhibited by the lack of availability of internal champions and external teachers, the pressures placed upon the plant to succeed, and how people view the relevance of the approach to their daily practices. Without Internal Champions and External Teachers, the level of teaching diminishes, and the success and relevance people have with the SD Approach is reduced. A gap arises between the expectations to succeed and the rate at which results become visible. This gap can lead to undue pressure to not learn the System Design Approach and instead apply individual tools whose success is limited.

CHAPTER 5: CONCLUSION

This thesis developed a resource allocation method to support Axiomatic Design. The resource allocation methodology is intended to support the development of projects that implement the MSDD and the System Design Approach within manufacturing organizations. The resource allocation method incorporates the path dependent nature of functional requirements to design parameters, and from design parameters to organizational resources. A monetary value based from the benefit of the system design is used as the basis to link the resource allocation methodology with other traditional components of project development and valuation. Monetary valuation is also applied to ensure system design implementation projects make the best use of organizational resources and extract the maximum value for the manufacturing organization.

This thesis also studied the organizational dynamics surrounding the adoption of the MSDD and the SD Approach within a manufacturing plant. A System Dynamics model was built to represent the plant's stakeholder dynamics as they adopted the approach. The reinforcing and inhibiting behavior captured in the system dynamics model was compared to change models in the literature, and the behavior within the plant was explained in relationship to the literature.

The contribution of this thesis can be viewed in the following three aspects:

1. This thesis reviewed the historical evolution of manufacturing systems and their resource allocation structures.

2. This thesis developed and applied a resource allocation methodology to support the implementation of the MSDD and System Design.

3. This thesis studied the organizational dynamics at a brown-field manufacturing plant that was attempting to adopt the SD Approach. Recommendations for future SD Approach adoption were developed from the experience at the case study plant.

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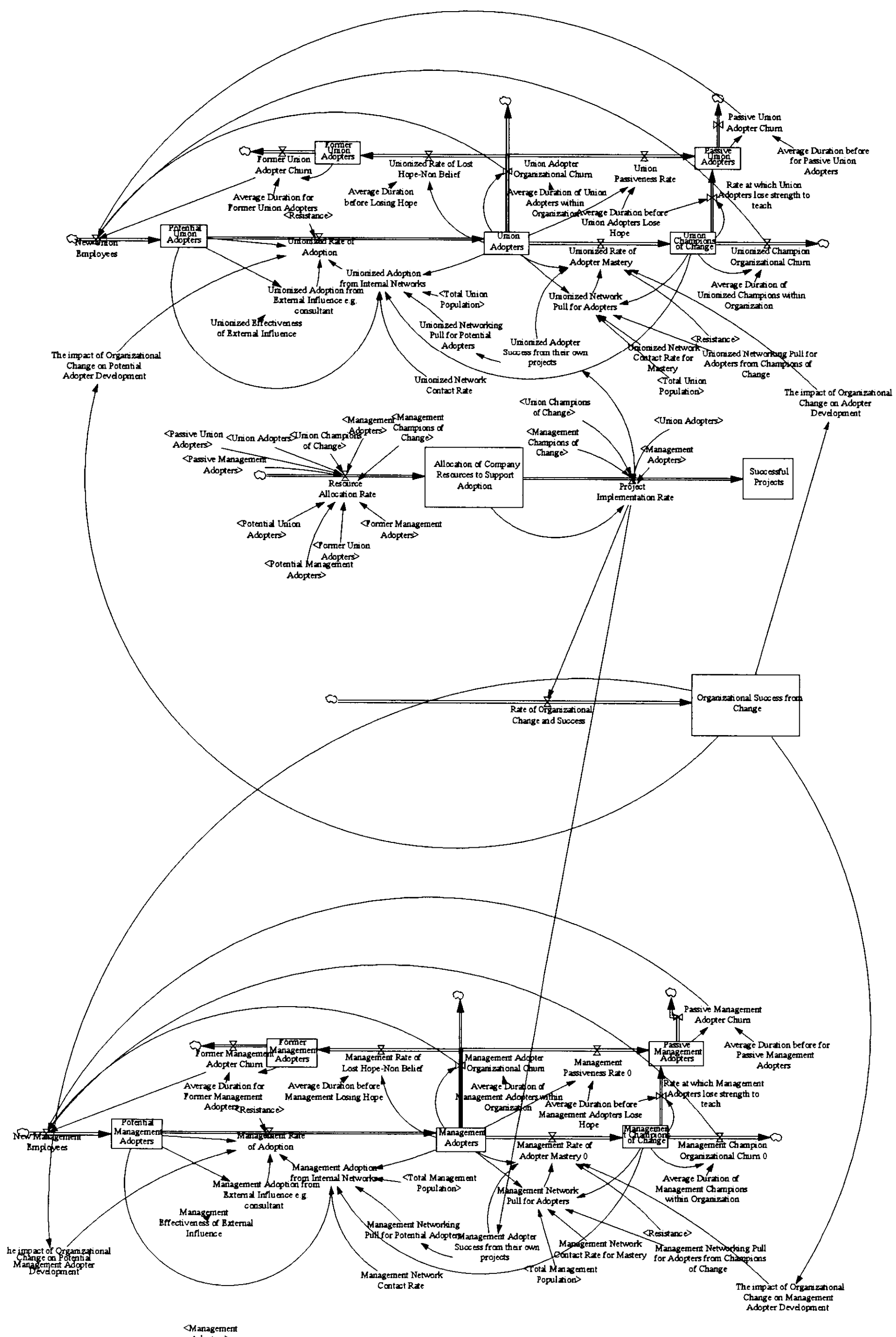
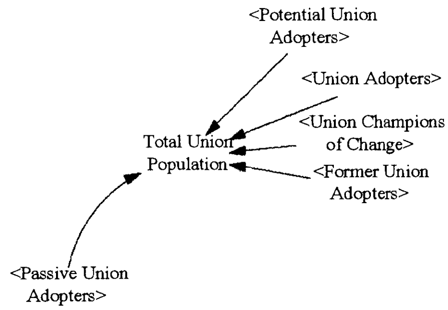
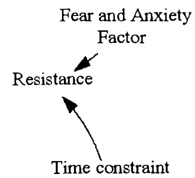
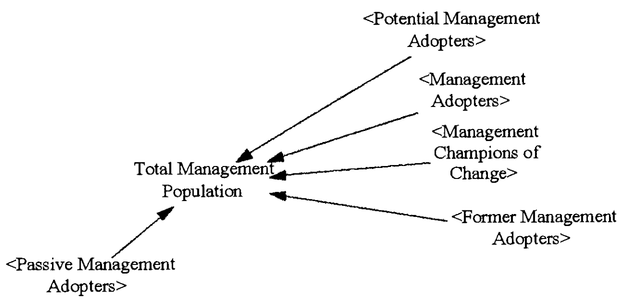
APPENDIX 2: SYSTEM DYNAMICS MODEL OF ADOPTION AT PLANT N

Stock and Flow Structure









System Dynamics Document

```
01)   Allocation of Company Resources to Support Adoption= INTEG (
            +Resource Allocation Rate-Project Implementation Rate,
                  0)
      Units: Dmnl

(02)  Average Duration before for Passive Management Adopters=
            12
      Units: Month

(03)  Average Duration before for Passive Union Adopters=
            12
      Units: Month

(04)  Average Duration before Losing Hope=
            12
      Units: Month
```

(05) Average Duration before Management Adopters Lose Hope=
12
Units: Month

(06) Average Duration before Management Losing Hope=
12
Units: Month

(07) Average Duration before Union Adopters Lose Hope=
12
Units: Month

(08) Average Duration for Former Management Adopters=
12
Units: Month

(09) Average Duration for Former Union Adopters=
12
Units: Month

(10) Average Duration of Management Adopters within Organization=
24
Units: Month

(11) Average Duration of Management Champions within Organization=
36
Units: Month

(12) Average Duration of Union Adopters within Organization=
24
Units: Month

(13) Average Duration of Unionized Champions within Organization=
36
Units: Month

(14) Fear and Anxiety Factor=
0
Units: People/Month

(15) FINAL TIME = 100
Units: Month
The final time for the simulation.

(16) Former Management Adopter Churn=
Former Management Adopters/Average Duration for Former Management Adopters
Units: People/Month

(17) Former Management Adopters= INTEG (
"Management Rate of Lost Hope-Non Belief"-Former Management Adopter Churn
,
0)
Units: People

```
(18)    Former Union Adopter Churn=
            Former Union Adopters/Average Duration for Former Union
Adopters
        Units: People/Month

(19)    Former Union Adopters= INTEG (
            "Unionized Rate of Lost Hope-Non Belief"-Former Union Adopter
Churn,
                    0)
        Units: People

(20)    INITIAL TIME  = 0
        Units: Month
        The initial time for the simulation.

(21)    Management Adopter Organizational Churn=
            Management Adopters/Average Duration of Management Adopters
within Organization
        Units: People/Month

(22)    Management Adopter Success from their own projects = WITH LOOKUP (
            Project Implementation Rate,
                    ([(0,0)-
(1,1)],(0.00611621,0.0263158),(0.235474,0.197368),(0.498471,0.666667
        ),(0.740061,0.885965),(0.993884,0.991228)
                    ))
        Units: **undefined**

(23)    Management Adopters= INTEG (
            +Management Rate of Adoption-Management Adopter Organizational
Churn-Management Rate of Adopter Mastery 0
        -Management Passiveness Rate 0-"Management Rate of Lost Hope-Non
Belief",
                    0)
        Units: People

(24)    "Management Adoption from External Influence e.g. consultant"=
            Management Effectiveness of External Influence*Potential
Management Adopters
        Units: Dmnl

(25)    Management Adoption from Internal Networks=
            (Management Network Contact Rate*Management Networking Pull for
Potential Adopters
        *Potential Management Adopters)/((Management Champions of Change
            +Management Adopters)/Total Management Population)
        Units: People/Month

(26)    Management Champion Organizational Churn 0=
            Management Champions of Change/Average Duration of Management
Champions within Organization
        Units: People/Month

(27)    Management Champions of Change= INTEG (
            Management Rate of Adopter Mastery 0-Management Champion
Organizational Churn 0
        -Rate at which Management Adopters lose strength to teach,
```

```
                0)
      Units: People

(28)  Management Effectiveness of External Influence=
            1
      Units: Dmnl

(29)  Management Network Contact Rate=
            1
      Units: People/People/Month

(30)  Management Network Contact Rate for Mastery=
            1
      Units: People/People/Month

(31)  Management Network Pull for Adopters=
            Management Network Contact Rate for Mastery*Management
Networking Pull for Adopters from Champions of Change
      *Management Adopters
            *(Management Champions of Change/Total Management Population
            )
      Units: People/Month

(32)  Management Networking Pull for Adopters from Champions of Change =
            1
      Units: Dmnl

(33)  Management Networking Pull for Potential Adopters= WITH LOOKUP (
            Management Adopter Success from their own projects,
                  ([(0,0)-
(1,1)],(0.0030581,0.00877193),(0.363914,0.135965),(0.565749,0.815789
      ),(0.804281,0.942982),(1,1) ))
      Units: **undefined**
      Networking Potential from Peer Success from Adoption\!\!

(34)  Management Passiveness Rate 0=
            Management Adopters/Average Duration before Management Adopters
Lose Hope
      Units: **undefined**

(35)  Management Rate of Adopter Mastery 0=
            Management Adopter Success from their own projects*Management
Adopters+Management Network Pull for Adopters
      -Resistance+
      The impact of Organizational Change on Management Adopter
Development*Management Adopters
      Units: People/Month

(36)  Management Rate of Adoption=
            "Management Adoption from External Influence e.g.
consultant"+Management Adoption from Internal Networks
      -Resistance+The impact of Organizational Change on Potential
Management Adopter Development
      *Potential Management Adopters
      Units: People/Month

(37)  "Management Rate of Lost Hope-Non Belief"=
```

Management Adopters/Average Duration before Management Losing Hope
Units: People/Month

(38) New Management Employees=
Management Adopter Organizational Churn+Management Champion Organizational Churn 0
+Former Management Adopter Churn+Passive Management Adopter Churn
Units: People/Month

(39) New Union Employees=
Union Adopter Organizational Churn+Unionized Champion Organizational Churn
+Former Union Adopter Churn+Passive Union Adopter Churn
Units: People/Month

(40) Organizational Success from Change= INTEG (
Rate of Organizational Change and Success,
0)
Units: Dmnl

(41) Passive Management Adopter Churn=
Passive Management Adopters/Average Duration before for Passive Management Adopters
Units: People/Month

(42) Passive Management Adopters= INTEG (
Rate at which Management Adopters lose strength to teach+Management Passiveness Rate 0
-Passive Management Adopter Churn,
0)
Units: People

(43) Passive Union Adopter Churn=
Passive Union Adopters/Average Duration before for Passive Union Adopters
Units: People/Month

(44) Passive Union Adopters= INTEG (
Rate at which Union Adopters lose strength to teach+Union Passiveness Rate
-Passive Union Adopter Churn,
0)
Units: People

(45) Potential Management Adopters= INTEG (
New Management Employees-Management Rate of Adoption,
100)
Units: People

(46) Potential Union Adopters= INTEG (
New Union Employees-Unionized Rate of Adoption,
100)
Units: People

(47) Project Implementation Rate=

```
            Allocation of Company Resources to Support Adoption*(Union
Champions of Change
      /Union Adopters+Management Champions of Change
            /Management Adopters)
      Units: Dmnl

(48)  Rate at which Management Adopters lose strength to teach=
            Management Champions of Change/Average Duration before
Management Adopters Lose Hope
      Units: People/Month

(49)  Rate at which Union Adopters lose strength to teach=
            Union Champions of Change/Average Duration before Union
Adopters Lose Hope
      Units: People/Month

(50)  Rate of Organizational Change and Success=
            Project Implementation Rate
      Units: Dmnl

(51)  Resistance=
            Fear and Anxiety Factor+Time constraint
      Units: Dmnl

(52)  Resource Allocation Rate=
            ((Union Champions of Change+Union Adopters)/(Union
Adopters+Union Champions of Change
      +Former Union Adopters+Passive Union Adopters
            +Potential Union Adopters))+(Management Champions of
Change+Management Adopters
      )/(Management Adopters+Management Champions of Change
      +Former Management Adopters+Passive Management Adopters+ Potential
Management Adopters
      )
      Units: Dmnl

(53)  SAVEPER  = 1
      Units: Month
      The frequency with which output is stored.

(54)  Successful Projects= INTEG (
            Project Implementation Rate,
                  0)
      Units: Dmnl

(55)  The impact of Organizational Change on Adopter Development= WITH
LOOKUP
       (
            Organizational Success from Change,
                  ([(0,0)-
(1,1)],(0.00611621,0.0219298),(0.373089,0.184211),(0.538226,0.688596
      ),(0.755352,0.890351),(0.990826,0.991228) ))
      Units: 1/Month

(56)  The impact of Organizational Change on Management Adopter Development
      = WITH LOOKUP (
            Organizational Success from Change,
```

```
              ([(0,0)-
(1,1)],(0.00611621,0.0219298),(0.373089,0.184211),(0.538226,0.688596
      ),(0.755352,0.890351),(0.990826,0.991228)
              ))
      Units: 1/Month

(57)  The impact of Organizational Change on Potential Adopter Development=
      WITH LOOKUP (
            Organizational Success from Change,
              ([(0,0)-
(1,1)],(0.0030581,0.00438596),(0.449541,0.149123),(0.556575,0.657895
      ),(0.828746,0.929825),(0.98471,0.982456) ))
      Units: 1/Month

(58)  The impact of Organizational Change on Potential Management Adopter
Development
       = WITH LOOKUP (
            Organizational Success from Change,
              ([(0,0)-
(1,1)],(0.0030581,0.00438596),(0.449541,0.149123),(0.556575,0.657895
      ),(0.828746,0.929825),(0.98471,0.982456) ))
      Units: 1/Month

(59)  Time constraint=
            0
      Units: People/Month

(60)  TIME STEP  = 1
      Units: Month
      The time step for the simulation.

(61)  Total Management Population=
            Management Adopters+Management Champions of Change+Former
Management Adopters
      +Passive Management Adopters+Potential Management Adopters
      Units: People

(62)  Total Union Population=
            Union Adopters+Union Champions of Change+Former Union
Adopters+Passive Union Adopters
      +Potential Union Adopters
      Units: People

(63)  Union Adopter Organizational Churn=
            Union Adopters/Average Duration of Union Adopters within
Organization
      Units: People/Month

(64)  Union Adopters= INTEG (
            +Unionized Rate of Adoption-Union Adopter Organizational Churn-
Unionized Rate of Adopter Mastery
      -Union Passiveness Rate-"Unionized Rate of Lost Hope-Non Belief",
              0)
      Units: People

(65)  Union Champions of Change= INTEG (
```

Unionized Rate of Adopter Mastery-Unionized Champion Organizational Churn
-Rate at which Union Adopters lose strength to teach,
0)
Units: People

(66) Union Passiveness Rate=
Union Adopters/Average Duration before Union Adopters Lose Hope
Units: **undefined**

(67) Unionized Adopter Success from their own projects= WITH LOOKUP (
Project Implementation Rate,
([(0,0)-(1,1)],(0.00611621,0.0263158),(0.235474,0.197368),(0.498471,0.666667),(0.740061,0.885965),(0.993884,0.991228)
))
Units: **undefined**

(68) "Unionized Adoption from External Influence e.g. consultant"=
Unionized Effectiveness of External Influence*Potential Union Adopters
Units: Dmnl

(69) Unionized Adoption from Internal Networks=
(Unionized Network Contact Rate*Unionized Networking Pull for Potential Adopters
*Potential Union Adopters)/((Union Champions of Change+Union Adopters)/Total Union Population
)
Units: People/Month

(70) Unionized Champion Organizational Churn=
Union Champions of Change/Average Duration of Unionized Champions within Organization
Units: People/Month

(71) Unionized Effectiveness of External Influence=
1
Units: Dmnl

(72) Unionized Network Contact Rate=
1
Units: People/People/Month

(73) Unionized Network Contact Rate for Mastery=
1
Units: People/People/Month

(74) Unionized Network Pull for Adopters=
Unionized Network Contact Rate for Mastery*Unionized Networking Pull for Adopters from Champions of Change
Union Adopters(Union Champions of Change/Total Union Population
)
Units: People/Month

(75) Unionized Networking Pull for Adopters from Champions of Change=
1

Units: Dmnl

(76) Unionized Networking Pull for Potential Adopters= WITH LOOKUP (
Unionized Adopter Success from their own projects,
([(0,0)-
(1,1)],(0.0030581,0.00877193),(0.363914,0.135965),(0.565749,0.815789
),(0.804281,0.942982),(1,1)))
Units: **undefined**
Networking Potential from Peer Success from Adoption\!\!

(77) Unionized Rate of Adopter Mastery=
Unionized Adopter Success from their own projects*Union
Adopters+Unionized Network Pull for Adopters
-Resistance+The impact of Organizational Change on Adopter
Development*Union Adopters
Units: People/Month

(78) Unionized Rate of Adoption=
"Unionized Adoption from External Influence e.g.
consultant"+Unionized Adoption from Internal Networks
-Resistance+The impact of Organizational Change on Potential Adopter
Development
*Potential Union Adopters
Units: People/Month

(79) "Unionized Rate of Lost Hope-Non Belief"=
Union Adopters/Average Duration before Losing Hope
Units: People/Month

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