Implementation of a Production Architecture For a Post-2000 Market: Demonstration of a Microfactory Concept

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(Abstract)

The development of a "Next Generation Manufacturing System" is currently an active area of research worldwide. The research described in this dissertation addresses one sub-element within this research area; namely, the demonstration of a decentralized, automated production architecture. The goal of the work is to increase the ability of a manufacturing enterprise to respond to rapid technological and market change in the post-2000 global economy. The research is comprised of three objectives; definition of a decentralized organizational structure of autonomous production activities, implementation of the defined organization in a real world manufacturing environment, and a comparison of historical (centralized architecture) performance data and decentralized performance data. To accomplish these objectives, the proposed production architecture is implemented at a real world manufacturing site and performance data are acquired and tested against a stated hypothesis.

The research entails the modification of a selected electronics module assembly activity in the following ways: 1) comprehensive automation of assembly processes; 2) simplification of production practice through a minimization of operator interaction and a reduction of assembly transaction points requiring operator intervention; and 3) restructuring of organizational functions resulting in decentralization and operational autonomy. The null hypothesis was successfully rejected and it was shown that the implementation of automation, simplification, and decentralization resulted in an enhancement of production performance (i.e., a reduction in throughput time, labor cost, overhead cost, and total product cost) without degrading production quality. A test of H_0 based on the data indicates a statistically significant (i.e., $p \leq 0.05$) reduction in throughput time, labor cost, overhead cost, and total product cost while no statistically significant difference in the before and after production quality data was shown. A possible interpretation of these results is that the implementation of automation, simplification, and decentralization did result in a reduction in the labor cost, overhead cost, and total product cost and did not result in a degradation in production quality.

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Glossary

1. *Agile Manufacturing*. The agile manufacturing concept is based on the use of information technology to form virtual enterprises which "agilely" respond to changing market demands, accomplished through the formation of flexible and dynamic manufacturing environments that can utilize a network of manufacturers to produce "customized" products. The concept is founded on the following key elements: the transformation of business, engineering, and production practices; the implementation of seamless information flow from design through production; the integration of computer and information technologies into all facets of product development and production processes; the application of communications technologies to enable collaborative work between geographically dispersed product development teams; and the introduction of flexible automation of production processes.

2. *Biological (Bionic) Manufacturing*. A design methodology for manufacturing systems that imitates biological construction (self-organization) and optimization (evolution) and is based on cooperative, flexible, and adaptive individual production units which can individually "evolve" to achieve an overall manufacturing strategy. Taken as a whole, the manufacturing system is seen as an individual organism that responds to environmental stimuli by producing products. Products are viewed as individual organisms that compete against other products in characteristics such as shape, function, cost, etc.

3. *BPR*. Business process engineering. An organizational strategy for implementation of change within a corporation which is founded on the idea that companies must re-engineer the most basic structures of the modern organization such as the division of labor, complex process controls, and the traditional managerial hierarchy in order to maintain competitiveness in the global marketplace.

4. *D10, D50*. Product designations given during the research to variants of the "D series" of electronic transceiver modules. Each module includes all functions for handling the selected radio channel, such as channel coding and decoding, modulation and demodulation, and power amplification.

5. *Focused Factories*. An organizational strategy introduced in the 1970's by Wickham Skinner that entailed the concentration of production resources to a narrow product mix for a particular market niche; thus, "focusing" resources on a narrow range of products.

6. *Fractal Company*. Arising from the perception of production process and control as an interacting system of atomistic components, the fractal company is an organizational strategy in which a company is created from small components, or "fractal objects," that have the ability to adapt quickly and reorganize in a rapidly changing market environment. The key characteristics of these fractal elements are self-organization, self-similarity, and self-optimization.

7. *Holonic Manufacturing*. Based on the ideas of Arthur Koestler who proposed the word "holon" to describe a basic unit of organization in biological and social systems, the holonic manufacturing concept draws on examples in biology in much the same way as the biological (bionic) manufacturing concept. The concept observes that in living organisms and in social organizations entirely self supporting, non-interacting entities do not exist. Rather every identifiable unit of organization is comprised of more basic units while at the same time forming a part of a larger unit of organization. A holonic approach to manufacturing design recognizes that a manufacturing system can be viewed as sub-ordinate parts that in turn are part of a larger whole (e.g., order holons, production holons, resource holons, etc.).

8. *IN-MI*. Product designation given during the research to a reduced size version of a radio base station transceivers cabinet for indoor use (See MAC-T, 19-T).

9. *IT*. Information Technology. Software and hardware technology used to create an infrastructure for information transmission and processing.

10. *Lean Production*. A production strategy which, in its most basic form, can be defined as the manufacture of a product with a minimum of waste. In a broader sense, "waste" includes more than just material scrap and unnecessary overhead, but also addresses all aspects of value-creating versus non value-adding activities.

11. *LM*. Product designation given during the research to a processing module that determines signal location.

12. *MAC-T, 19-T*. Product designations given during the research to radio base station transceivers cabinets containing a modem function, radio frequency and digital backplanes, data connection boards, and power and cooling units (See IN-MI).

13. *Microfactory*. An organizational and process transformation concept brought about through the application of automation, simplification, and decentralization, resulting in the development of a manufacturing system comprised of autonomous production units formed around product families.

14. *Multiple - Microfactory Architecture*. A manufacturing business strategy in which multiple microfactories are networked using electronic information transfer to realize an overall integrated manufacturing system in which each production unit or microfactory contributes production services from order to delivery as part of an overall product portfolio and business strategy.

15. *NGMS*. Next Generation Manufacturing System. The concept of developing and integrating state of the art ideas across a complete manufacturing environment (i.e., from the work unit level to the factory level to the enterprise level) to achieve a "virtual" enterprise consisting of globally distributed assemblies of autonomous work units capable of operating in an environment of abrupt, often unpredicted, change.

16. *NPI*. New Product Introduction. The process of converting a prototype design to a manufacturable product ready for introduction to the marketplace.

17. *NTI*. New Technology Introduction. The process of converting a basic research technology to engineering applications and the development of associated engineering models.

18. *OTD*. Order to delivery cycle time. The time from receipt of a customer order to the delivery of product to the customer.

19. *Project α*. A new technology introduction program tasked with the introduction of new technology on existing production lines.

20. *Project γ*. A new technology introduction program tasked with demonstrating a prototype microfactory.

21. *Project π*. A new technology introduction program responsible for the configuration of state-of-the-art process automation equipment into a fully automated production line.

22. *Radio Base Station*. A transmitting and receiving facility that functions as a local geographic node within a cellular telephone network consisting of an enclosure, multiple electronic transceiver modules, and associated test, power, and environmental systems.

23. *STS*. Socio-technical system. A system comprised of interrelated technical and social subsystems. In production system design, a socio-technical system view combines both "humanistic," social concerns such as working conditions and personal development opportunities for employees and technical concerns such as lowering cost and improving throughput times.

24. *T1-5, T10, T30*. Product designations given during the research to variants of the "T series" of electronic transceiver modules. Each module includes all functions for handling the selected radio channel, such as channel coding and decoding, modulation and demodulation, and power amplification.

25. *TTP*. Technology to product cycle time. The time from identification and development of a basic product technology to the generation of a manufacturable product ready for introduction to the marketplace.

26. *Value Stream Mapping*. A production analysis technique using a graphical representation of the main components in a manufacturing process to identify elements that can be streamlined to reduce inventory or waste, or to cut production time. The technique is comprised of a three phase process involving, first, the drawing of a picture of each of the main elements in a production activity to produce a "current state map." Second, a "future state map" is outlined which represents the improvements to be implemented and the third and final phase is the actual implementation of these changes.

27. *Wilcoxon Signed Rank Test*. Proposed in 1945 by Frank Wilcoxon, the Wilcoxon Signed Rank test is a non-parametric statistical method used to test the hypothesis that two independent samples have come from the same population by comparing two (i.e., before and after treatment) sample sets. This test is used to determine the probability that observed differences between such two sample sets occurred by chance. Because the test is non-parametric and makes no assumptions about the distribution of the data, it is well suited for small sample sets with unknown distributions.

Chapter 1

Introduction

1.1 Problem Statement

As is more fully discussed in later Sections 1.2 and 1.3, the expanding and rapidly changing global marketplace is driving companies (especially in the electronics industry) to shorten technology-to-product (TTP) and order-to-delivery (OTD) times and increase responsiveness to market change while reducing product cost without degrading production quality. These concerns provide the basis for the problem studied during the research; namely, the investigation of one possible strategy to reduce throughput time and product cost, while maintaining production quality. This strategy entailed a threefold approach to production process automation and organizational change involving:

- an increase in automation of production processes,
- simplification of operational practice,
- and decentralization of production activities

The results of the research provide an indication of the effectiveness of using such a strategy to reduce throughput time and product cost without degrading production quality.

1.1.1 Scope and Importance

Later Sections 1.2 and 1.3 discuss the rapidly increasing rate of human technological innovation. The effect of this on business has been to force shorter and shorter response times to the integration of technology into new and existing products. The need for rapid integration of technology into a product is driven by a very basic market tenet; namely, the first to reach the market with new technology is presented with a unique opportunity to dominate the market. Companies that introduce the technology to the market at a later stage must compete on a cost or feature enhancement basis.

This shortening of TTP response time is more or less pronounced depending upon the industry concerned. For instance, manufacturers of paper sheets for such applications as typing or computer printout address small incremental changes in technology that are introduced to the market almost entirely on the basis of reduced production cost. On the other hand, the electronics industry is currently experiencing considerable technological innovation that is measured in weeks and months rather than years [1].

As an example, change is so rapid that the linear development of new semiconductor architectures has been compressed to the point where development on several generations of microprocessors are occurring simultaneously. In addition, response time shortening can be scaled according to the type of industry considered. For example, the construction of large aircraft takes several years to go from concept to product while the introduction of electronic games can go from concept to product in a matter of months. Because of this, the electronics industry in particular is being driven to shorten OTD times to address decreasing product life cycles. Furthermore, product costs must be continually reduced to maintain competitiveness.

In the post-2000 economy, most, if not all, companies have to function within a highly fluid, global market. One way of addressing such a market is to develop production elements that quickly respond to these market changes. To accomplish this, companies have to transform large-scale organizational elements into smaller, less complex units in order to increase responsiveness to market change.

These issues (i.e., the need for reduced TTP, OTD, and product costs while increasing responsiveness) form the basis for the thrust of the research. The motivation of this research is to demonstrate an organizational template that utilizes the three-component production strategy (i.e., automation of production processes, simplification of operational practice, and decentralization of production activities) described in Section 1.1. It is anticipated by the Investigator that this demonstration will provide an indication of performance changes in throughput time, labor cost, overhead cost, and total product cost and a measure of changes, if any, in production quality that result from the implementation of the organizational template. The quantification of monetary savings of such improvements is beyond the scope of this research. The importance of the research is the possibility of identifying a production strategy that allows a decrease in throughput time and product cost. Each of these performance gains is highly advantageous to electronics manufacturing activities that are having to deal with rapidly accelerating technological and market change.

The thrust of the research focuses on electronics production, but can probably be expanded to include other industries that have similar fast TTP and OTD requirements and that compete in rapidly changing markets requiring companies to respond quickly to be successful. This may not be the case for industries which compete in more sedate, mature markets (e.g., such as the auto industry or paper industry) which traditionally have TTP times of several years and OTD times of several months. Such industries usually have very complex, low unit volume, expensive products such as aircraft or automobiles. Or they may have very high unit volume, very low cost products that are subject to little if any design changes such as the basic paper industry (and where, for all practical purposes, product obsolescence is nonexistent). In such industries, the application of the organizational strategy investigated in this research would probably not be the most effective solution.

1.1.2 Hypothesis

This research involves an investigation of changes in throughput time, cost, and production quality that occur when process automation and organizational change through decentralization and simplification are applied to an actual electronics assembly company. The following question is addressed.

IF an electronics module assembly activity is altered in the following ways:

- Comprehensive automation of assembly processes
- Simplification of production practice through a minimization of operator interaction and a reduction of assembly transaction points requiring operator intervention
- Restructuring of organizational functions through decentralization and simplification of a centralized configuration to provide organizational and operational autonomy to the assembly activity

THEN will the following parameters change?

- Throughput Time – The time from receipt of order to shipping of product
- Labor Cost – The cost of labor to produce the product
- Overhead Cost – The cost of associated overhead activities comprised of administration, finance, manufacturing technology, human resources, quality, and information technology costs
- Total Product Cost – The total cost of producing a product
- Production Quality – The failure rates for functional tests and time tests

The hypotheses are as follows:

H_0: The parameters (throughput time, labor cost, overhead cost, total product cost, and production quality) do not change.

H_1: The parameters (throughput time, labor cost, overhead cost, and total product cost) decrease without degrading production quality (i.e., production quality does not change).

The two hypotheses represent: 1) no change (i.e., the null hypothesis, H_0); and 2) throughput time and cost performance improvement without degrading production quality (i.e., the alternative hypothesis, H_1).

1.1.3 Research Objectives

Investigation of the hypothesis presented in the previous section is the basis for the research presented in this dissertation. The research demonstrates the threefold process and organizational change strategy of automation, simplification, and decentralization entailing the implementation of each of these three elements at a real world manufacturing site. The resulting decentralized activity is referred to by the Investigator as a "microfactory." The definition of the microfactory concept is an organizational and process transformation brought about through the application of automation, simplification, and decentralization, resulting in the development of a manufacturing system comprised of autonomous production units formed around product families. These units are then networked using electronic information transfer to realize an overall integrated manufacturing system in which each production unit or microfactory contributes production services from order to delivery for a specific product family as part of an overall product portfolio and business strategy.

The demonstration of this organizational conversion provides data that are anticipated to accept or reject the previously stated hypothesis. This is accomplished through a comparison of performance data from the original centralized assembly activity with data from a decentralized microfactory implementation. The research addresses a series of three objectives that are selected to provide relevant information and insight into the previously stated hypothesis. These objectives are as follows:

Research Objective 1.
Develop a Microfactory and Supporting Multiple-Microfactory Architecture (Section 3.1)

Research Objective 2.
Demonstrate a Microfactory Prototype in a Real World Production Environment (Section 3.2)

Research Objective 3.
Compare Microfactory Performance with Historical Pre-Microfactory Performance (Section 3.3)

In order to accomplish these research objectives, an existing production line in an operational electronics assembly manufacturing facility is modified. This modification incorporates the organizational strategy that is outlined in the hypothesis. A comparison of historical data with contemporary data, as acquired from the modified line and other unmodified production lines, should provide evidence of any performance changes that occur.

1.1.4 Assumptions and Limitations

There are assumptions and limitations associated with the research (i.e., the investigation of one possible strategy that might provide a solution to the need for reduced throughput time and product cost, while maintaining production quality). The Investigator believes changes in performance that occur are associated with the implementation of the microfactory. To support the soundness of this assumption, measurements are also made on other production activities that were unaltered during the microfactory conversion.

There are also limitations to the research. The electronics manufacturer, which is allowing the conduct of the research within its facilities, is embracing an overall organizational change strategy that includes most of the elements of the multiple-microfactory concept discussed by the Investigator later in Section 3.1.2. However, the research is only directed toward the demonstration of the fundamental building block of this concept; namely, the microfactory. The microfactory model represents a fundamental production element that can be used to assemble much larger distributed manufacturing systems from single microfactory components. This being the case, the successful demonstration of this basic element is critical to the success of an overall multiple-microfactory implementation. It is also recognized that the demonstration of a microfactory for only electronics production is a further limitation in that the concept may indeed also be successful in other types of production. In addition, due to the proprietary nature of some business data, the exact identification of products is not presented in this dissertation and cost data are delayed so that current cost data are not published.

1.2 Overview

Over the past centuries of human history, the organization of business activities, much like the development of political systems, has evolved into a well defined form which has been refined by years of industrial evolution. In the modern day, such business organizations are characterized by a centralized command and control architecture defined by monolithic communications channels with matrixed functionality at the bottom level of the command pyramid. Although there are a myriad of variations on this type of organizational structure, several very distinct characteristics are evident in almost every monolithic command and control structure. Some of the more beneficial attributes can be found in the slow, well-studied response to change that is characteristic of multiple levels of command structures. Change within the organization must go through several levels of checks and balances to determine the validity of the changes being considered. Multiple levels of review usually ensure that an alteration in the enterprise activity will have a high probability of success in accomplishing the desired result of the change. In short, the assumption is that there is safety in the slowness of response. Impulsive changes that are not well thought through are either attenuated or terminated before being enacted. This multiple review process is designed to "weed out" weaknesses in proposed changes before such changes are implemented and institutionalized. Furthermore, the high level of centralization that is present allows very tight control over all operations from the bottom to the top of the enterprise. Almost all aspects of all activities can be monitored and controlled by upper levels of the command and control structure. In such an organization, activities tend to be fully synchronized across the enterprise providing concerted action by all elements to achieve the results desired by upper level corporate management.

Then again, weaknesses can be found in the interdependency that defines centralization and the slowness inherent in multiple levels of command bureaucracy. Because there is a high level of centralization of functional elements, domino-like failures in functionality can impact other elements within the system. To counter this, an added level of robustness is built into each functional component. This is accomplished by over-resourcing the organizational elements to ensure functional redundancy. The result is the formation of a layer of underutilized resources that contribute to the overhead inherent in large bureaucracies. Information flow also suffers from the same bureaucratic inertia being channeled through multiple paths and numerous transaction points.

However, in the post-2000 marketplace, such organizational structures are hard pressed to respond to the rapidly changing demands of the marketplace. Hitt [2] characterizes this new marketplace dynamic as follows:

> The competitive landscape of the new millennium will be characterized by substantial and discontinuous change. It will be rugged and large. Multiple strategic discontinuities will occur and the changes will be rapid. In other words, the periods of stability will be short. The substantial change in and the size and complexity of this landscape produce significant uncertainty.

Furthermore, Calantone and Benedetto [3] point out that these changes are forcing companies to shorten product development cycles. In their words:

> Today's marketplace is characterized by shortening product life cycles and windows of opportunity that remain open for increasingly shorter durations; thus, there is pressure to get the product through the development cycle at ever quicker rates. Additionally, a quicker launch can result in premium pricing and higher sales levels.

In concurrence with this view, Terwiesch and Bohn [1] describe the high technology industry as being characterized by:

> …shrinking product life cycles and increasingly expensive production equipment and up-front costs. The market window for selling many products has shrunk to less than a year in industries such as disk drives and telecommunications. These forces pressure organizations to cut not only their development times (time-to-market), but also the time it takes to reach full production volume (time-to-volume) in order to meet their financial goals for the product (time-to-payback).

This increasingly rapid development rate and the associated contraction of order-to-delivery (OTD) cycle times that characterize modern technological innovation are driving traditional enterprise organizational and operational structures to seek higher performance capabilities. As a result, traditional company structures are experiencing change driven by the competitive requirements of the post-2000 marketplace. St. John et al. [4] state that, "…The new millennium promises more demanding customers, greater competitive intensity, and increased complexity in production technology and coordination." In the 1980's, George Stalk recognized that this future global market rewards shortened response times and that time performance had become a competitive advantage. He wrote in the July/August 1988 issue of the Harvard Business Review [5]:

> Like competition itself, competitive advantage is a constantly moving target. For any company in any industry, the key is not to get stuck with a single simple notion of its source of advantage. The best competitors, the most successful ones, know how to keep moving and always stay on the cutting edge.
>
> Today, time is on the cutting edge. The ways leading companies manage time – in production, in new product development and introduction, in sales and distribution – represent the most powerful new source of competitive advantage.

Indeed, the global marketplace is characterized by diminishing technology-to-product (TTP) cycle intervals driving increasingly shorter product lifetimes which, in turn, demand shorter OTD cycle times. Askin and Standridge [6] state that, "…Industry is learning that constant improvement is a prerequisite for continued existence." Eugene S. Meieran, Intel Fellow and Director of Manufacturing Strategic Support at the Technology Manufacturing Group of Intel Corporation notes that [7]:

> The difference between the Fortune 500 lists of the 1950's and 1960's and today's list is a group of companies that did not respond to cataclysmic change.

Conventional monolithic organizations that are highly centralized across an enterprise are seeking to reorganize to reduce bureaucratic inertia and increase the ability to respond effectively in such a rapidly changing market. As observed by Wang [8], "… The era of today's design and manufacturing systems with its downstream information flow is passing and will be gradually phased out, because the conventional design and manufacturing technologies are insufficiently flexible, due in part to their rigid system architecture." This relates somewhat indirectly to the physical law that size (mass) is directly associated to inertia and resistance to change. One can imagine that a reduction in the size of organizational components within an enterprise may increase the ability of those components to respond more rapidly to changes in the business environment. One such implementation might be to fragment a traditional centralized enterprise into a loosely linked network of small, highly autonomous elements. Osborn [9] states that:

> It is becoming increasingly recognized that new-form organizations offer new design choices for resolving this paradox [ed. between organizational flexibility and stability]. Innovative organizational forms that represent alternatives to hierarchy have emerged as rates of change increase in many industries. New choices are developing between firms and within them. Interorganizational relationships such as alliances and joint ventures offer potential innovations, particularly where alliances reduce costs by de-integrating previously vertical structures. New organizational structures, such as "networked" organizations, promise shorter information paths (for faster response time) and broader cross-functional knowledge support (for stability).
>
> One common theme emerging from innovative organizational designs is that new-form organizations are likely to reorganize more explicitly around processes than the structures they replace. From this perspective, processes (and the systems that support them) become central design elements in ensuring sustainable competitive performance.

Traditionally, the computer industry has existed on the cusp of this change and has embraced the concept of modularity, most notably in product design and production. Baldwin and Clark [10] comment on the response of the computer industry to change and a trend toward modularity stating that:

> In the nineteenth century, railroads fundamentally altered the competitive landscape of business. By providing fast and cheap transportation, they forced previously protected regional companies into battles with distant rivals. The railroad companies also devised management practices to deal with their own complexity and high fixed costs that deeply influenced the second wave of industrialization at the turn of the century.
>
> Today the computer industry is in a similar leading position. Not only have computer companies transformed a wide range of markets by introducing cheap and fast information processing, but they have also led the way toward a new industry structure that makes the best use of these processing abilities. At the heart of their remarkable advance is modularity - building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole. Through the widespread adoption of modular designs, the computer industry has dramatically increased its rate of innovation. Indeed, it is modularity, more than speedy processing and communication or any other technology, that is responsible for the heightened pace of change that managers in the computer industry now face. And strategies based on modularity are the best way to deal with that change.

The importance to a country of maintaining production competitiveness can hardly be overstated. A world class production capability is of critical importance to the quality of human life and the strength of nations. Hitomi [11] notes that manufacturing is the creator of wealth for any nation and, in fact, in the modern world is the basic means of human existence. Rembold et al. [12] assert that, "…For the industrialized nations, the manufacturing industries have become the most important contributors to prosperity." This being the case, it is of paramount importance to the industry of a nation to stay competitive in the world marketplace. To accomplish this, the industrial infrastructure must evolve with the market. As pointed out by Pereira and Paulre [13]:

> One of the characteristics of modern organizational management is evolution. Management must be capable of flexible responses to constantly changing offers of new products or product variants. In the same way, the increasing pressure exercised by technological development and the demand variability, compel firms to be flexible.

1.3 Background

Hitt [2] identifies two main drivers for the post-2000 marketplace, the technological revolution and increasing globalization, and states that:

> The technological revolution is characterized by an increasing rate of technological change and diffusion, greater knowledge intensity, and the importance of knowledge to competitive advantage. Globalization is characterized by the liberalization of developing economies and emerging markets, new economic alliances and rules, and the growing interdependencies of national economies, along with worldwide economic development.

From a production viewpoint, the Investigator believes that, of these two drivers described by Hitt [2], the technological revolution can be further divided into two distinct elements associated with manufacturing; namely, the increasing complexity found in modern manufacturing systems and the extraordinary advances that have occurred in information technology. Consequently, the Investigator views the development of modern manufacturing technology as the convergence of three technological trends: 1) increasing complexity, 2) advances in information technology, and 3) globalization of the marketplace.

The first of these trends is the increasing complexity of manufacturing systems. Overall, production processes and practices have evolved slowly for thousands of years, gradually gaining momentum in concert with an increasingly rapid growth in technological knowledge. As manufacturing became more refined, the tools utilized for production became increasingly complex. However, it wasn’t until after the Industrial Revolution in the mid-1700’s that truly complex industrial machinery and modern day production techniques began to be developed. By the late 1700’s, the beginnings of the Industrial Revolution ushered in the era of modern manufacturing which has seen technology growth over the past 200 years that is several orders of magnitude beyond the technology developed over the previous thousands of years. The speed of technology development has placed modern manufacturers in a fluid production environment characterized by the rapid introduction of new technology from a "bottom up" systems view which, in turn, drives "top down" changes in the complexity of management and control systems.

A second trend that is shaping the modern manufacturing environment is the rapid development of information technology. Unprecedented advances in this area have transformed the modern day management and control environment from a staid institution into a continuously changing organizational structure. Until the last 100 years, human-made machinery was essentially "mindless," being completely dependent on human operators to function. Any automated activity was based on mechanical repetition. The lack of an ability to think by machinery was due in large part to a limited understanding of how one could make a machine think and to the absence of a medium in which "thinking" functions could be feasibly implemented. Both of these obstacles were surmounted during the 20th century in a phenomenally short length of time. Advances in this technology soon manifest itself in the development of digital electronic computer systems and computer controlled manufacturing. Consequently, increasing performance in a modern day production facility usually entails a minimization of human/system interaction, increased efficiency of material acquisition and handling, and high speed automation of production processes.

A third trend that is shaping modern manufacturing is the escalating competitiveness of an increasingly interconnected global marketplace. The pervasiveness of this modern global connectivity is, in essence, a consequence of the just discussed advances in information technology that have occurred over the past half-century. In fact, this phenomenon is part of a larger social revolution, driven by advances in overall communications technology…the culmination of which has yet to be seen. Although evident during the past 200 years, the impact of this momentous change only began to be recognized during the latter half of this century. Sampler and Short [14] note that:

> The idea that modern society has begun an information revolution is not a new one. The change in traditional society brought about by modern communications (radio, telephone, television) was chronicled by Lerner in *The Passing of Traditional Society* in 1959 [15], and Bell's, *The Coming of the Post-Industrial Society*, published in 1973 [16], looked at changes in industrial organization and society brought about by successive waves of new technologies.
>
> Given the amount of writing on the subject, it is easy to underestimate the scale of future impact. Bell wrote that the problem with understanding change lay not so much in our ability to describe changes in social, political and economic institutions, it was instead the problem of understanding the change in our own knowledge about the institutions we create. In essence, the forecaster's problem was understanding the change within.

For the field of manufacturing, these advances in IT have resulted in the ability to rapidly process, move, and store information almost anywhere in the world. The development of the Internet has allowed the development of a global marketplace where location and distance have become immaterial, at least for information manipulation. On the other hand, the transport of physical material and personnel is still hindered by distance and, in some instances, location. The increasing performance of modern day information technology seems to hold the future promise of complete command and control of manufacturing facilities that are physically dispersed around the world.

1.4 Outline of Research Document

Chapter 1 provides an introduction to the work that is to be conducted, including an overview and statement of the problem being addressed by the research. Chapter 1 also outlines the hypothesis, research objectives, and the assumptions and limitations related to the problem. Chapter 2 reviews related literature and the current state of research in the field of next generation manufacturing systems and discusses the basis for the research described in this dissertation. Chapter 3 outlines the research approach including the identification of the microfactory/multiple-microfactory architecture and also discusses the selection of a target production activity for conversion to a microfactory. Chapter 4 describes the experimental design and performance measures to be utilized in the research. The results of the research are tabulated in Chapter 5. The Wilcoxon Signed Rank test results on cost performance are also presented in this chapter. Finally, Chapter 6 presents the conclusions reached based on the data detailed in Chapter 5. Additionally, possible future research opportunities are discussed in Chapter 6.

Chapter 2

Literature Review

The survey of literature is divided into several areas which address major research themes considered in the implementation of a microfactory demonstration. These areas are:

- Development of Organized Production Command and Control Structures
- Rise of Broad-Based Organizational Change as a Market Response Strategy
- Emergence of New Organizational Concepts that Target a Post-2000 Marketplace
- Integration of Post-2000 Concepts into a Next Generation Manufacturing System

The final section of this chapter discusses how the issues presented in the literature survey are used to form the technical basis of the microfactory concept.

2.1 Development of Organized Production Command and Control Structures

As discussed in Chapter 1, the goal of the research is to demonstrate the use of production practice simplification and organizational decentralization to attain cost and throughput performance enhancement. In order to address such organizational change, one must realize that the traditional implementation of centralized command and control has been honed by centuries of human development. However, the modern manifestation of production management is born out of the Industrial Revolution of the 1700's. In the United States, modern management practice remained in its infancy until after the War Between the States in the first half of the 1860's. In 1832, a Professor of Mathematics at Cambridge University, Charles Babbage, had published a book entitled, *On the Economy of Machinery in Manufactures*, that outlined many of the basic tenets of modern scientific management. These ideas were not widely accepted until they were championed by a retired consulting engineer in the U.S., Frederick W. Taylor, who, in 1911, published a culmination of his ideas in a book entitled, *The Principles of Scientific Management*. Taylor, later known as the "father of scientific management," addressed comprehensive issues in a bottom-up manner from working conditions and wages to the responsibility of top level management for the planning, directing, and organizing of the work [17].

Taylor's concepts of task management, known as "Taylorism," were soon extended by Henry Ford to "management by synchronization" with the development of the synchronized, standardized, assembly line and the division of labor that characterizes modern mass production. As technology advanced in the second half of the century, management embraced the automation of production and by the 1980's integration and centralization became a key to increasing production performance. This concept of "management by systems," known as "neo-Fordism," encompassed not only the comprehensive integration of computers into the manufacturing process but also promoted a total management view of the enterprise at the corporate level [11].

2.2 Rise of Broad-Based Organizational Change as a Market Response Strategy

The 1990's saw an ever-increasing rate of both social and technological change. This decade served as a harbinger of the post-2000 marketplace. During this time, several managerial and organizational transformation strategies were developed to "manage change." However, as of yet, there seems to be no overwhelming consensus on the most effective way to address the type of social and technological change that is occurring in the global marketplace. And, in fact, Sorensen and Stuart [18] maintain that such change is the necessary fountainhead of innovation that drives the market, stating that:

> …as organizations age, they generate more innovations: the competence to produce new innovations – or at least patents – appears to improve with age, but these gains in organizational competence come at a price, namely, an increasing divergence between organizational competence and current environmental [ed. market] demands.

Methodologies for adapting organizational change to keep up with such "environmental" market change are ranging from the gradual evolutionary integration of change into existing process and practice to the relatively faster introduction of change supported by Business Process Reengineering (BPR) as discussed later in this section. Each addresses the limitations of centralized organizational structures which are most pronounced in large, well-established companies. These limitations are described by Pascale et al. [19] who observe:

> As a result of age, size, or competitive intensity, most organizations exhibit a deterioration in vital signs that is inconsistent with - in fact, often destructive to - their ambitions and purposes.
>
> The members of start-up organizations have a sense of individual and collective power; they feel they can make a big difference in the pursuit of the goals they all share. Employees identify with the enterprise as a whole, alignment and informal teamwork are commonplace. When conflicts occur people handle them directly and almost never allow them to interfere with getting things done. The whole organization is open to learning, trial and error are the norm.
>
> As organizations grow older and larger, however; the vigor of these four vital signs [ed. power, conflict, identity, and learning] deteriorates. Instead of power, people often develop a sense of resignation in response to seemingly insurmountable obstacles or to lack of support from their superiors in the daily hassle of getting things done. As organizations become more complicated and demanding, people strive to carve out private patches of turf where they can exercise responsibility, protect themselves, and keep the world at bay. When it comes to their identity, therefore, employees lose their sense of teamwork and alignment with the entire enterprise and begin to seek the safely of their particular profession, union, function, team, or location. People in mature organizations tend to avoid conflict for fear of blame or of having one take their disagreement personally. Alternatively, they may take part in a succession of routine collisions that lead to stalemate rather than resolution.

As a reaction to this type of entrenched mentality, in 1993, Michael Hammer and James Champy published *Reengineering the Corporation: A Manifesto for Business Revolution*. This book outlined a Business Process Reengineering (BPR) methodology for the implementation of change within a corporation [20]. The BPR strategy promotes the idea that companies must reengineer the most basic structures of the modern organization. Such structures included the division of labor, complex process controls, and the traditional managerial hierarchy. Proponents of a BPR methodology maintain that the success of such change is dependent upon an implementation that is within specific strategic goals directly related to competitive advantage, customer satisfaction, and productivity [21].

Unfortunately, as experience has been gained with the Hammer and Champy form of BPR, the strategy has not proven to be the panacea that was hoped for during its initial development. In his 1995 book, *Reengineering Management*, James Champy cites the fact that reengineering does not seem to progress beyond the upper echelons of corporations, leaving lower managerial levels unchanged or extremely resistant to the reengineering process [22]. Grover [23] states that:

> Business Process Reengineering has been prominently discussed and implemented in a large number of firms around the world. While the notion of radical change is intuitively appealing to "fix" organizational woes, it has not always met with the degree of success originally claimed by its many proponents.

As problems with BPR have become apparent, several researchers have proposed modified BPR strategies to counter weaknesses in the concept. Orman [24] discusses the integration of information technology (IT) and BPR and presents several decision guidelines which can be utilized to model a BPR implementation.

In a review paper, Mitev [25] provides a comparison between BPR and a similar antecessor methodology known as socio-technical system (STS) design, a technique that addresses the alignment of social and technical systems. A socio-technical system is comprised of interrelated technical and social subsystems. In production system design, a socio-technical system view combines both "humanistic," social concerns such as working conditions and personal development opportunities for employees and technical concerns such as lowering cost and improving throughput times.

Both BPR and STS design focus on the same goals with BPR directly incorporating IT into an aggressive strategy of revolutionary "clean slate" change. However, STS design promotes a more "humanistic," evolutionary approach to change such as improving efficiency through a process approach and tempering the accelerated work process of BPR with social concerns. Appelbaum [26] further adds that STS design is based on the assumption that an organization is comprised of both social and technical components requiring collateral optimization in order to achieve optimal performance. The Applebaum [26] STS approach supports an organizational structure comprised of self-regulating workgroups performing interrelated technological tasks and stresses that humanism and effectiveness must be linked in the design of both work process and practice.

More recently, there has been a trend from BPR toward "business process change management" which is, in actuality, the management of five specific sub-elements of the reengineering process; namely, change management, project management, continuous process management, strategic planning, and technology management. Grover [23] discusses this trend and its associated impact on business practices, stating that:

> The results [ed. of his study] show remarkable consistency in the importance of nontechnology management issues concerning strategy, change, and people. Further, the notion of continuous change seems to be becoming more important.

2.3 Focused Factories

As discussed in Section 1.1.3, the research objectives address the demonstration in a real world manufacturing environment of a threefold process and organizational change strategy comprised of automation, simplification, and decentralization. The implementation of this change strategy embodies, in part, the tenets of an earlier concept known as the "focused factory," first introduced in the 1970's by Wickham Skinner. The focused factory concept entails the concentration of production resources to a narrow product mix for a particular market niche; thus, "focusing" resources on a narrow range of products. Skinner [27] explains:

> The conventional factory attempts to do too many conflicting production tasks within one inconsistent set of manufacturing policies. The chief result is that the plant is likely to be non-competitive because its policies are not focused on the one key manufacturing task essential to successfully competing in its industry.

Skinner maintains that companies which attempt to do too many things under a single organizational structure in order to reduce investment requirements and overhead costs are destined to become mired in an unmanageable mixture of a broad range of problems. He states that by decentralizing the production effort to units individually focused on specific products, these organizational units (called focused factories) can address a more manageable set of problems specifically related to the product focus. Further information on focused factories can be found in Tannous and Mangiameli [28]. They make arguments for and against the focused factory concept in light of the more traditional vertical integration strategy of a centralized organizational structure. They point out that the focused factory concept can reduce product costs and delivery times while improving quality. Conversely, they note that vertical integration improves profitability for companies with a large market share and, in fact, "…a monopolistic firm may integrate in order to use its market strength at one level of competition to further its interests at another…" [28].

2.4 Emergence of New Organizational Concepts that Target a Post-2000 Marketplace

A variety of "new" organizational models for manufacturing enterprises are currently being developed and refined. This research and development is international in scope, as can be seen in the following list, which delineates several archetypes of note:

- Biological (bionic) manufacturing originating from Japan
- The fractal company concept originating from Germany

- Lean production originating from the United States
- Agile manufacturing originating from the United States
- Holonic manufacturing system concepts originating from Japan

Each of these organizational theories is summarized in this section. Overall integration of the attributes of each theory into a more comprehensive concept widely known as the Next Generation Manufacturing System (NGMS) is presented in the following section.

2.4.1 Biological Manufacturing

Biological manufacturing (or bionic manufacturing as it has more recently come to be known) is a design methodology for manufacturing systems that imitates biological construction (self-organization) and optimization (evolution) and is based on cooperative, flexible, and adaptive individual production units which can individually "evolve" to achieve an overall manufacturing strategy. Taken as a whole, the manufacturing system is seen as an individual organism that responds to environmental stimuli by manufacturing products. These products are also viewed as individual organisms that compete against other products in characteristics such as shape, function, cost, etc. This model of manufacturing as a biological system was worked on by Kanji Ueda at the Information Processing Center of Kobe University in Japan. The basic tenets of the approach are discussed in Ueda [29] and entail a shift away from centralized control with emphasis on what Ueda refers to as "interactive" manufacturing.

In such a model, the designer, manufacturer, and consumer "interact" throughout a product life cycle as opposed to a more traditional approach that views the life cycle sequence as a linear process of minimally related stages. Robert W. Galvin, Chairman of the Executive Committee of the Board of Directors for Motorola has stated that, "…as global companies grow to mammoth proportions, the only way they will be managed effectively is by using a biological model that mimics the self-governing and learning techniques of a complex organism…" [30]. In general, bionic manufacturing structures mimic cellular activity with characteristics such as the static, genetic information found in deoxyribonucleic acid (DNA), or the adaptive, learned information found in brain neurons. Tharumarajah et al. [31] highlight the similarities between organic cellular systems and manufacturing processes stating that:

> A biological viewpoint has close parallels in manufacturing. For example, production units on the shop floor can be compared to cells in biology. Biologically, a cell is separated from outside by a membrane through which material enters and exits. In a cell there is an organelle, which creates the cell's functions. Cells are immersed in an environment which is chemical. Substances are taken in from this environment. There is also an internal environment and the cell operations exchange (chemical) information with both inside and outside environments. A cell changes its own conditions by its operations and it can do multiple and different operations. These properties correspond closely with autonomously operating manufacturing units…
>
> These units obtain the needed inputs from the factory floor and perform operations. Outputs of these operations flow back to the environment. The operations require information from both internal and external environments.

2.4.2 Fractal Company

The concept of a fractal company has its origin from a 1993 book written by Hans-Jurgen Warnecke entitled, *The Fractal Company: A Revolution in Corporate Culture*. In the book, Warnecke [32] proposes an organizational strategy through which a company can be created from small components, or "fractal objects," that have the ability to adapt quickly and reorganize in the face of a rapidly changing market environment. The key characteristics of these objects include:

- Self-organization - there is no functional intervention required by a higher authority for operation or regeneration.

- Self-similarity - each object in a fractal firm is similar to all others, supporting similar components and sharing similar goals.

- Self-optimization - each object performs continuous internal self-improvement.

The inspiration for the term fractal organization arises from the perception of production process and control as an interacting system of atomistic components. Venkatadri et al. [33] discuss the implementation of fractal concepts in a job shop production environment. They describe their work as an alternative to the agile manufacturing concept [agile manufacturing is discussed in the Section 2.4.4], stating that:

> It was in this context that the fractal layout was originally conceived, intended to be an agile manufacturing alternative achieved through the creation of multifunction mini factories within the confines of a factory.

Spivey et al. [34] observe that the success of a fractal solution is dependent upon a comprehensive top-to-bottom implementation such as that espoused by the BPR concept. Spivey et al. [34] state that:

> …each of these factors cascades into several interrelated sets of concerns. For example, the management factors comprise concerns about leadership and the management system. The resource factors include concerns about information infrastructure, time, and money.
>
> Regardless of the level of detail at which the framework is viewed, improving the NPD [ed. new product development] process requires attention to all of these factors, by all levels within the organization. For example, visionary leadership on the part of senior management will have little effect if middle management and line supervisors fail to provide the necessary leadership for their respective groups of subordinates.

2.4.3 Lean Production

The characteristics of lean production are first identified and encapsulated in a 1990 book entitled, *The Machine that Changed the World*, written by James P. Womack, Daniel T. Jones, and Daniel Roos. The lean production concept is based on an earlier five year study of the automobile industry by the International Motor Vehicle Program (IMVP) at the Massachusetts Institute of Technology [35]. The book presents a cautionary treatise warning that companies in the United States must adopt "lean" production process and practice policies to compete successfully with Japanese companies. This concept is further formalized in a later book by Womack and Jones [36] entitled, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. As implied by the title, lean production is, in its basic form, the manufacture of a product with a minimum of waste. However, the treatise by Womack and Jones [36] takes a broader view of "waste" than just that of material scrap and unnecessary overhead and proposes that a lean implementation address all aspects of value-creating activities.

The concept of lean production represents the natural evolution of "Just in Time" (JIT), a production concept pioneered by Toyota. This idea is to make only what is needed when it is needed. Noori and Mavaddat [37] discuss lean production issues and link them to enterprise-wide integration of information and coordination of decisions. Furthermore, they recognize the importance of IT in maintaining competitiveness and company focus, stating that:

> The necessity of maintaining lean operations and becoming an 'agile enterprise', in which the speed and flexibility at which a company functions matches that of its technology, is widely accepted. Information technology is providing the means for companies to integrate better their internal and external activities.

Furthermore, Plonka [38] discusses the workforce required to support lean and agile enterprises and observes that:

> The cognitive demands that accompany technological innovation will require readying the work force for a more demanding environment. Workers have to look beyond loading parts in machines. They will need to be continually involved with the process and to intervene when required. Operators must be familiar with equipment technology in order for them to suggest improvements in the reliability, precision, and serviceability of equipment, controls, and sensors. These demands will require acquisition of new knowledge, accelerated learning, and just-in- time delivery of training.

2.4.4 Agile Manufacturing

Agile manufacturing was introduced by Steve L. Goldman, Kenneth Preiss, R. N. Nagel, and Rick Dove in a 1991 report by the Iaccoca Institute at Lehigh University in Bethlehem, Pennsylvania entitled, *21st Century Manufacturing Enterprise Strategy.* The concept presented in the study has since been championed by the Agile Manufacturing Enterprise Forum (now known as the Agility Forum) which has defined the generally accepted long term view of agility in production. Numerous research and development programs are ongoing in this area. A few notable examples include: the Agile Manufacturing Initiative sponsored by the Defense Advanced Research Projects Agency (DARPA) and the National Science Foundation (NSF) which has a mandate to demonstrate and evaluate the processes described in the report; The Technologies Enabling Agile Manufacturing (TEAM) program sponsored by the U.S. Department of Energy with the goal of demonstrating the benefits of integrating multiple software systems within an agile manufacturing enterprise; and the establishment of a series of Agile Manufacturing Research Institutes (AMRI's) which support the teaming of university and industry with the goal of developing the principles and practices that define agile manufacturing.

Despite this high level of interest in agility, the actual definition of the concept is vague and somewhat expansive. Even the Agility Forum notes that the idea of agile manufacturing is not a specified technique with a clearly delineated list of components. As a result, researchers have adopted a wide range of approaches to agility. As an example, Lee [39] defines agility as, "…the ability of a manufacturing system to manufacture a variety of components at a low cost and in a short period of time." This approach focuses on interventions early in the design stage of a product, the reduction of lead times for a product, and an increased utilization of resources. On the other hand, DeVor et al. [40] observe that the agile concept is evolving from an initial localized implementation to become a strategic methodology that utilizes "proactive adaptability." This strategic view results in a more comprehensive, less specific perspective as can be seen in the definition of agility provided by Gunasekaran [41]. He defines agility "…as the capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services…." Gunasekaran [41] further notes that the concept embodies an inherent paradox as companies must compete and cooperate in the same market environment.

In general, the fundamental tenet of agile manufacturing is the use of modern information technology to form virtual enterprises which "agilely" respond to changing market demands. This is accomplished through the formation of a flexible and dynamic manufacturing environment that can utilize a network of manufacturers to produce "customized" products. To accomplish an agile implementation, five elements are proving to be key [42]:

- Changes in business, engineering, and production practices
- Seamless information flow from design through production
- Integration of computer and information technologies into all facets of product development and production processes
- Application of communications technologies to enable collaborative work between geographically dispersed product development team members
- Introduction of flexible automation of production processes

Jung et al. [43] describe a strategy for the rapid development of agile manufacturing systems and identify nine architectural elements that must be addressed successfully to achieve agility; control, process, function, information, communication, distribution, development, implementation, and reference. Weston [44] provides insight into the information (and associated software) infrastructure issues that need to be addressed in an agile implementation and Reimann and Sarkis [45] discuss an organizational framework for achieving agility by linking companies to form a "virtual" enterprise.

2.4.5 Holonic Manufacturing

The treatise of holonic manufacturing is founded on concepts presented in 1967 by the Hungarian author and philosopher, Arthur Koestler, who proposed the word "holon" to describe a basic unit of organization in biological and social systems [46]. The holonic manufacturing concept draws on examples in biology in much the same way as the biological (bionic) manufacturing concept. The concept observes that in living organisms and in social organizations entirely self supporting, non-interacting entities do not exist, but rather every identifiable unit of organization is comprised of more basic units while at the same time forming a part of a larger unit of organization. Holon is a combination of the Greek word "holos," meaning whole, and the suffix "on" meaning particle or part. Koestler defined the term, holon, as an identifiable part of a system with a unique identity that is comprised of subordinate parts and is also part of a larger whole.

A holonic approach to design a manufacturing system recognizes that such a system can also be defined as a collection of sub-ordinate parts that in turn are part of a larger whole. This approach recognizes production activities of varying automation and a principle of self-organization that does not depend on a hierarchical command structure [47]. Nonetheless, as Sun and Venuvinod [47] point out, "…A holonic organization is not an independent company. Autonomy of a holonic work organization is not absolute and is subject to the requirements of the higher level organization." The strength of holonic organizations is in their ability to support very complex systems that are readily adaptable to change within the modern production environment. The functional and structural concepts of holonic manufacturing support both distributed autonomy and cooperative control [31].

The first experimentation with the idea of holonic manufacturing occurred in Japan in the late 1980's. Toshiba and Hitachi, while working independently on unique implementations of the concept, began seeking international partners to expand the research. This attracted the interest of the Japanese Intelligent Manufacturing Systems (IMS) Promotion Center. In 1989, the Center integrated the two programs into a research and development component of the then newly formed IMS Consortium. In 1995, the IMS Consortium was implemented as a full-scale, 10-year research and development program involving Japan, the United States, Australia, Canada, the European Community (EC), and the European Free Trade Association (EFTA) [48]. The holonic component of the IMS, known as the Holonic Manufacturing System (HMS) project is comprised of 41 industrial, academic, and research partners. It is one of six research and development areas sponsored by the IMS which include:

- Holonic Manufacturing Systems - System Components Of Autonomous Modules And Their Distributed Control
- Clean Manufacturing in the Process Industry
- Global Concurrent Engineering
- Globeman 21 - Enterprise Integration for Global Manufacturing Toward the 21st Century
- Rapid Product Development
- Knowledge Systematization - Configuration Systems For Design And Manufacturing (GNOSIS)

The goal of holonic manufacturing development is to translate the observations of Koestler into a production implementation that can sustain efficiency, stability, adaptability, and flexibility within a constantly shifting market environment. Cselenyi and Toth [49] discuss fundamentals of holonic production systems and delineate the following holonic "production unit" characteristics:

- Each production unit is economically independent, supporting independent financial management and accounting
- Each production unit is independent in ownership
- Each production unit is cooperative with other production units and is supported by joint services

In an integrated design-to-control approach to holonic manufacturing, Wang [8] states that, "…Based on the holonic concept, the next generation of IMS could form distributed re-configurable virtual factories, in which human, machines, and control modules interact in dynamically formed virtual clusters. Such a system could be built from intelligent, autonomous, and cooperative elements or holons." Along these lines, Valckenaers et al. [50] discuss the design of holonic manufacturing systems and identify three holon types; the resource holon, the product holon, and the order holon. The resource holon is a physical resource and the information processing that controls it. The product holon contains the process and product knowledge needed for making a product. The order holon represents a task within the manufacturing process. Using these three holon types, Valckenaers et al. [50] are able to construct a holonic-based manufacturing system model. Bagshaw and Newman [51] take a higher level view and construct an entire small manufacturing enterprise from a three holon system as follows:

> [ed. This model] represents the enterprise as an enhanced organization holon which can further be categorized into three sub-holons namely: the executive holon that represents the ultimate decision-making process within the company, the business holon that covers administration activities such as order processing, finance, costing, process planning and scheduling etc., and the manufacturing holon involves the execution and monitoring of the process plans produced by the business holon.

2.5 Integration of Post-2000 Concepts into a Next Generation Manufacturing System

The advanced manufacturing concepts that have been described in the previous sections (i.e., biological/bionic, fractal, lean, agile, and holonic) are being developed to address the characteristics of a post-2000 market environment. Of the five, leanness and agility tend to focus more on procedural change with supporting organizational change. Agility embraces the utilization of information technology to form virtual enterprises that can "agilely" respond to changing market demands via a flexible, dynamic production environment. In practice, agile manufacturing comprises cooperation among partnered elements with an overall operational unit that are linked by electronic communications channels. The remaining three concepts, biological/bionic, fractal, and holonic, are organizational architectures which define manufacturing systems as a network of distributed, autonomous, flexible production elements. Tharumarajah et al. [31] point out that:

> …[ed. bionic, fractal, and holonic] concepts describe, in quite general terms, the underlying principles of designing manufacturing systems which are highly flexible in their structure and operation. These principles advance an organization of distributed autonomous modules that are capable of self-organizing behaviors to carry out the necessary functions. However, the concepts differ in their approach to design of these features.

Each of these concepts is characterized by a networked structure of basic units…for bionic it is the cell, for fractal it is the fractal object, and for holonic it is the holon. A fractal implementation is comprised of self-similar objects (which may differ internally as they self-organize) that continuously react to the external environment to achieve a common system of goals. Fractal objects are very dynamic, reconfiguring or even restructuring in response to changes in the environment. A holonic architecture, although similar to a fractal implementation, is instead decomposed by function in which a holon, unrestricted by geographic location, can define anything from an informational element to a specific machine and may have numerous, overlapping "whole-part" relationships. A bionic architecture supports a more layered approach to its cell structure than fractal and holonic implementations. Its evolutionary ability, like a fractal implementation, is unrestricted by functional definition and; therefore, supports a more dynamic reproduction capability than a functionally-defined holonic architecture. This capability, unlike a fractal architecture which is based on an initial design, is borne from a natural genesis that passes on basic "DNA" information as each new cell is formed.

As illustrated in Figure 2.1, during the past few years, researchers have been working on the integration of these concepts into a production architecture known as a Next Generation Manufacturing System (NGMS). Two of the more recent and more prominent examples of NGMS research and development are: 1) the United States sponsored NGM project and 2) the international NGMS/IMS (Next Generation Manufacturing Systems/Intelligent Manufacturing Systems) development program. The former of these programs is the United States' sponsored Next Generation Manufacturing Project (NGM). Conducted from 1996 to 1997, the NGM project was a collaborative effort between several government agencies (i.e., National Science Foundation, Department of Energy, Department of Defense, and National Institute of Standards and Technology) and industry to identify the elements that define the next generation of production systems. Project coordination for NGM was provided by a team of three organizations: the Agility Forum at Lehigh University; the Leaders for Manufacturing (LFM) program at the Massachusetts Institute of Technology; and the Technologies Enabling Agile Manufacturing (TEAM) program at the Department of Energy's Sandia National Laboratories. The program published their results in an extensive 700 page report released in 1998, entitled, *Next-Generation Manufacturing Project: A Framework for Action*.

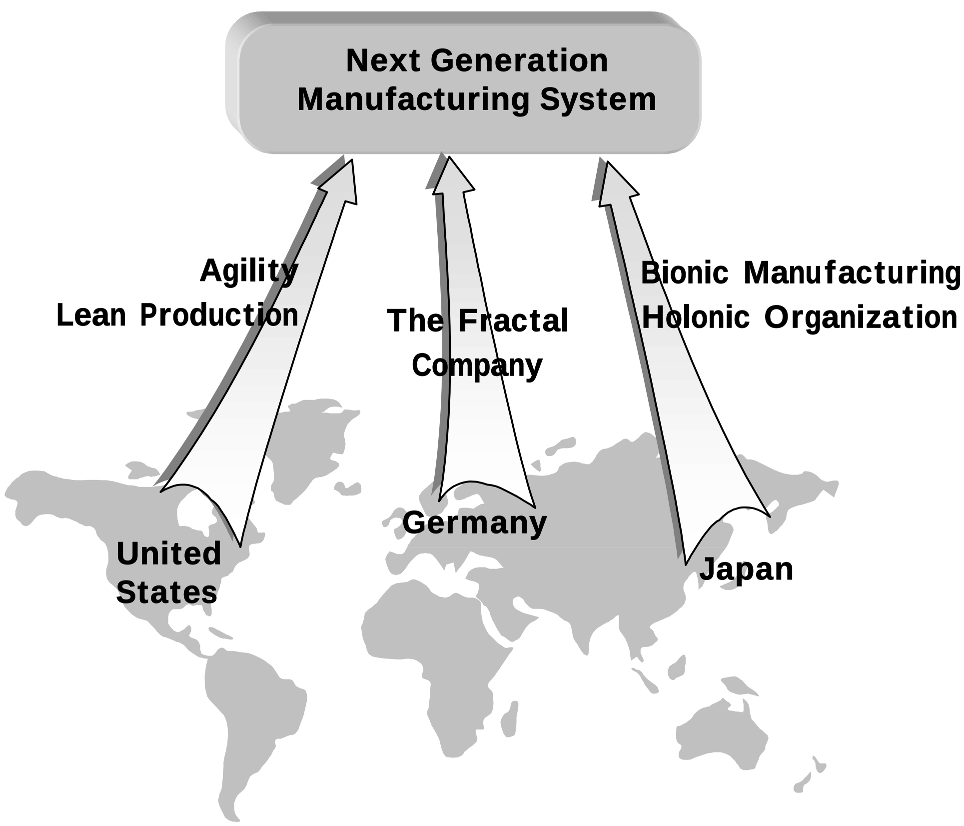


Figure 2.1. Integration of Antecedent Technologies into NGMS Development

As one would infer from the extensive involvement of the Agility Forum and TEAM elements, the NGM program has originated from many of the tenets that define agility. The NGM project specified a set of generic enabling practices and technologies that are critical for achieving a Next Generation Manufacturing System implementation. These enabling components are:

- Workforce Flexibility - a set of practices, policies, processes, and culture that enable employee security and ownership, while capitalizing on creativity, commitment, and discretionary effort and maintaining the size and skill flexibility of the workforce

- Rapid Product/Process Realization - the integration of product/process development utilizing cross-functional development teams supported with an integrated computer environment

- Innovation Management - comprehensive solution creation ranging from business practices to the technology used to develop and deliver products and services

- Change Management - the continuous application of deliberate change to the current state of the organization to achieve a more competitive future state

- Next-Generation Manufacturing Processes and Equipment - the development of reconfigurable, scaleable, and cost-effective manufacturing processes, equipment, and systems to support an up-to-date knowledge base of product and process technology

- Adaptive, Responsive Information Systems - the implementation of information systems that can be dynamically reconfigured into new systems by adding new elements, replacing others, and changing how modules are connected to redirect data flows through the total system

- Extended Enterprise Collaboration - the seamless integration of companies and suppliers in a collaborative effort to create and support a timely and cost-effective service or product

- Enterprise Integration - the interconnection of personnel, processes, systems, and technologies to provide the right information at the right location, with the right resources, at the right time

- Pervasive Modeling and Simulation - the practice of the modeling and simulation of all production decisions to replace current "build-and-test" methods

- Knowledge Supply Chains - the application of supply chain management to the relationships between industry, universities, schools, and associations to rapidly provide and continuously update the knowledge and talent needed to run businesses in a timely and cost-efficient manner

NGMS/IMS (Next Generation Manufacturing Systems/Intelligent Manufacturing Systems) development originated from the Intelligent Manufacturing Systems (IMS) program, described in the previous section. The NGMS/IMS program is coordinated by the Consortium for Advanced Manufacturing - International (CAM-I) in Bedford, Texas. It is an international program sponsored by the core participants of the original IMS program; namely, Japan, the United States, Australia, Canada, the European Community (EC), and the European Free Trade Association (EFTA) which includes Austria, Finland, Sweden, Norway and Switzerland. The goal of the research is to:

- Generate a unifying description of a Next Generation Manufacturing System
- Create facilities to identify, monitor, and evaluate advanced technologies and advanced materials that can be used to implement the NGMS description
- Develop models and simulations which integrate process and practice across an entire globally distributed virtual enterprise

2.6 Current State of Research

As one considers the research trends discussed in earlier sections of this literature review, an overall picture of the post-2000 manufacturing environment begins to emerge. It is one in which rigid, static, and hierarchical manufacturing systems give way to systems that are more adaptable to rapid change. Small production lots respond to specific customer demands while trying to remain cost-competitive. Sambamurthy and Kirsch [52] describe the pressures facing businesses in the post-2000 marketplace:

> Most contemporary firms face dramatic pressures for continual change and adaptation in their business environments. Pressures toward globalization, competitive agility, and customer centeredness are compelling firms to re-examine their traditional structure and work processes and engineer new value-adding processes. Further, information technologies are becoming critical to the capabilities developed by firms to compete effectively in the emerging information-intensive business environments.

The Investigator believes that future manufacturing systems will be characterized by networks of autonomous, distributed, and cooperative elements which are electronically linked either directly or indirectly to all other elements. These elements may interact as single virtual enterprises or may grow from alliances and outsourcing of sub-functions. Sen and Egelhoff [53] note that there are several reasons that companies are turning to such cooperative alliances stating that:

> The number of technical alliances has been rapidly increasing. There are multiple reasons for this growth: The fast rate of technology change, the increasing complexity and cost of developing new technologies, the advantages of early entry, and the emphasis some firms place on allocating resources to existing core technologies. Other reasons include shortening of the product life cycle, the importance of standards, and the reduction of R&D risk.

In any case, companies will operate in an environment that Quinn [54] describes as "somewhat orderly chaos:"

> No one manager or team controls the hurricane of worldwide supplier, customer and competitor innovations; and yet the hurricane has some broadly predictable characteristics – for example, greater bandwidth, speeds, wireless capabilities and interconnectivity. To keep up with the pace, leading organizations are reforming into circular, independent modes with knowledge centers that broadly match anticipated changes but little visible authority or ownership structure.

At the core of this concept is the more general view that competitive manufacturing in the next century will require a network of flexible and nimble manufacturing elements. Moreover, each of these elements must be capable of rapid and continuous "batch manufacturing" of small production lots at low cost in order to deliver near single unit customization. This vision is described by Ming et al. [55] who state that:

> …it is becoming increasingly important to develop manufacturing systems and equipment control architectures that are modifiable, extensible, reconfigurable, adaptable, and fault tolerant. Centralized control architectures have given way to hierarchical schemes, where higher levels of the hierarchy control the lower level via a master slave relationship. However, to achieve even greater levels of reconfigurability and adaptability, the newer manufacturing systems are adopting heterarchical control structures that are made up of multiple, distributed, locally autonomous entities, thus allowing a cooperative approach to global decision making.

Wang et al. [56] support this view and offer the following description of such systems:

> They will be multi-agent systems containing distributed control functions and application entities that can dynamically collaborate to satisfy both local and global objectives. Such IMS's [ed. Intelligent Manufacturing Systems] will be comprised of dynamically reconfigurable factories having virtual organization and decentralized control structure. The constituent resources will be capable of addressing both knowledge processing and material processing requirements simultaneously.

As described in the previous sections of this literature survey, the 1980's and 1990's have seen the coalescing of several manufacturing concepts (i.e., biological/bionic, fractal, lean, agile, and holonic) into a more general manufacturing systems structures known as Next Generation Manufacturing Systems (NGMS).

2.7 Basis for the Research

This dissertation addresses the application of one possible element of an NGMS strategy, an autonomous production unit that can be networked with other similar units to form a "virtual" enterprise. The research approaches this through the demonstration in a real world manufacturing environment of an autonomous production unit that integrates the concepts of decentralization, automation, and simplification. The basis for the research is founded in current NGMS concepts as discussed in Sections 2.5 and 2.6 which, in turn, stem from previous work in bionic, fractal, and holonic organizational structures. More specifically, the Investigator draws on these concepts in three ways:

1) First, the demonstration prototype is autonomous and can be represented as a parent holon containing subordinate holons that further subdivide the production process and practice. The functionality of the parent holon is a single product family manufacturing activity that can be viewed as a fractal component of the overall business enterprise. Venkatadri et al. [33] allude to this while discussing the implementation of fractal concepts, referring to each fractal as a "multifunction mini factory."

2) Secondly, the research utilizes the NGMS concept of a virtual enterprise by supporting the comprehensive integration of information technology to link each of the system components both internally and to external sources. This is supported by Rockart [57] who writes, "…Information technology, with its information handling capabilities, is now the coordination tool of the 1990's and the next century."

3) And finally, the present research embodies the tenets of the "focused factory" concept discussed in Section 2.3. Developed by Wickham Skinner in the 1970's, this concept entails the concentration of production resources to a narrow product mix for a particular market niche; thus, "focusing" resources on a narrow range of products.

Chapter 3

Method of Procedure

The method of procedure outlined in this chapter is a conceptual framework for the experiment reported in Chapter 4. The research procedure embodies the development and implementation of a real world production architecture, based on NGMS concepts, to demonstrate the synthesis of decentralization, automation, and simplification to reduce throughput time and product cost while maintaining production quality. As detailed in Section 1.1.3, the research is defined by three objectives. Research Objective 1, the development of a microfactory and supporting multiple-microfactory architecture, is detailed in Section 3.1. Research Objective 2, the demonstration of a microfactory prototype in a real world production environment, is discussed in Section 3.2. And finally, Research Objective 3, the comparison of microfactory performance with historical pre-microfactory performance, is outlined in Section 3.3.

3.1 Research Objective 1: Development of Microfactory/Multiple-Microfactory Architecture

This section describes the work on Research Objective 1: "Develop a Microfactory and Supporting Multiple-Microfactory Architecture." This objective involves the identification and development of a prototype architecture that integrates the concepts of decentralization, automation, and simplification into an autonomous production unit. This production architecture is referred to as a "microfactory" by the Investigator. This architecture is not physically implemented during the completion of Research Objective 1. Rather the accomplishment of Research Objective 1 entails the development of an organizational design based on decentralization, automation, and simplification that considers the "line" production environment in which it is to be implemented. The actual implementation of the microfactory concept is accomplished during the completion of Research Objective 2, "Demonstrate a Microfactory Prototype in a Real World Production Environment." Performance measurement of this implementation is then completed during Research Objective 3, "Compare Microfactory Performance with Historical Pre-Microfactory Performance."

In addition to the design of the microfactory architecture during Research Objective 1, further work is conducted on identifying the elements required to assembly a series of microfactories into a "multiple-microfactory" organizational architecture. At the multiple-microfactory level, the microfactory unit functions as a single independent element that is part of an overall manufacturing enterprise based on a network of microfactories. These microfactory and multiple-microfactory architectures incorporate the three concepts outlined in the research basis in Section 2.7. They comprise: 1) holonic/fractal elements, 2) a networked virtual enterprise similar to that described by NGMS researchers, and 3) a "focused factory" type organizational structure.

3.1.1 Microfactory

In order to distill the critical elements required to structure a microfactory production activity, a basic manufacturing implementation is built up in complexity until the production requirements are satisfied. This section describes such a process, beginning with a discussion of the basic components of a manufacturing system, followed by an overview of the evolution of a such a system into an integrated business, and finally presenting a more detailed description that focuses on the implementation of a microfactory element.

3.1.1.1 Basic Components of a Manufacturing System

Manufacturing in its basic form is the conversion of naturally occurring raw materials into products [58]. This activity is driven by an individual or group, the customer, compensating another, the manufacturer, to make the product. Harrington [59] divides the process into three parts and notes that:

> It is convenient to think of this sequence as having three parts – extraction of the naturally occurring materials from the environment, culling, and concentration; the conversion of these materials into a specialized form in bulk; and the conversion of bits of the bulk material into discrete parts which, when assembled with other parts, constitute the desired end-products.

Singh [60] presents a more current CAM-I definition of manufacturing which states that:

> Manufacturing is a series of interrelated activities and operations involving design, material selection, planning, production, quality assurance, management, and marketing of discrete consumer and durable goods.

Considering these, it can be seen that the first definitions by Harrington [59] and Kalpakjian [58] specify what one might term the actual manufacturing process. On the other hand, the CAM-I definition expands the scope specifically to identify supporting activities. The Investigator views these two definitions in their most basic form as two components: a mechanical/electrical sub-system of tools and machinery that comprises the production process, and a supporting shell of human activities and interactions that surround the production process. For the electronics assembly manufacturing process of interest, Figure 3.1 illustrates the Investigator's view of the most basic representation of the manufacturing activity.

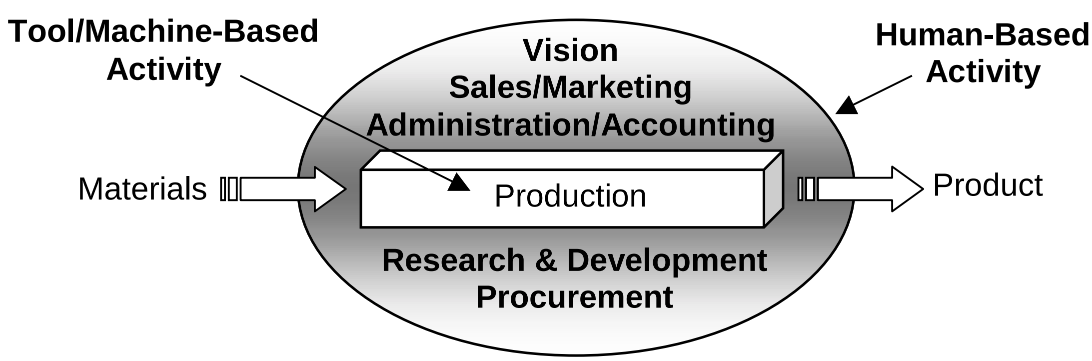


Figure 3.1. Elements of a Basic Manufacturing System

As can be seen in Figure 3.1, the production element of the manufacturing system is tool/machine-based and, in some cases, can be entirely automated. The remaining elements of the manufacturing system are human-based activities, requiring some form of human interaction. It can be seen that the production process is entirely responsive to the human interaction shell that provides the reason for manufacturing in the first place, the customer. Accordingly, the production element within the manufacturing system is entirely dependent upon sales. The remaining manufacturing elements exist for the support of sales and production.

In a basic form of a manufacturing activity (one individual makes a product for a second individual), the human-based parts of the system are all contained within one individual (i.e., as in a cottage industry business). However, as sales increase (resulting in production increases), the functions of these elements become too complex and time consuming for one individual to accomplish and the elements become dispersed among several individuals. As the company grows larger, the number of individuals supporting an element grows until it is large enough to support separate administration and accounting components. At this point, the element becomes a unique organizational entity.

3.1.1.2 Elements of a Microfactory

Building on the fundamental manufacturing concepts discussed in Section 3.1.1.1, one can see that the basic production element in a manufacturing system is the customer-sales-production-customer cycle. Sales acquires orders from the customer base which triggers production of goods that are then delivered back to the customer base. The factory system being designed during Research Objective 1 encapsulates this customer-sales-production-customer cycle into autonomous units called "microfactories." As can be seen in Figure 3.2, the microfactory concept converts a production line (or group of similar production lines) into autonomous self-contained production elements. As shown in this figure, the microfactory architecture does not encompass higher level management components of the enterprise, but rather integrates the elements needed to maintain the customer-sales-production-customer cycle. In this organizational structure, upper level management elements including corporate management, marketing, and research and development are separated from, but interfaced electronically to, the sales, production, and delivery elements of the enterprise. These elements are then fragmented into small self-sustaining production units (i.e., microfactories). The microfactory units are expected to respond to short term market change without interaction from the upper level management elements which provide long term direction to the overall enterprise rather than short term management of production. A more detailed view of the interactions between elements of a microfactory-based system is illustrated in Figure 3.3.

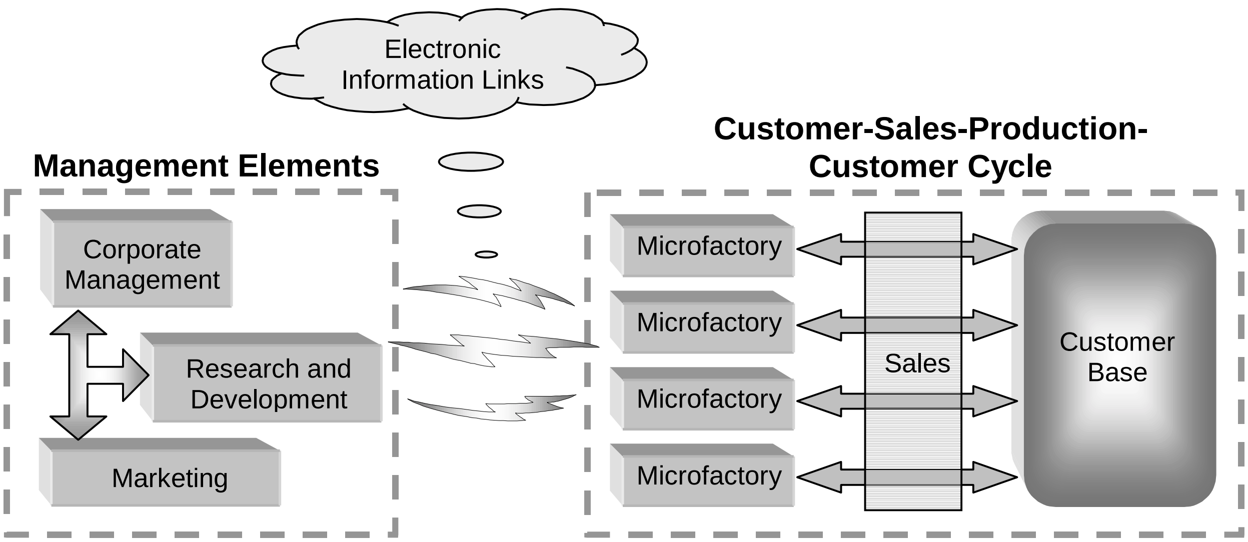


Figure 3.2. Production Function Implemented Using Microfactory Elements

As can be seen in Figure 3.3, the microfactory is the engine that runs the customer-sales-production-customer cycle. Sales acquires orders from the customer base which triggers production of goods that are then delivered back to the customer base. Material acquisition is accomplished through a procurement component that is a part of the microfactory. As long as sales can generate orders from the customer base, this cycle can continue without interaction with the other three elements of the system; corporate management, marketing, and research and development. However, in reality, this customer-sales-production-customer cycle is not self-sustaining and interaction with the three remaining elements is required to stay competitive within the market. Corporate management defines the business goals and provides the strategic vision necessary to give long term direction to the company. Marketing identifies both short term and long term customer requirements, ensures current product recognition, and identifies future product functional needs. Research and Development identifies emerging technologies and/or develops new technologies to support the market goals of the company.

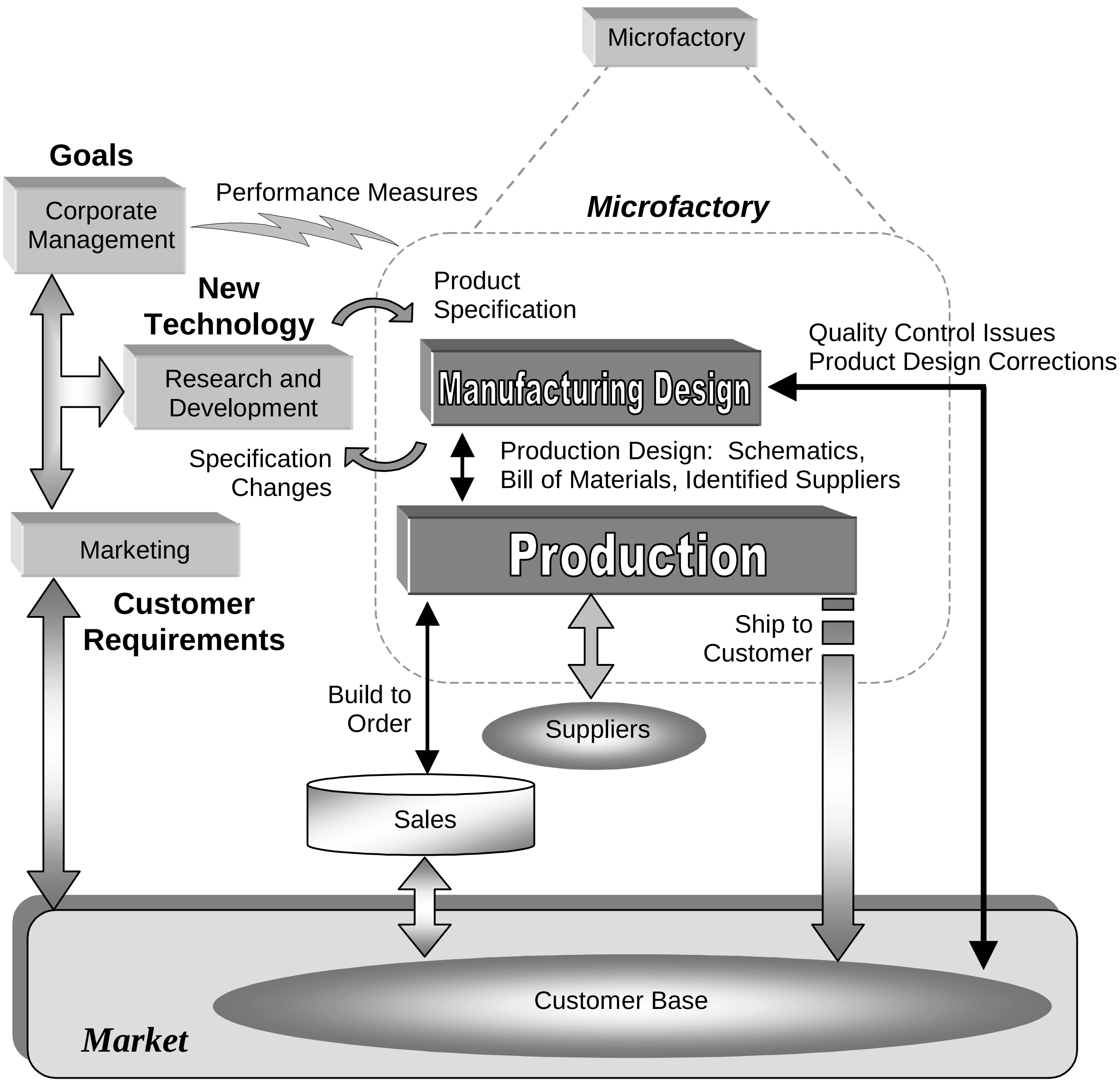


Figure 3.3. Interaction in a Microfactory-Based Production System

The interactions shown in Figure 3.3 utilize information technology (IT) to provide a mechanism to counteract the problems associated with a decentralized organizational structure. The appropriate use of IT maintains strategic direction and ensures the synchronization of component activities at the macro level. Concurrently the instantaneous nature of electronic information interchange allows the various remote elements of the organization to work in concert as one enterprise.

As can be seen in Figure 3.3, the microfactory is comprised of two major elements, Production and Manufacturing Design. The Production element monitors sales and interacts with suppliers to manufacture products based on product designs provided by the Manufacturing Design element. Manufacturing Design works closely with the Research and Development function of the overall enterprise. It maintains involvement with the design of products from the standpoint of manufacturability issues and is responsible for the development of production prototype schematics and associated bills of material. The prototype product schematics are designed for manufacturability based on production process constraints and the availability (including lead time considerations) of materials and sub-assemblies. Once a product is in the field, then quality control and product design problems are reported back to Manufacturing Design, which interacts with both Research and Development and Production to remedy identified problems.

3.1.1.3 Microfactory Life Cycle

An outline of the life cycle of a microfactory is shown in Figure 3.4. As can be seen in Figure 3.4, the life cycle of a microfactory from development through deployment to disassembly is a partially closed loop anchored by a microfactory development function that implements new microfactories with each new product specification received from corporate research and development. The new microfactory development function is identified as the Advanced Manufacturing Development Laboratory, or AMDL.

The result of the AMDL development process is a series of new microfactory introductions that, for clarity in Figure 3.4, are chronological in nature. The newest introduction (i.e., Microfactory #4) is depicted closest to the AMDL, while the oldest introduction (i.e., Microfactory #1) is shown furthest from the AMDL. In Figure 3.4, it can be seen that Microfactory #1, at the end of its life cycle, has reached obsolescence and is being disassembled.

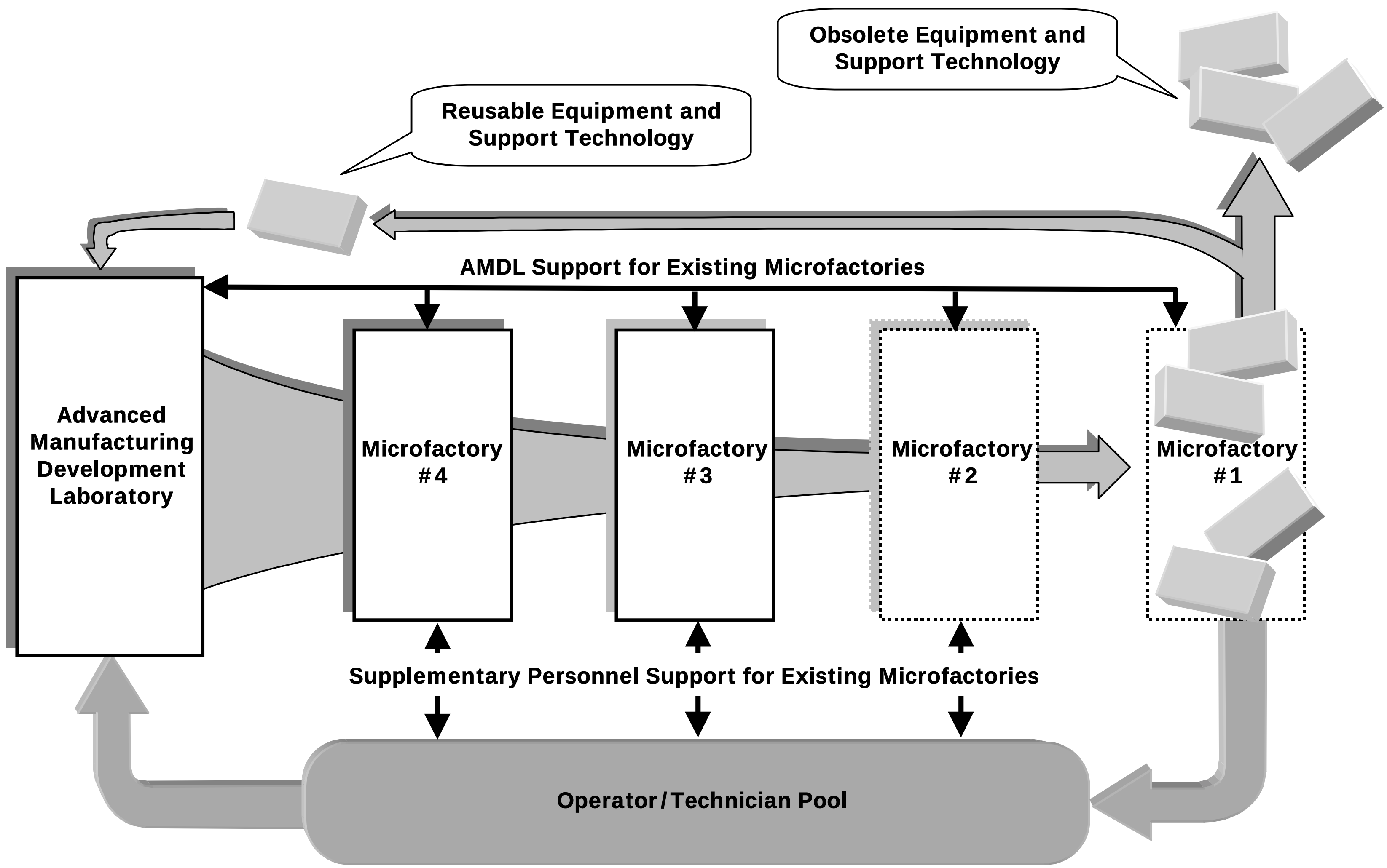


Figure 3.4. Microfactory Development, Deployment, and Disassembly Life Cycle

During the disassembly process, the equipment and supporting technology utilized by Microfactory #1, if found to be obsolete, are scrapped for either recycle or salvage value, while any equipment or technology that is still viable for application in new microfactory implementations is once again made available to the AMDL development process. Operational personnel (i.e., operators and technicians) that handled and maintained Microfactory #1 return to a central personnel pool, which, in turn, provides personnel to the AMDL for new microfactory introductions. Furthermore, this labor pool must provide supplementary personnel to support existing microfactories when changes in production demands require an increase in labor.

Once a microfactory is deployed, the AMDL provides on-going engineering, procurement, and financial support for the microfactory. The level at which this support is maintained is dependent on the characteristics of the microfactory. If the activity has need for, and can support, full time engineering, procurement, and/or financial positions, then such personnel are directly assigned to work for a specific microfactory. If, on the other hand, the microfactory has a need for only part time employment of such personnel, then the AMDL provides the necessary support.

3.1.1.4 Advanced Manufacturing Development Laboratory

As discussed in Section 3.1.1.3, the Advanced Manufacturing Development Laboratory, or AMDL, is responsible for the development, implementation, and life cycle support of microfactories. The support provided by the AMDL ranges from detailed technical engineering to advanced procurement and financial support. In essence, the AMDL serves as a fountainhead for a series of microfactories that target a specific technology or product line. The AMDL environment, in a manner similar to a university environment, serves as an incubator for new ideas and methods in advanced manufacturing technology. Accordingly, the AMDL places advanced development personnel in proximity to associated production activities, and its internal organizational structure and associated mechanisms of external interaction are depicted in Figure 3.5. The heart of the AMDL is the new product/microfactory design and implementation function. This function is comprised of development teams that incorporate all aspects of product design and manufacture required for a new product introduction, or NPI.

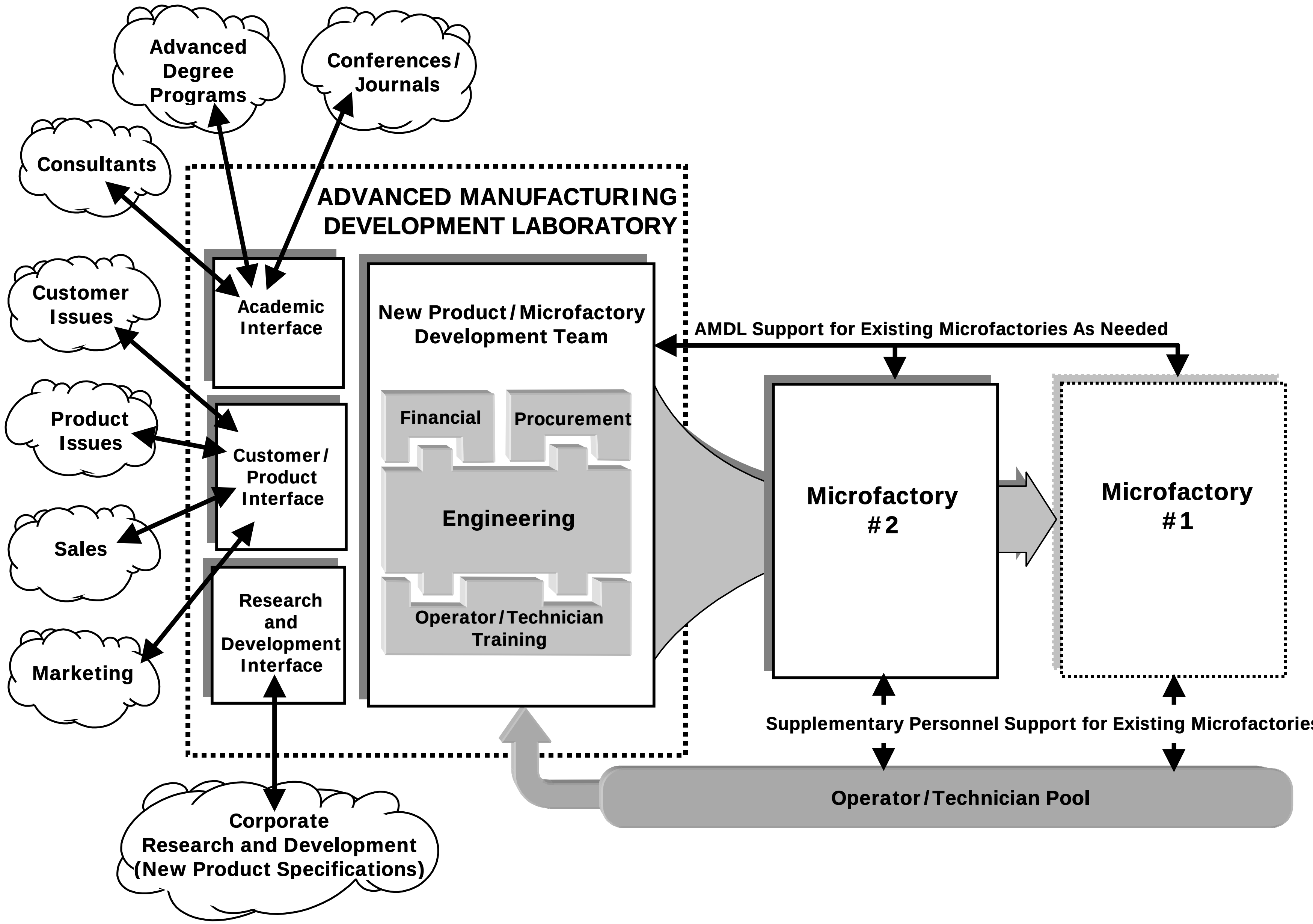


Figure 3.5. Organizational Structure of the Advanced Manufacturing Development Laboratory

The NPI process in an AMDL/microfactory environment is initiated with the acceptance of a new product specification from corporate research and development elements. Such information provides the AMDL with bracketing specifications for the form, fit, and function of the product and suggested technologies (e.g., chip sets, software tools, etc.) to be used in the implementation of the product. Based on this specification, the AMDL begins an NPI process that concurrently combines financial, procurement, engineering, manufacturing development, and operator/technician training with the development of a product implementation that is designed for manufacturability.

Once a microfactory is deployed, the AMDL serves as a source of expertise as needed by the microfactory. Generally, the microfactory is self-contained, supporting its own financial, procurement, engineering, and, of course, production elements. As shown in Figure 3.5, there are three components of the AMDL that lie outside of the core new product/microfactory development activity; namely, research and development interface, academic interface, and customer/product interface.

The research and development interface serves as an information interchange to other research and development components within the company. This interface supports information interchange on new product specifications and technology updates of interest to the AMDL. The academic interface provides interchange with external academic resources such as consultants, advanced degree programs, conferences, and journal publications. This interface maintains a list/pool of consultants who can provide external "expert" assistance to AMDL/microfactory activities as needed. In addition, the academic interface promotes advanced degree programs for employees and encourages attendance of academic conferences and the submission of journal publications. Overall, the academic interface ensures that employees are provided career enhancing educational opportunities and that the AMDL/microfactory workforce can apply the latest advances in business, science, and engineering.

The AMDL architecture also includes a customer/product interface. Although the size and dominion of this interface can vary depending upon assigned responsibility, the most basic mandate is to provide an interface to sales and marketing components and to coordinate customer and product issues as needed. At a very minimum, the mandate specifies the support of direct submissions (preferably electronic) to the AMDL of any technical issues that occur in the field with respect to products of interest to the AMDL and associated microfactories. In addition, the interface maintains an on-going dialog with sales and marketing and are available to respond to technical issues concerning customer installations and products. In a more extensive implementation, the customer/product interface takes on the functionality of customer support and becomes a collaborative partner with sales in total product life cycle support for the customer base.

3.1.2 Multiple-Microfactory Architecture

The overall microfactory life cycle system shown in Figure 3.4 is, for the most part, self-contained with a single AMDL producing and supporting a multiple microfactory implementation from product specifications developed and submitted by corporate research and development elements. Figure 3.6 illustrates a multiple-microfactory architecture encompassing both AMDL/microfactory systems and external support elements.

Figure 3.6 illustrates a scenario in which a multiple-microfactory is comprised of three AMDL/microfactory systems supported by two main external elements, Corporate-Level Management and a Plant Services Provider. The AMDL/microfactory systems are associated with specific product families. The AMDL in each system supports expertise relating to a particular product family. In addition, it should be noted that the demarcation of a multiple-microfactory does not necessarily entail geographical co-location, but more appropriately is defined by the product or product family to be manufactured. However, in most cases, it is anticipated that geographic co-location may expedite production materiel transport and control.

The first of these two external supporting elements shown in Figure 3.6 is the Plant Services Provider. As the name implies, the function of the Plant Services Provider is to furnish plant services to individual microfactories and AMDLs that are not directly related to the actual microfactory development or production process. Such indirect services would include the rental of floor space, janitorial services, HVAC (heating, ventilation, and air conditioning) support, food services, plant security, etc. The second external supporting element shown in Figure 3.6 is Corporate-Level Management. Corporate-Level Management functions as an overall administrative coordinator by implementing, monitoring, and maintaining the aggregate activities of the AMDL/microfactory systems. Furthermore, Corporate-Level Management provides an interface between the multiple-microfactory system and other external enterprise-wide resources.

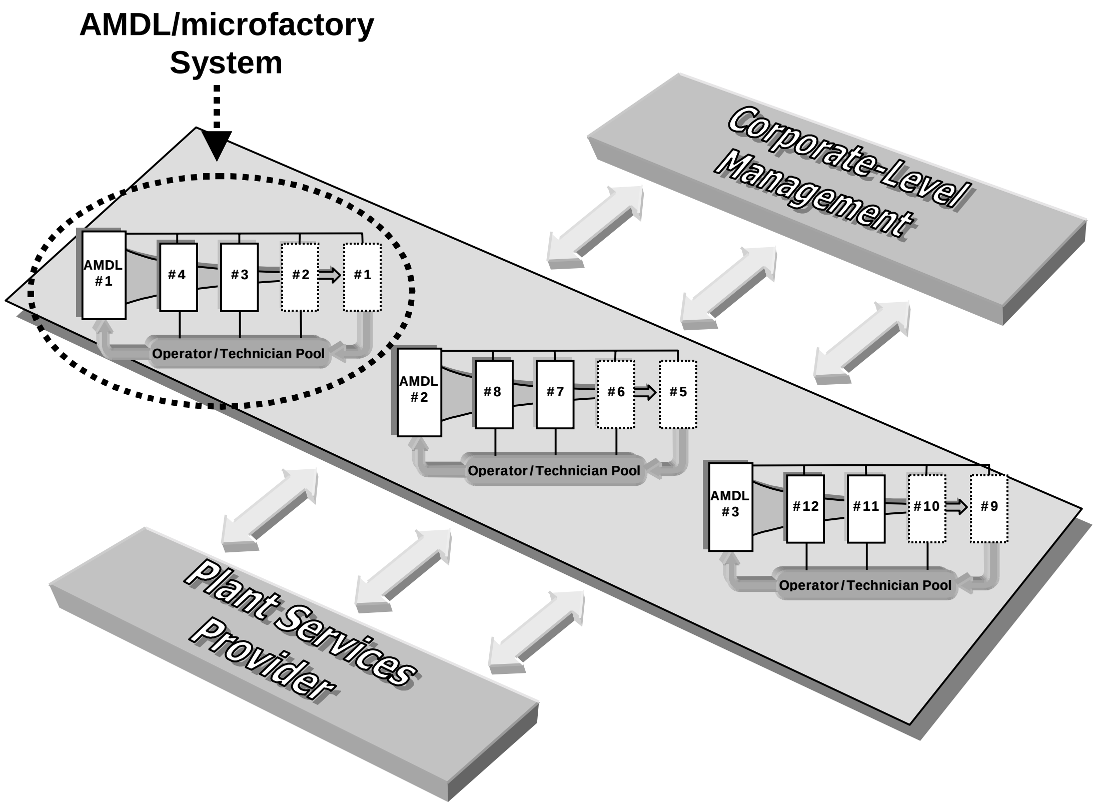


Figure 3.6. Multiple-Microfactory Architecture

3.2 Research Objective 2: Demonstration of a Microfactory in a Real World Production Environment

Section 3.1 details the development of the microfactory concept leading toward the accomplishment of Research Objective 1: "Develop a Microfactory and Supporting Multiple-Microfactory Architecture." This section describes the work on Research Objective 2: "Demonstrate a Microfactory Prototype in a Real World Production Environment." The goal of Research Objective 2 is to implement the concept developed in Section 3.1; namely, a prototype microfactory production architecture in a real world manufacturing environment.

3.2.1 Framework of the Implementation

This section describes the framework of the microfactory implementation based on automation, simplification, and decentralization in a real world production environment. In order to accomplish this, a real world manufacturer was identified and the company management was asked to participate in the work. In 1997 the Investigator approached the management of a global microelectronics production facility in the United States. At the time, the selected facility supported over 4,500 employees. Production at the site is divided between wireless handset production and wireless systems infrastructure in which these two production activities functioned as business units independent of one another. Of the approximately 4,500 employees, approximately 1,000 worked for the systems infrastructure business unit. The systems infrastructure product line consisted of two types of wireless infrastructure base stations and over 2,000 subcomponent modules.

After identifying and contacting the manufacturer, the Investigator wrote a series of reports outlining the microfactory concept. The proposed concept entailed integrating holonic and fractal concepts with a focused factory strategy in order to form a decentralized automated production architecture in which product "families" are basic units of the organizational structure. As a result, management agreed to implement a microfactory for the production of electronic modules used in wireless communications networks.

The targeted research environment is an electronics module assembly activity in the infrastructure division that employed approximately 100 individuals and supported a product family consisting of three types of electronics modules. This research environment is well suited for the desired microfactory concept demonstration as the products have short life cycles of 1 to 2 years which, in turn, drive short time-to-market cycles. Such characteristics provide an appropriate test-bed for the demonstration of NGMS concepts. The purpose of the research from the standpoint of the company's management is the demonstration and possible expanded implementation of a strategy that would reduce throughput time and product cost. The research goal as discussed previously is the demonstration of NGMS concepts through the implementation of an automated decentralized production architecture and, with the acquisition of throughput time, product cost, and production quality data, the acceptance or non-acceptance of the hypothesis stated in Section 1.1.2.

The research required coordination of the microfactory implementation with other new technology introduction (NTI) projects being conducted by the manufacturer. The prototype microfactory development is coordinated with two other NTI programs; new process practice and new process technology introductions as shown in Table 3.1.

Table 3.1. Microfactory Coordination with Ongoing NTI Projects

NTI Project	Area of Concern	Introduction Goal
Project α (alpha)	Current Production Practice	To enhance current practice performance by introduction of new practice methods targeted for existing production systems and integration of appropriate concepts developed by project γ.
Project γ (gamma)	Microfactory Concept	Development of microfactory concept for new product introduction (NPI).
Project π (pi)	Manufacturing Process Technology	Implementation of latest manufacturing technology in project γ architecture.

In the Table 3.1, Project α and Project π are ongoing NTI projects, while Project γ represents the prototype microfactory demonstration. The interaction between these projects is illustrated in Figure 3.7.

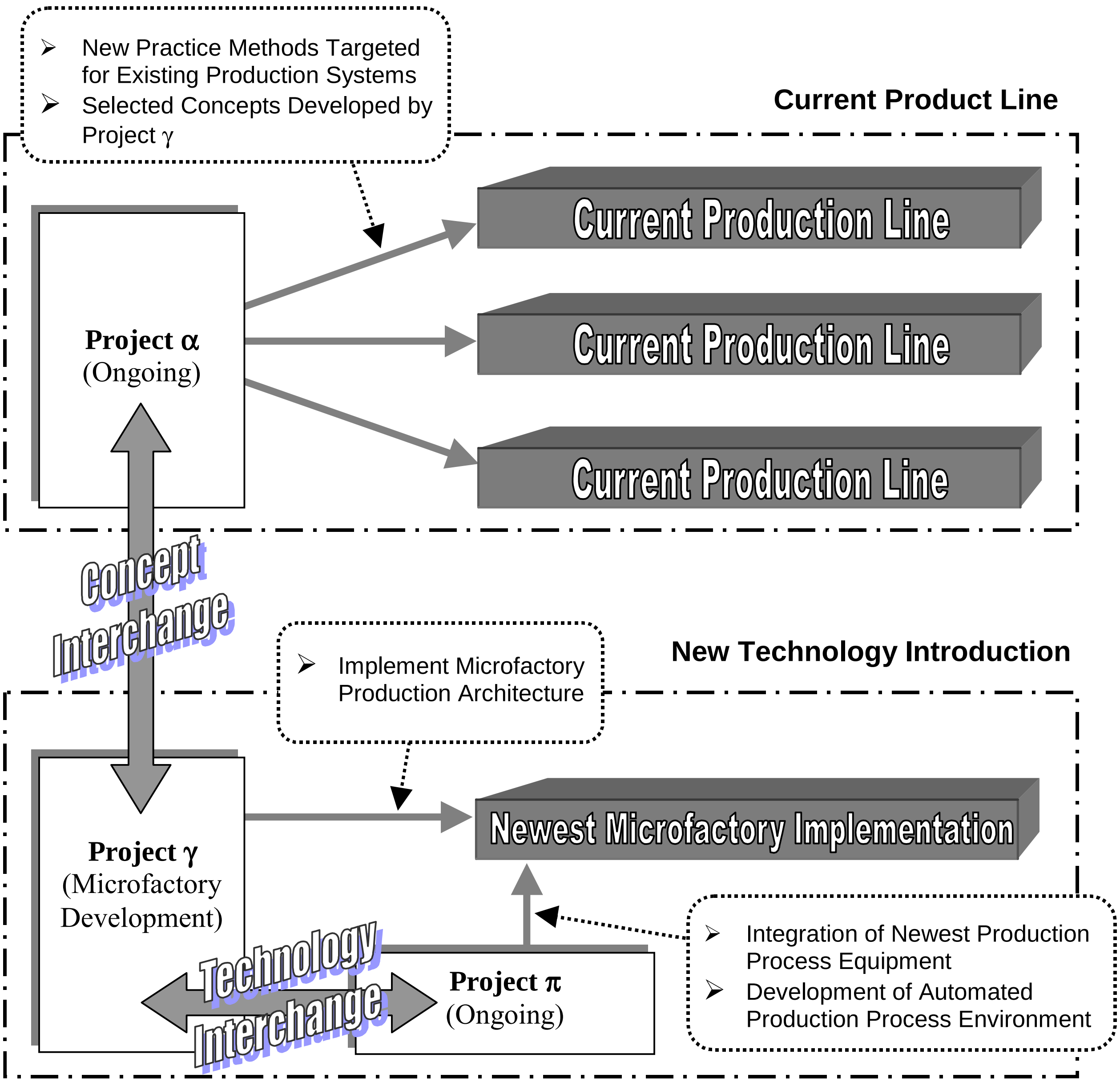


Figure 3.7. Interaction of Microfactory Development with Other NTI Projects

As can be seen in Figure 3.7, Project α is tasked with the introduction of new technology on existing production lines. This technology may come from within the project or may incorporate selected concepts being developed by Project γ. Candidate technologies that can be implemented on current production lines migrate from Project γ to Project α Conversely, technology developed by Project α that can enhance the Project γ microfactory demonstration migrates back to Project γ. Project γ, of course, is responsible for demonstrating a prototype microfactory.

The remaining NTI project is Project π with the responsibility to configure the latest production process equipment into an automated production line. The demonstration architecture was implemented at the beginning of the third calendar quarter (July) in 1998 at which time the production activity supported approximately 30 employees and assembled four product types. Data acquisition was completed at the end of the third calendar quarter in 1999, giving a data range inclusive of the second calendar quarter of 1997 to the third calendar quarter of 1999. The accomplishment of Research Objective 2, the implementation of the microfactory concept, entails the following: 1) restructuring of organizational functions through decentralization to provide increased autonomy to the assembly activity (discussed in Section 3.2.4), 2) automation of assembly processes (discussed in Section 3.2.5), and 3) simplification through a minimization of human/process interaction (discussed in Section 3.2.6). This implementation of the microfactory was based the idea of decentralized architectures characteristic of holonic and fractal systems and integrated the concept of product focus embodied by the focused factory strategy in order to form a decentralized automated production architecture in which product "families" are basic units of the organizational structure.

3.2.2 Value Stream Mapping

Value Stream Mapping (VSM) is a technique based on the graphical representation of the main components in a manufacturing process. Using this graphical "map," one identifies areas that can be streamlined to reduce inventory or waste, or to cut production time. It is a component of the lean manufacturing concept discussed in Section 2.4.3. First pioneered by Toyota, VSM was studied by Rother and Shook [61] who published the concept in book entitled, *Learning to See*. VSM is comprised of a three phase process involving, first, the drawing of a picture of each of the main elements in a production activity to produce a "current state map." Second, a "future state map" is outlined which represents the improvements to be implemented. In the case of the present research, the future state map represents the prototype microfactory. The third and final phase is the actual implementation of these changes. Utilizing the VSM idea of graphically mapping a value/process stream, the following sections describe the original centralized architecture and discuss the application of automation, decentralization, and simplification to convert this architecture to a microfactory implementation.

3.2.3 Selected Centralized Architecture (Before Microfactory Implementation)

As discussed previously, the candidate production function selected for implementation as a microfactory prototype is a previously existing electronic module assembly activity. The selected activity manufactures three variants of an electronic transceiver module that is used as a component in a radio base station. These three products are identified in this dissertation as T1-5, T10, and T30 and represent three, one-board, variants from the same product family. The production activity encompasses the placement of components and input/output fixtures on a bare circuit board with the final product being a "plug in" module for a wireless base station electronics rack. The firm's organizational structure, which contains the selected production activity, is shown in Figure 3.8 before the implementation of the microfactory. In Figure 3.8 the order-to-shipping product flow is overlaid on the organization chart of the business unit. As shown in Figure 3.8, Logistics functions as an overall command, control, and inventory center. As such, Logistics receives new orders and places concurrent "internal" orders for systems and associated modules required to build the systems. When the modules are produced, they are inventoried by Logistics from which they are used by Base Operations to build the ordered systems. Once the systems are completed, they are shipped by Logistics. As can be seen in the VSM outlined in Figure 3.9, the order to shipping process is broken into five stages, each with an associated throughput time: order processing by Logistics (1 day); module production by Shop Operations (11 days); Logistics inventory (2 days); system assembly by Base Operations (2 days); and order fulfillment by Logistics (1 day). The throughput times are as reported by the Program Manager and observed by the Investigator.

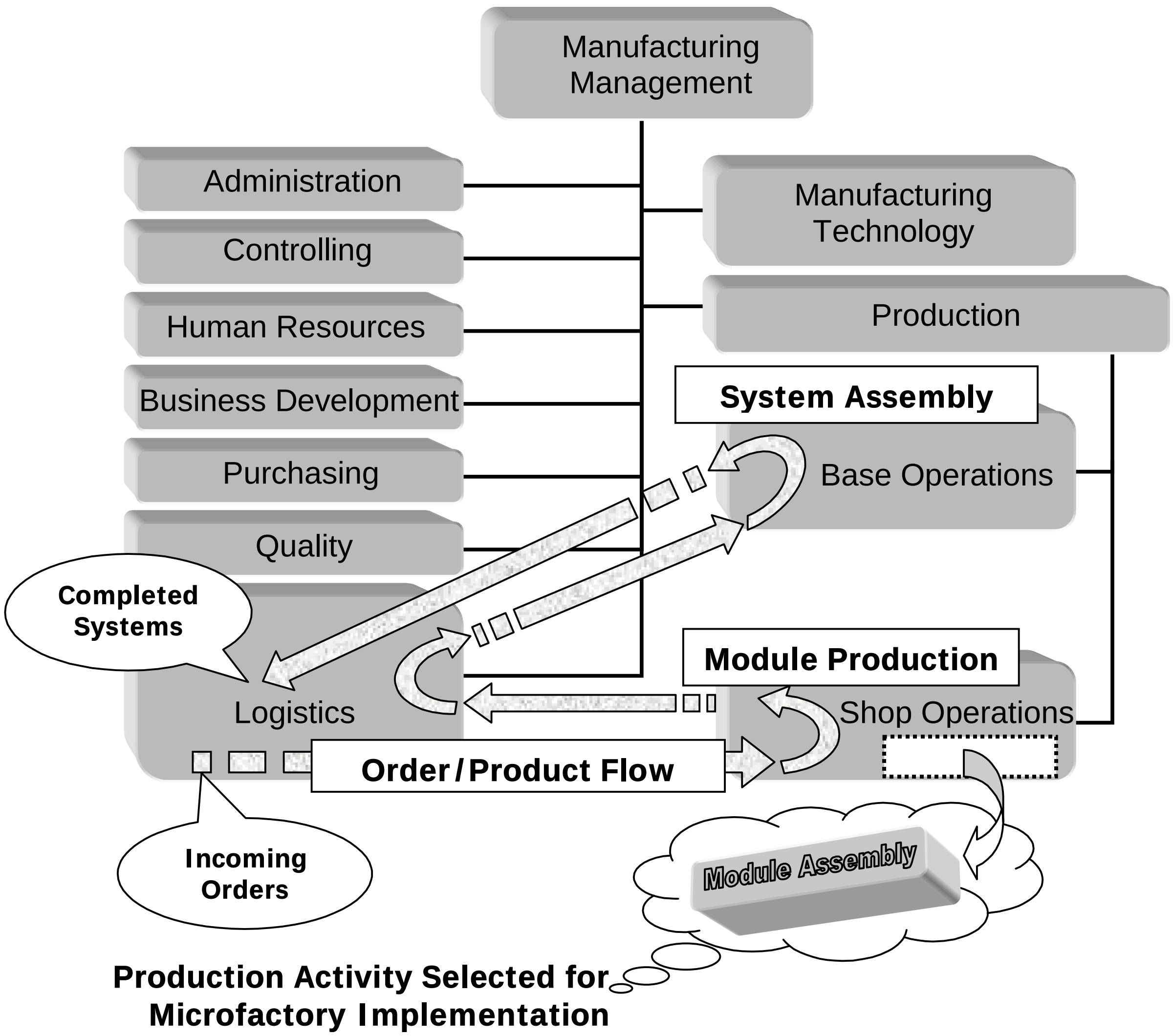


Figure 3.8. Product Flow Through the Organizational Elements of the Selected Business Before the Microfactory Implementation

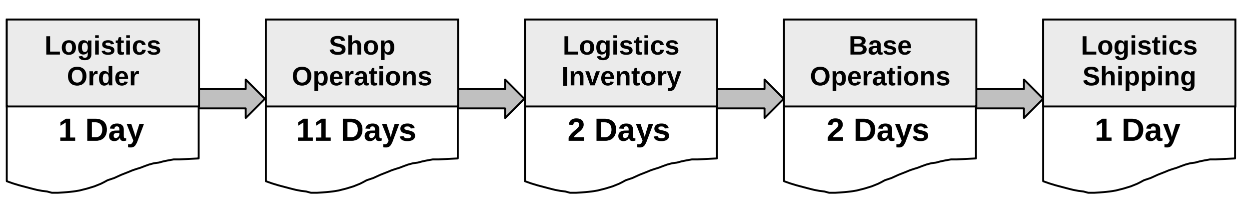


Figure 3.9. Value Stream Map Elements Showing Throughput Time for Product Flow Through the Organization of the Selected Business Before the Microfactory Implementation

The VSM depicted in Figure 3.9 shows a total of 17 days from order to shipping for products manufactured under the original organizational structure before the introduction of the core microfactory concepts; namely, automation, decentralization, and simplification. In addition, Figure 3.8 shows the module assembly activity (contained within Shop Operations) selected for implementation as a microfactory. Product flow within the selected module assembly activity before microfactory implementation is shown in Figure 3.10. The associated VSM is outlined in Figure 3.11.

As can be seen in Figure 3.10, this activity is spread across a multiple department organizational structure. The module assembly activity is segmented into five functional components: screen print/surface mount, in-circuit test, buffer stock, module assembly, and test. A VSM representing these five functions and the associated throughput time for each is shown in Figure 3.11. The five functional components illustrated in Figure 3.10 are grouped into three departments: screen print and surface mount operations (known as Surface Mount Assembly or SMA), Module Assembly, and Test. During the SMA process, integrated circuits and discrete components are placed on bare circuit boards on any one of five production lines. These boards are then sent to a workstation (one for each line) for manual in-circuit testing. Once testing is completed, the finished boards are placed in one of three temporary inventory sites as buffer stock. This buffer stock is used to smooth variations that occur due to transport between departments and varying demand that is generated by the next step of the module assembly process.

As needed, finished boards are transported to the assembly department which is comprised of anywhere from thirty to fifty workstations where components are placed by hand. In this department, the remaining components and input/output fixtures are inserted on the board. The completed modules are then sent to the test department for function and time testing. Testing is accomplished on twenty manual workstations and, once a module is verified, it is sent to Logistics inventory for delivery to Base Operations.

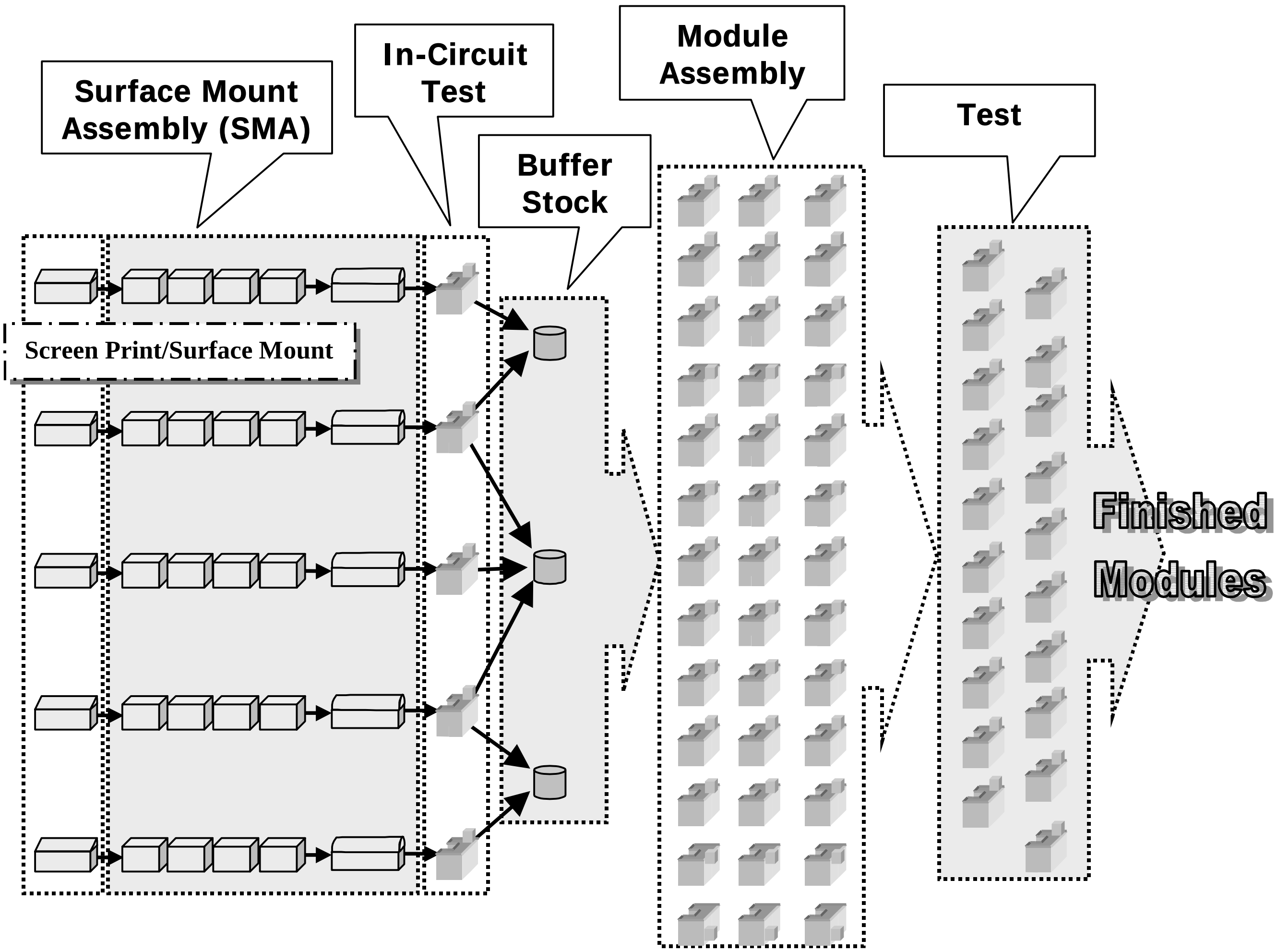


Figure 3.10. Product Flow Through the Selected Module Assembly Production Activity Before the Microfactory Implementation

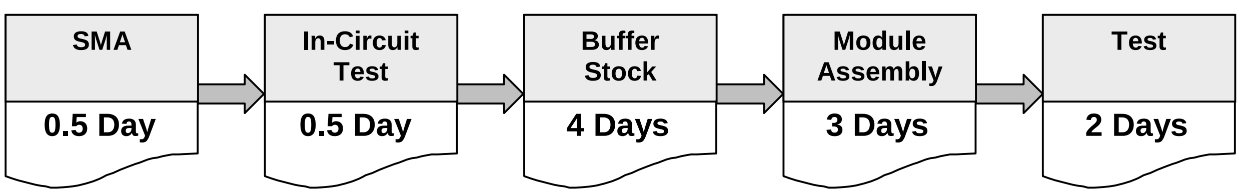


Figure 3.11. Value Stream Map Elements Showing Throughput Time for Product Flow Through the Selected Module Assembly Production Activity Before the Microfactory Implementation

As can be seen in the VSM shown in Figure 3.11, the module assembly process is broken into five stages, each with an associated throughput time: integrated circuit and discrete component placement by SMA (0.5 days); in-circuit testing (0.5 days); buffer stock (4 days); module assembly (3 days); and test (2 days). The throughput times are as reported by the Program Manager and observed by the Investigator. The VSM depicted in Figure 3.11 shows a total of 10 days for module assembly under the original organizational structure before the introduction of the core microfactory concepts of automation, decentralization, and simplification.

3.2.4 Decentralization

The conversion of the module assembly process (identified in Figure 3.8) to a microfactory implementation encompasses the application of decentralization, automation, and simplification. Decentralization, described in this section, is approached in two parts. First, at the facility level, the module assembly activity is extricated from the overall product flow path pictured in Figure 3.8. Then, secondly, at the department level, the assembly process is removed from the original departmental-based organizational structure depicted in Figure 3.10.

The goal of decentralization at the facility level is to provide organizational and operational autonomy to the microfactory within the facility itself. This facility-wide reorganization is illustrated in Figure 3.12. Previously, the system assembly process was contained within Production directly under Manufacturing Management. Production is, in turn, comprised of Shop Operations (i.e., sub-assembly fabrication) and Base Operations (i.e., system assembly). Separate from Production is Manufacturing Technology which serves as engineering support to Production in the same manner as the other support functions shown (i.e., Administration, Controlling, Human Resources, Business Development, Purchasing, Logistics, and Quality).

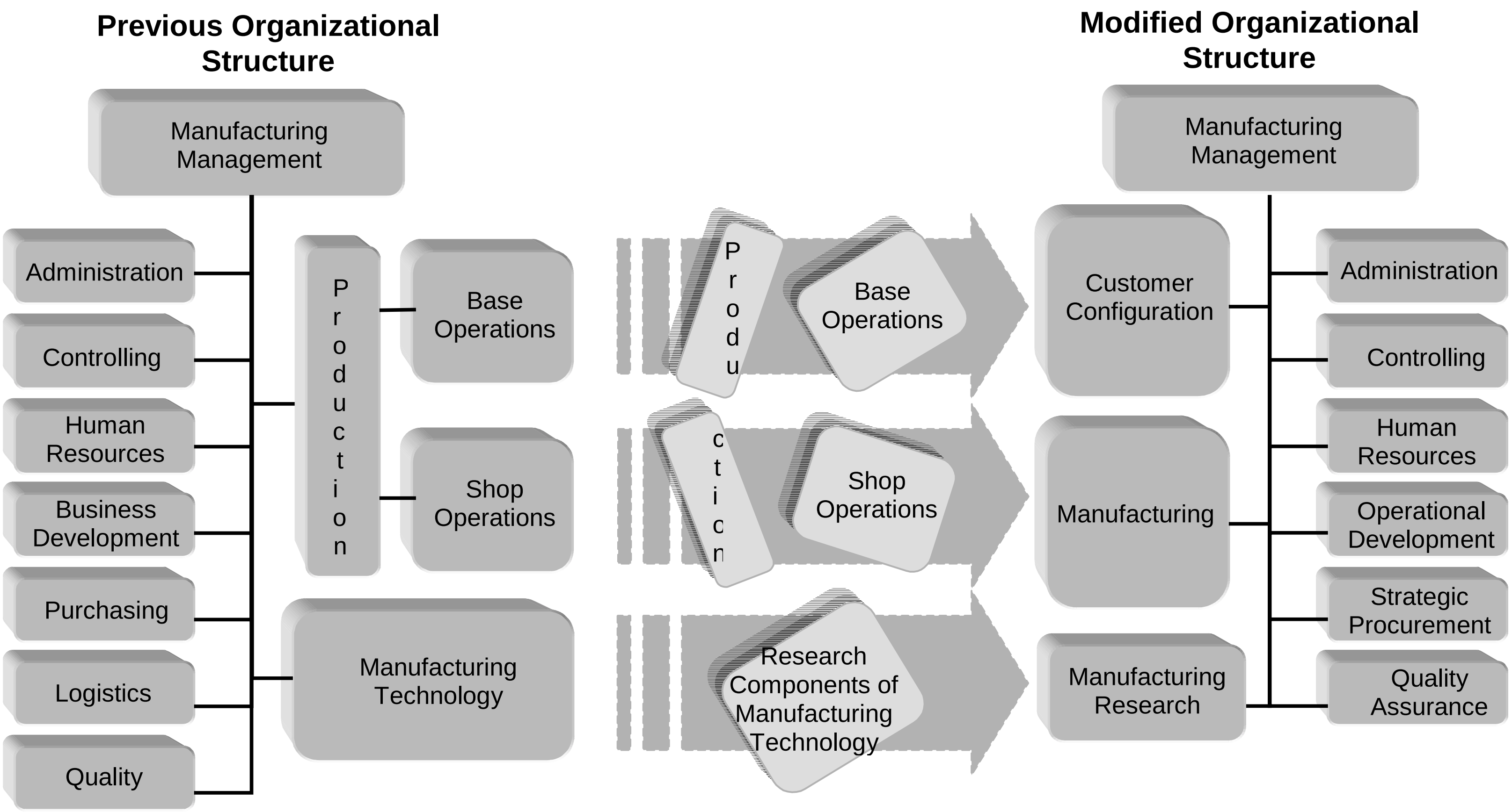


Figure 3.12. Modification of Facility-wide Organizational Structure in Support of a Microfactory Implementation

After reorganization, Production and its subordinate divisions, Base Operations and Shop Operations, are converted into Manufacturing and Customer Configuration. The new Manufacturing, comprised of resources from the original Production and Shop Operations, is responsible for the fabrication of sub-assemblies. The new Customer Configuration includes the remaining resources of the original Production and Base Operations and is given the responsibility for assembling complete systems using sub-assemblies provided by Manufacturing. Furthermore, the original Manufacturing Technology is reduced in size by integration of engineering elements into the new Manufacturing and new Customer Configuration. The new Manufacturing Research becomes responsible for basic research and development in support of the new Manufacturing and new Customer Configuration. In addition, Business Development, Purchasing, and Logistics are moved into Operational Development and Strategic Procurement and given a more strategic role, while procurement resources are moved directly into Manufacturing and Customer Configuration. Other supporting activities (i.e., Administration, Controlling, Human Resources, and Quality) remained the same.

As a result of this reorganization, the module assembly activity and associated support are grouped into one internal business unit (i.e., Manufacturing) under the control of a single top level manager. This allowed the microfactory implementation to proceed without the problems associated with crossing political and organizational boundaries. As an example, the splitting of procurement resources from the original Purchasing and Logistics and merging the remaining resources into Strategic Procurement allows purchasing and logistics resources to be subsumed by Manufacturing. Figure 3.13 shows the resources made available to the microfactory after the facility-wide reorganization. As shown in Figure 3.13, once the facility-wide reorganization (depicted in Figure 3.12) is completed, Manufacturing, as an independent business unit of the organization, had gathered the resources needed to pursue freely the implementation of the microfactory concept. As discussed previously, decentralization is accomplished as a two part process. First, at the facility level, the module assembly activity is extracted from the overall product flow path pictured in Figure 3.8, while the second part focused on the decentralization of the module assembly activity within the newly organized Manufacturing itself.

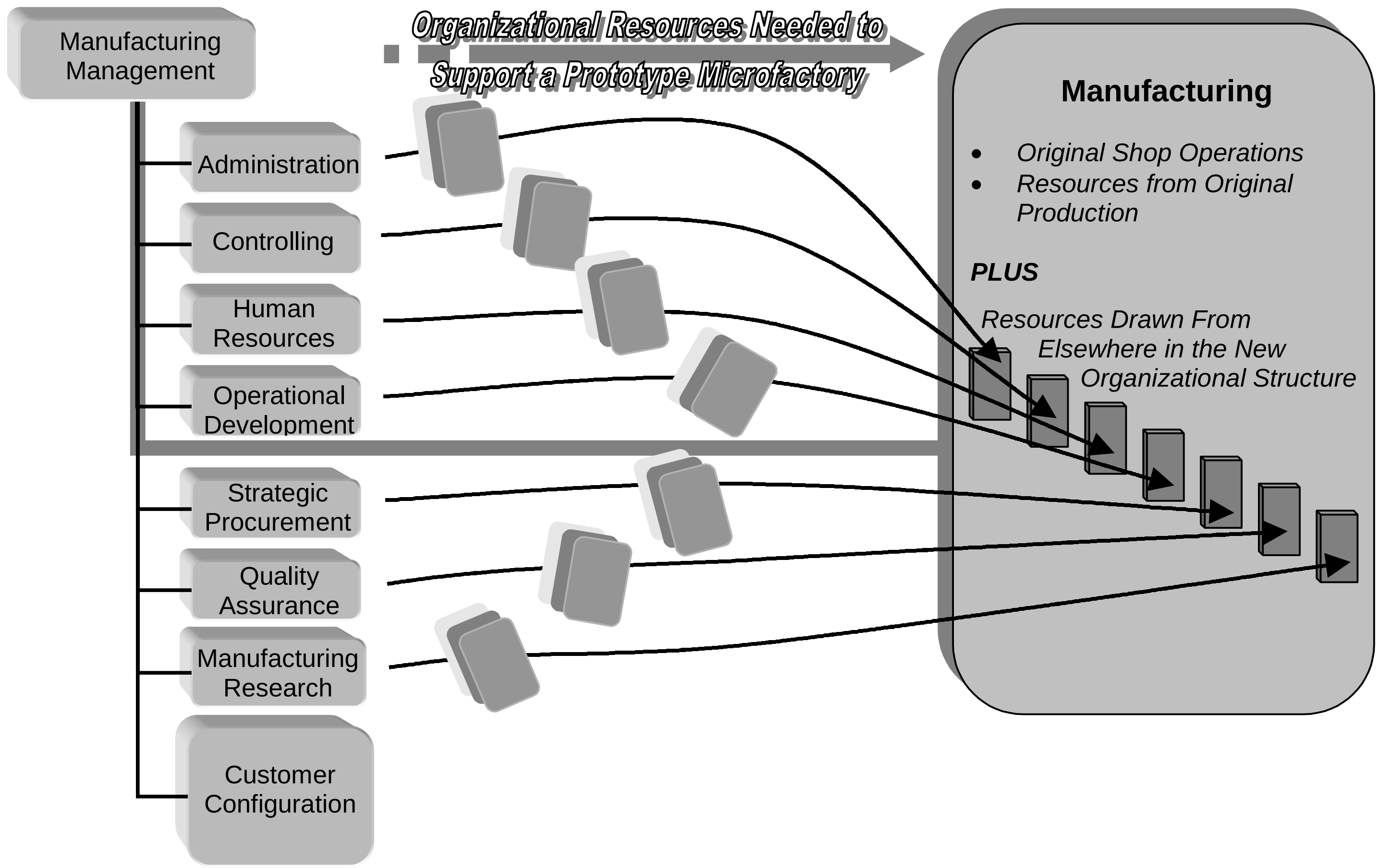


Figure 3.13. Resources Made Available to the Prototype Microfactory Through Facility-Wide Reorganization

This decentralization involved movement of the module assembly activity out of the original department-based organizational structure depicted in Figure 3.10 and its implementation as an autonomous microfactory. Decentralization entailed separating the five assembly functions shown in Figure 3.10 (i.e., screen print/surface mount, in-circuit test, buffer stock, module assembly, and test) from the three department (i.e., SMA, Module Assembly, and Test) organizational structure and grouping the activities into a microfactory.

As a result of decentralization, selected resources of the original Shop Operations (shown in Figure 3.10) are removed from the original organizational structure to form a microfactory capable of assembling three variants of an electronic transceiver module (T1-5, T10, and T30) used in radio base stations. They are three, one-board, variants from the same product family. In the original organizational structure, this "T series" (i.e., T1-5, T10, and T30) electronic module assembly process is integrated across the SMA, Module Assembly, and Test departments. However, in the microfactory implementation, the components of SMA needed to support the T1-5, T10, and T30 product variants are incorporated into the microfactory itself rather than maintained as disparate parts of separate departments. Figure 3.14 illustrates the internal organizational structure of the T series microfactory that is implemented.

As can be seen in Figure 3.14, the internal organizational structure of the prototype microfactory implementation is comprised of Administration and Finance, Materials (including a Buyer/Planner function), Engineering, Test (including Quality Control), and, of course, the Module Assembly process itself. Referring back to Figure 3.3, it can be seen that the original microfactory concept incorporated Manufacturing Design and Production functions. During the implementation of the microfactory, this manufacturing design function is realized in Engineering and Test/Quality Control shown in Figure 3.14. The Production function is realized in Materials, Module Assembly, and Administration and Finance shown in Figure 3.14.

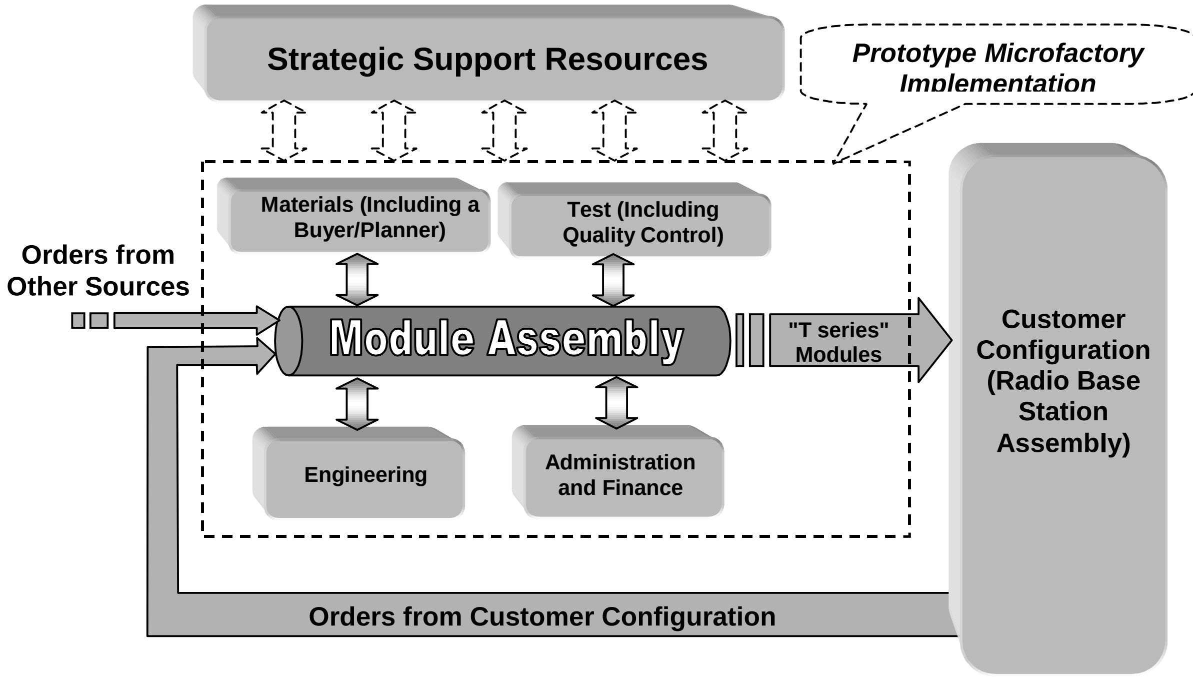


Figure 3.14. Internal Organizational Elements of the Prototype Microfactory

3.2.5 Automation

As discussed previously, the implementation of the microfactory encompasses the application of decentralization, automation, and simplification. Automation of the electronic module assembly activity is described in this section. This entailed converting the electronic module assembly process (screen print to test) from its original mostly manual activity (i.e., hand placed components) to an entirely automated process. This conversion is depicted in Figure 3.15.

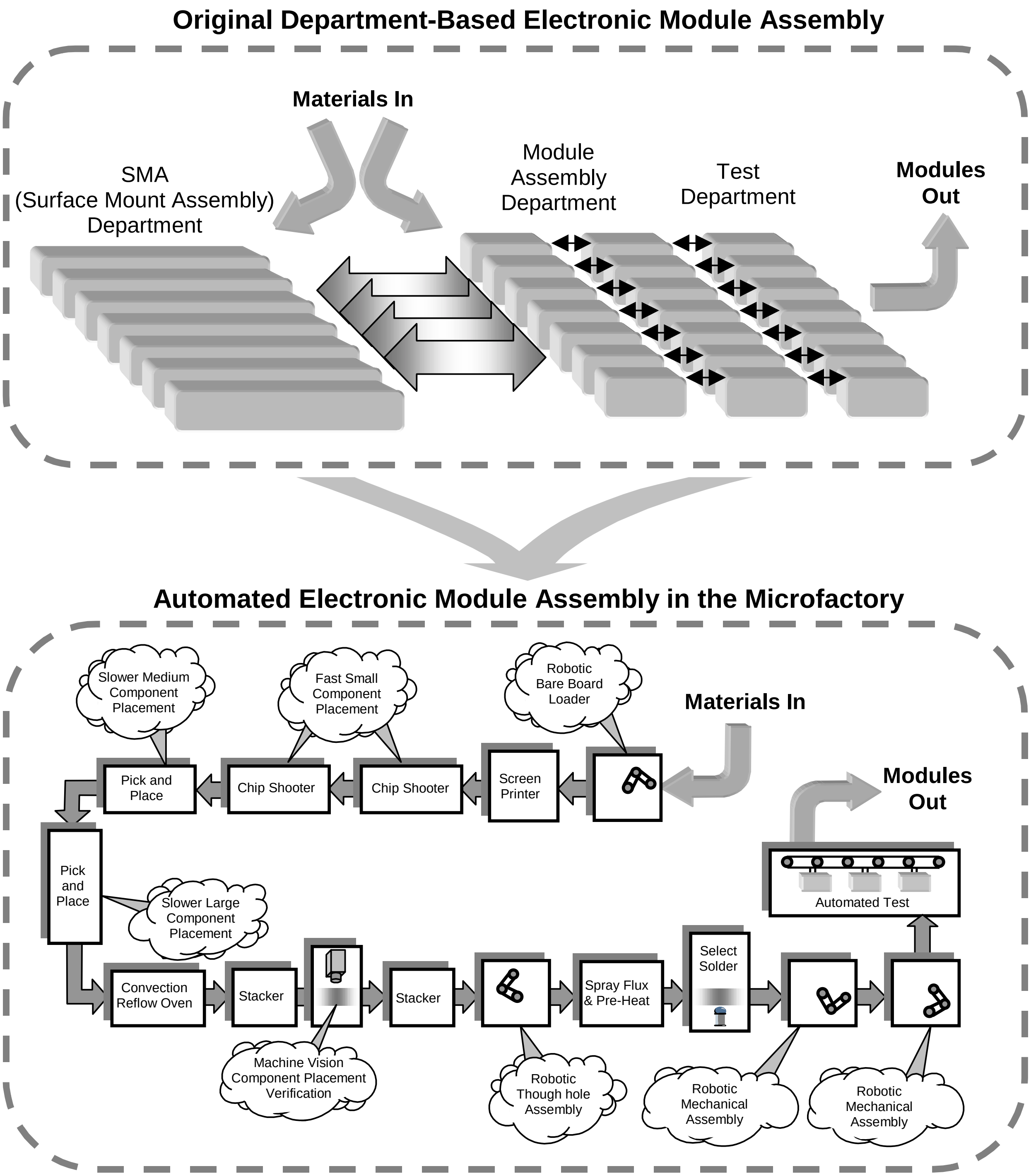


Figure 3.15. Automation of the Electronic Module Assembly Activity

In the original department-based assembly activity shown in Figure 3.15, it can be seen that the electronic module assembly process encompassed two product "handoffs" between three departments. The SMA process is automated in this original centralized model and the product is hand assembled and hand tested in the other two departments (i.e., Module Assembly and Test). Figure 3.15 also outlines the process once automation is completed. As can be seen, the automated assembly process is designed to accept bare circuit boards and fabricate a finished module without operator intervention in the process or product handling during the process. As illustrated in Figure 3.15, the microfactory automated assembly is configured so that production flow follows a circular process path with materials flow in and completed modules out being located in the same "upper right" corner of the floor plan.

As discussed previously, the transformation of the module assembly activity to a microfactory model entailed the automation of hand-placed component operations and the conversion of hand testing of modules to automated in-line testing, resulting in a reduction of human interaction with the process. Human interaction is limited to parts replenishment and machine maintenance by operators. In addition, the machinery on the line is fully integrated across the process and is capable of operating on a "build-to-order" basis, allowing production lot sizes as small as one.

3.2.6 Simplification

The final part of the microfactory concept is simplification, which is realized as part of the implementation of decentralization and automation. Simplification during decentralization can be seen in Figure 3.16 which shows the T series module flow path from order to system delivery after decentralization (discussed in Section 3.2.4). A VSM that encompasses electronic module production in Manufacturing and system completion in Customer Configuration and the associated throughput time for each is shown in Figure 3.17. These throughput times are as reported by the Program Manager and observed by the Investigator.

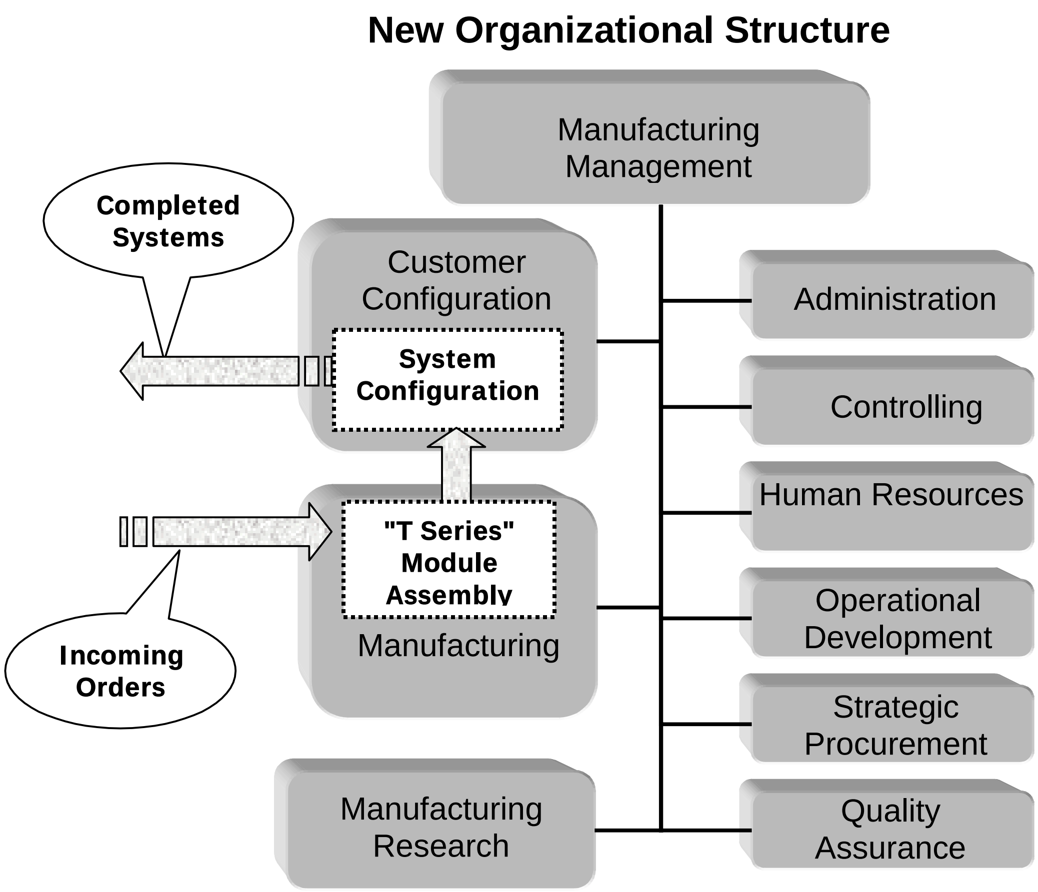


Figure 3.16. T Series Electronic Module Flow Path from Order to System Delivery After Implementation of the Prototype Microfactory

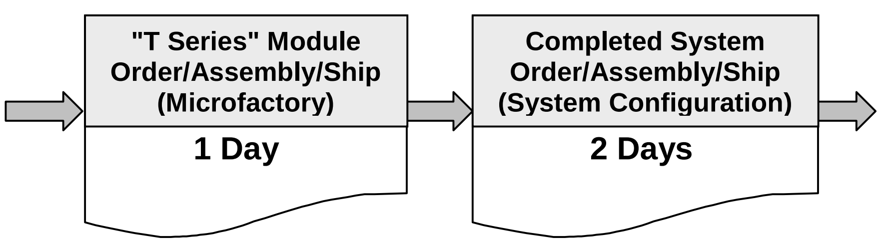


Figure 3.17. Value Stream Map Elements Showing Throughput Time for Product Flow After Reorganization and the Implementation of the Prototype Microfactory

In Figure 3.16, it can be seen that T series module order, assembly, and delivery to Customer Configuration are accomplished in the prototype microfactory within Manufacturing. Customer Configuration then assembles and ships completed systems based on specific customer requirements. As depicted in Figure 3.17, the associated throughput time for these two steps is 1 day for T series module order/assembly/ship and 2 days for order/assembly/ship of the completed systems. Accordingly, a total of 3 days is needed from order to shipping of completed systems manufactured under the new organizational structure after decentralization (and the implementation of the microfactory). Simplification that occurred from decentralization can be seen if one refers back to Figure 3.9 which shows a throughput time for system order to shipping of 17 days under the original five process step organizational structure while decentralization simplified this to two process steps requiring 3 days as shown in Figure 3.17.

In addition, simplification is also realized during the automation of the T series module assembly activity. As described in Section 3.2.5, automation of the module assembly activity resulted in minimizing human/product interactions with the process and eliminating human/product transaction points in the process path. The automated system depicted in Figure 3.15 is designed to accept bare circuit boards as input, then assemble and test T series electronic modules, producing fully assembled and tested modules.

This is accomplished without requiring human handling of the modules at any point in the process. The only human interaction required is for parts replenishment and machine maintenance. The simplification achieved during automation is seen in the elimination of module assembly by hand-placing components and the elimination of multiple "in process" module handoffs between hand placement workstations. Instead, the prototype microfactory implementation is based on a continuous, automated assembly line that requires no product handling by operators during the assembly process.

3.3 Research Objective 3: Comparison of Microfactory Performance with Historical Pre-Microfactory Performance

This section discusses Research Objective 3: "Compare Microfactory Performance with Historical Pre-Microfactory Performance." The accomplishment of this objective entails the comparison of historical (i.e., pre-microfactory) data with microfactory data to ascertain if performance changes occur when the microfactory is implemented. The performance parameters that are measured during the experiment are based on the goal of the research; namely, the acceptance or non-acceptance of the hypothesis stated in Section 1.1.2. Commenting on performance attributes, Bititci et al. [62] note that, "The nature of competition has changed dramatically over the last two decades. Quality, speed, and flexibility, in addition to cost, have emerged as the three most important competitive attributes." Additionally, Ghalayini et al. [63] state that, "In order to achieve and maintain a competitive edge in the world marketplace, manufacturing companies must produce high quality products at low cost with increasing variety, over shorter lead times." As a reflection of this, the performance measures that are selected for the research addressed cost, quality, and throughput time. These measures are delineated in the hypothesis in Section 1.1.2, wherein it is stated that if the microfactory elements are implemented, the following performance parameters will NOT change:

- Throughput Time
- Labor Cost
- Overhead Cost
- Total Product Cost
- Production Quality

Accordingly, the performance parameters to be measured are the same as the parameters stated in the hypothesis. The experiment requires a comparison of these parameters for both pre-microfactory and post-microfactory performance to ascertain if a change occurs as a result of the conversion to a microfactory. The alternative hypothesis (i.e., H_1) states that throughput time, labor cost, overhead cost, and total product cost will decrease without degrading production quality.

Chapter 4

An Industry Experiment

Chapter 4 discusses the experimental design to test the research hypothesis. The experiment is designed to accomplish Research Objective 3: "Compare Microfactory Performance with Historical Pre-Microfactory Performance" as discussed in Section 3.3. The basis of the experiment is to compare historical performance data (i.e., throughput time, labor cost, overhead cost, total product cost, and production quality) with microfactory performance data to discover if changes occur when the microfactory is implemented.

4.1 Experimental Design

The experiment conducted is based on the application of the microfactory concept through decentralization, automation, and simplification to an electronic module assembly activity. The microfactory concept consists of the decentralization of organizational functions to provide organizational and operational autonomy to the production activity, the comprehensive automation of production processes, and the simplification of both the order to delivery flow path and the assembly activity. Martin [64] states:

> If the purpose of the experiment is to test two competing theories and one theory predicts a difference in behavior for the two levels while the second predicts either no change or an opposite change, then a two-level experiment is adequate to distinguish between the theories.

Furthermore, Kraft and Van Eeden [65] note that:

> An approach to obtaining information about [ed. a hypothesis] is to observe the behavior of two groups of subjects. One group, called the treatment group, will have experienced the treatment…during the observation period. The other group, called the control group, will not have experienced the treatment. Aside from this difference, the experiences and conditions for both groups should be as alike as possible.

Because the hypothesis being tested entails the observation of performance changes that occur when the microfactory concept (i.e., the treatment) is applied to a production activity (i.e., the treatment group), a two level experimental design is selected based on a treatment group/control group architecture. This design is depicted in Figure 4.1.

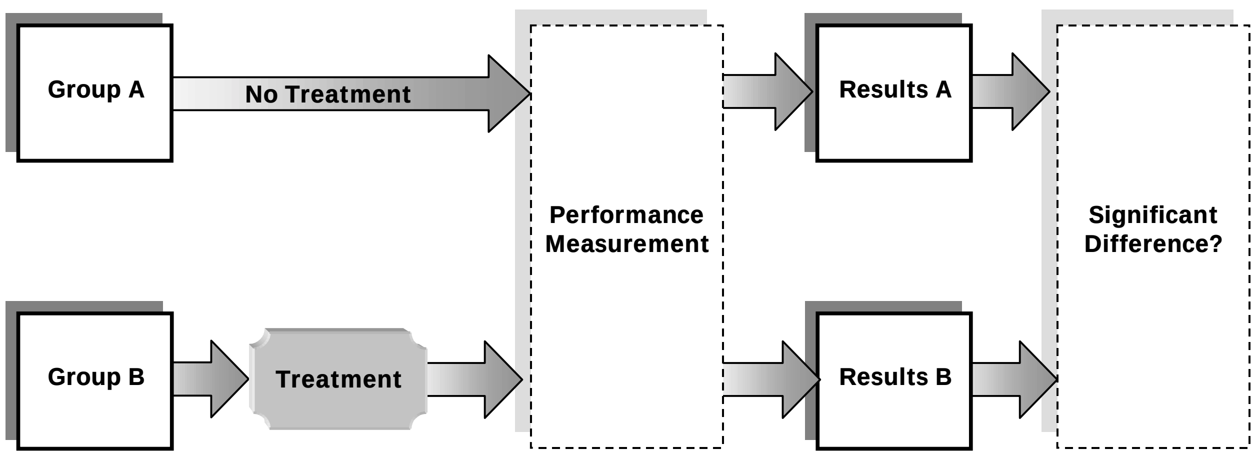


Figure 4.1. Selected Two Level Experimental Design Based on a Treatment Group/Control Group Architecture

As discussed in Section 3.3, the selected performance measures were throughput time, labor cost, overhead cost, total product cost, and production quality. Of these measures, labor cost, overhead cost, and total product cost may be affected by external facility-wide cost changes that are not related to cost changes attributable to the implementation of the microfactory concept. Consequently, as depicted in Figure 4.2, these three cost parameters are measured against an external "control group" set of products that are not subject to the treatment.

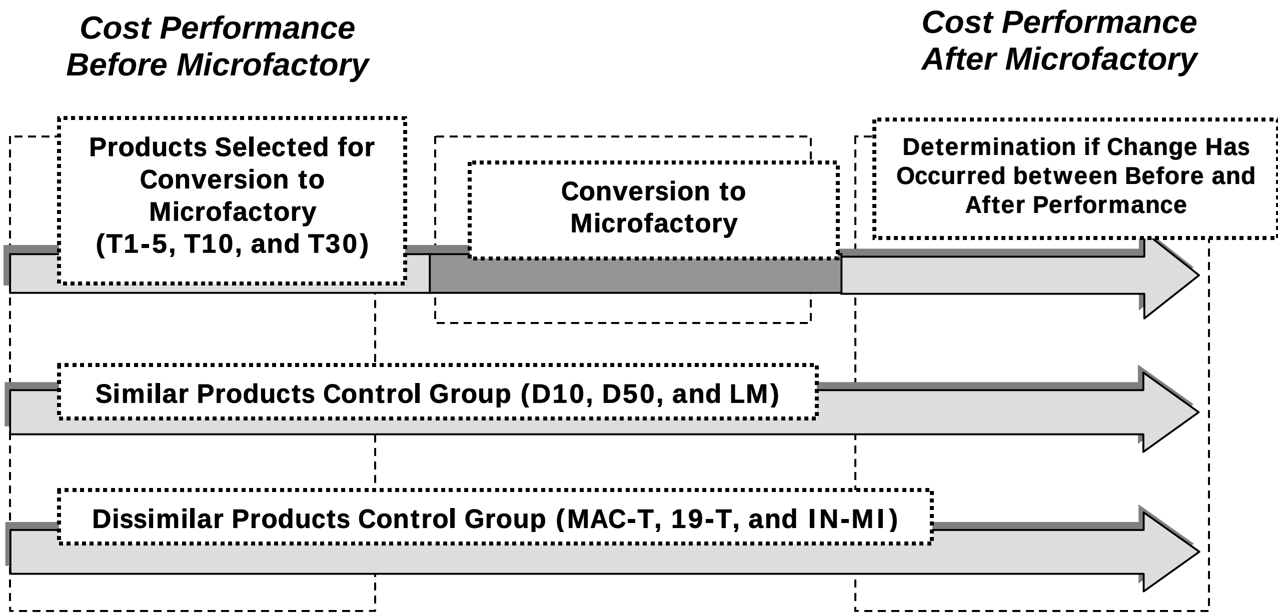


Figure 4.2. Cost Performance Experiment Encompassing "Control Group" Product Set

The cost performance experiment outlined in Figure 4.2 analyzes cost data from three product sets. One set is converted into a microfactory. A second set of "control group" products, which is comprised of products similar to the microfactory product set, does not receive treatment. And a third set of "control group" products, which are dissimilar to the microfactory products, also do not receive the treatment.

The remaining two performance measures, throughput time and production quality, are internal to the production activity. The experimental sequence for the measurement of these two parameters is outlined in Figure 4.3. Once the experiment is completed, before and after performance data are acquired and analyzed using the Wilcoxon Signed Rank test as discussed in Section 4.2.

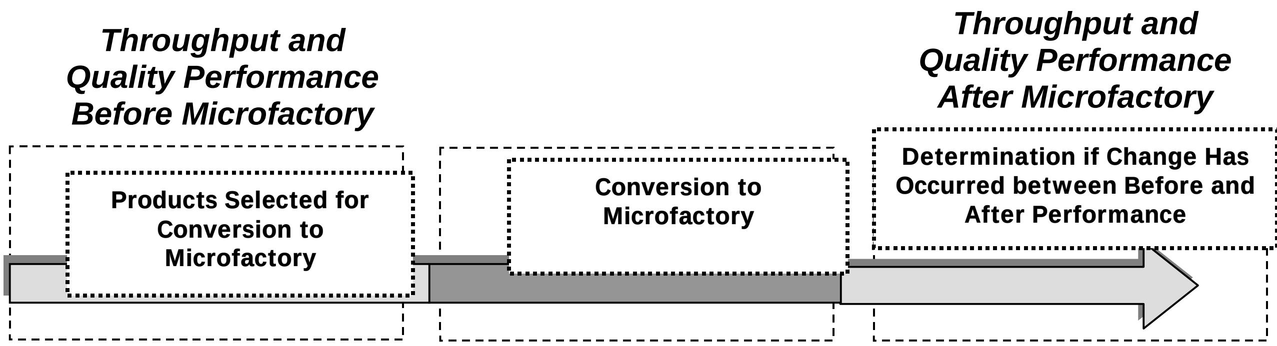


Figure 4.3. Experiment to Measure Throughput and Quality Performance

4.2 Wilcoxon Signed Rank Test

Proposed in 1945 by Frank Wilcoxon, the Wilcoxon Signed Rank test is a non-parametric statistical method used to test the hypothesis that two independent samples have come from the same population by comparing two (i.e., before and after treatment) sample sets [66]. It is used to determine the probability that observed differences between two sample sets occurred by chance [64]. Because it is non-parametric and makes no assumptions about the distribution of the data, it is well suited for small sample sets with unknown distributions. Furthermore, the Wilcoxon Signed Rank test, which utilizes not only sign information but also the magnitude of differences between pairs, is more powerful than simpler sign tests that do not fully utilize the information available [67]. The point of using a paired test is to control for experimental variability. Some factors that are not controlled in the experiment affect the before and the after measurements equally so they will not affect the difference between before and after samples. By analyzing only the differences, a paired test is insensitive to such sources of variability.

The experiment acquires quarterly (i.e., three month) data over a 10 quarter period (i.e., two and a half years) for five quarters before the microfactory conversion and for five quarters after the microfactory conversion, resulting in a small sample set of ten points (i.e., five pairs). Furthermore, the distribution of the before and after sample sets is not known. Given these characteristics of the data, the Wilcoxon Signed Rank test is chosen to test the null hypothesis stated in Section 1.1.2.

This is accomplished by using a paired set of data points comprised of points measured before microfactory conversion, $x_{i\text{-before}}$, points measured after microfactory conversion, $x_{i\text{-after}}$, and the absolute difference between paired points, $|x_{i\text{-before}} - x_{i\text{-after}}|$, to determine the Wilcoxon values by ranking $|x_{i\text{-before}} - x_{i\text{-after}}|$. Accordingly, $\mathbf{rank}|x_{i\text{-before}} - x_{i\text{-after}}|$ denotes the rank as a number between 1 being the smallest value and n being the largest value where n is the total number of $|x_{i\text{-before}} - x_{i\text{-after}}|$ values. Furthermore, each of these ranks is assigned a positive or negative value based on the value of $x_{i\text{-before}} - x_{i\text{-after}}$. The Wilcoxon values ($T^+$ and T^-) are calculated by summing the negative ranks and then the positive ranks as follows:

$$T^+ = \boldsymbol{\Sigma}\, \mathbf{rank}|x_{i\text{-before}} - x_{i\text{-after}}|, \text{ for all } |x_{i\text{-before}} - x_{i\text{-after}}| \text{ in which } x_{i\text{-before}} - x_{i\text{-after}} > 0$$

$$T^- = \boldsymbol{\Sigma}\, \mathbf{rank}|x_{i\text{-before}} - x_{i\text{-after}}|, \text{ for all } |x_{i\text{-before}} - x_{i\text{-after}}| \text{ in which } x_{i\text{-before}} - x_{i\text{-after}} < 0$$

As discussed previously, the experiment acquired quarterly (i.e., three month) data over a 10 quarter period, five quarters before the microfactory conversion and five quarters after the microfactory conversion. Consequently, five data pairs are available for analysis using the Wilcoxon Signed Rank test. Furthermore, the sum of the total number of unsigned ranks for a five pair data set is as follows [68]:

$$T_{max} = n(n+1)/2 = 5(6)/2 = 15$$

Therefore, the maximum possible value of T (in the case where all signs are the same) is 15. Freund and Walpole [67] state that if the number of pairs is equal to or greater than 15, it is considered reasonable to assume the distribution of T is approximately normal. For smaller sample sizes, such as the five pairs acquired during this research, Kraft and Van Eeden [65] show the distribution of a small sample set can be determined by enumerating all possible results. Table 4.1 shows the possible combinations of plus and minus signs that could be distributed among the rankings of a five pair data set and the associated critical value, T, for each. Figure 4.4 provides a graphical representation of these enumerated ranks, showing the resulting distribution. Because the alternative hypothesis presented by the Investigator predicts a reduction in costs, then a one-tailed test is conducted. As can be seen in Figure 4.4, in a one tailed test, the probability, p, of $T \geq 11$ is $p = 2/32 = 0.0625$ and the probability of $T \geq 15$ in a one tailed test is $p = 1/32 = 0.03125$ [68].

The standard level of significance widely recognized by researchers is $p \leq 0.05$ [64], [69]. The use of $p \leq 0.05$ as a standard threshold for significance dates back to work by R. A. Fisher who published statistical tables from the 1920's to the 1970's in which, instead of providing a broad range of probabilities, Fisher set specific thresholds for significance [70]. Fisher's use of $p \leq 0.05$ as a threshold has been accepted by researchers as benchmark for significance. This $p \leq 0.05$ significance level means that there is a probability that a Type I error (i.e., the statistical analysis will falsely report an effect when no effect is present) will occur five times out of one hundred tests. The $p = 0.03125$ significance level that can be shown using the Wilcoxon Signed Rank test with five data pairs is less than the standard $p \leq 0.05$ level of significance. With five data pairs a result of $T = 15$ gives $p = 0.03125$. This occurs when:

$$T^{+} = \boldsymbol{\Sigma}\,\mathbf{rank}|x_{i\text{-before}} - x_{i\text{-after}}| = \text{the sum of all ranks} = 1+2+3+4+5 = 15$$

and

$$T^{-} = \boldsymbol{\Sigma}\,\mathbf{rank}|x_{i\text{-before}} - x_{i\text{-after}}| = 0$$

Table 4.1. Enumeration of a Five Pair Wilcoxon Signed Rank Test

Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	T
-	-	-	-	-	-15
+	-	-	-	-	-13
-	+	-	-	-	-11
-	-	+	-	-	-9
+	+	-	-	-	-9
-	-	-	+	-	-7
+	-	+	-	-	-7
-	-	-	-	+	-5
-	+	+	-	-	-5
+	-	-	+	-	-5
-	+	-	+	-	-3
+	-	-	-	+	-3
+	+	+	-	-	-3
-	-	+	+	-	-1
-	+	-	-	+	-1
+	+	-	+	-	-1
-	-	+	-	+	1
+	-	+	+	-	1
+	+	-	-	+	1
-	-	-	+	+	3
-	+	+	+	-	3
+	-	+	-	+	3
-	+	+	-	+	5
+	-	-	+	+	5
+	+	+	+	-	5
-	+	-	+	+	7
+	+	+	-	+	7
-	-	+	+	+	9
+	+	-	+	+	9
+	-	+	+	+	11
-	+	+	+	+	13
+	+	+	+	+	15

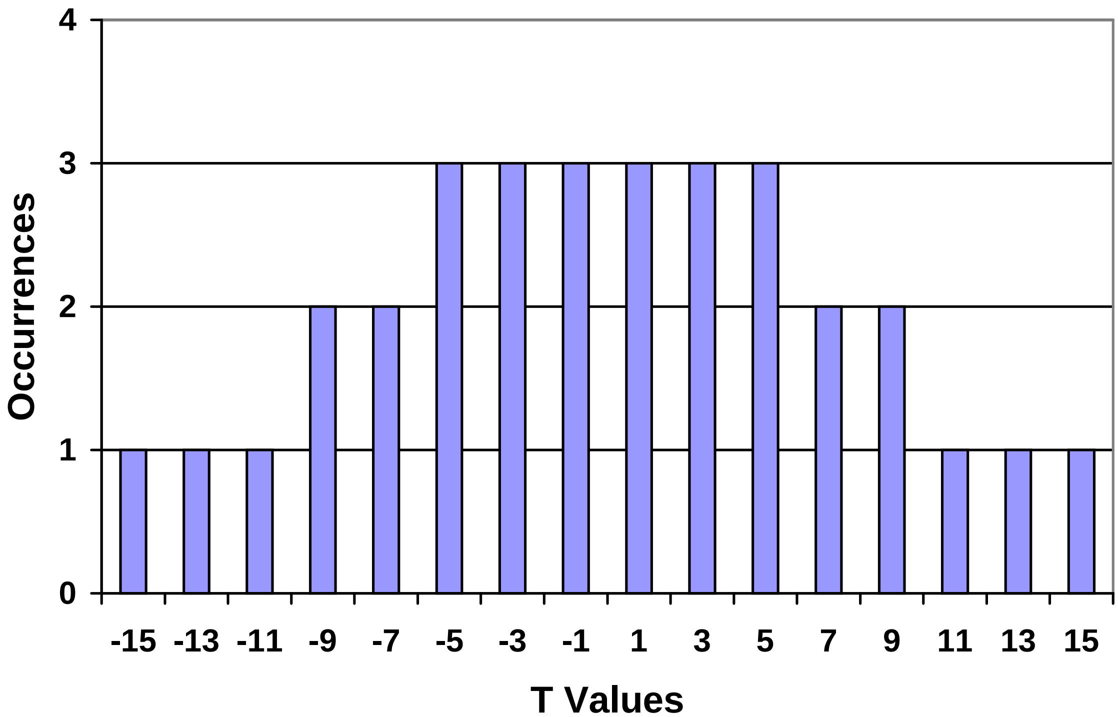


Figure 4.4. Graphical Representation of Enumerated Ranks for a Five Pair Wilcoxon Signed Rank Test

Furthermore, because the Wilcoxon test discards data pairs where $|x_{i\text{-before}} - x_{i\text{-after}}| = 0$, then only data sets in which none of the $|x_{i\text{-before}} - x_{i\text{-after}}| = 0$ can show significance (i.e., $p \leq 0.05$). Moreover, to ensure a more rigorous determination of significance, the data pairs are ordered in opposed descending and ascending columns. This ensures that significance (i.e., $p \leq 0.05$) can only occur when every one of the $x_{i\text{-before}}$ data points are greater than the $x_{i\text{-after}}$ data points or when every one of the $x_{i\text{-before}}$ data points are less than the $x_{i\text{-after}}$ data points.

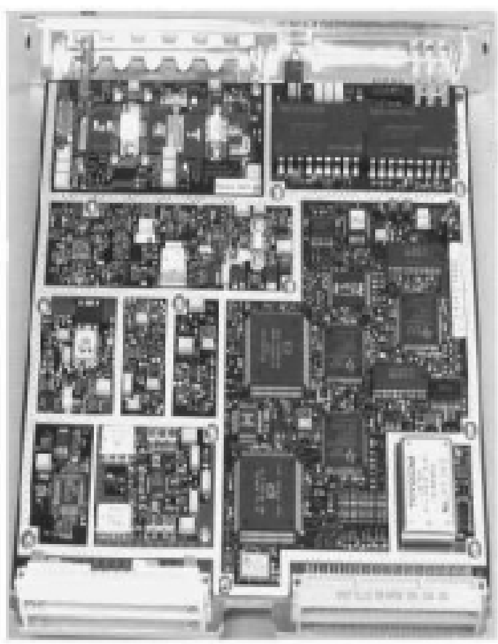
4.3 Products Selected

To complete the experimental design, a series of products is selected as a basis for testing the hypothesis stated in Section 1.1.2. Table 4.2 outlines the selected products, which consist of both products that are converted to microfactory production and products that are not converted to microfactory production. Both product groups are assembled in the same manufacturing facility. As discussed in Chapter 3, throughput, quality, and cost data are acquired both before and after conversion to a microfactory for products designated T1-5, T10, and T30.

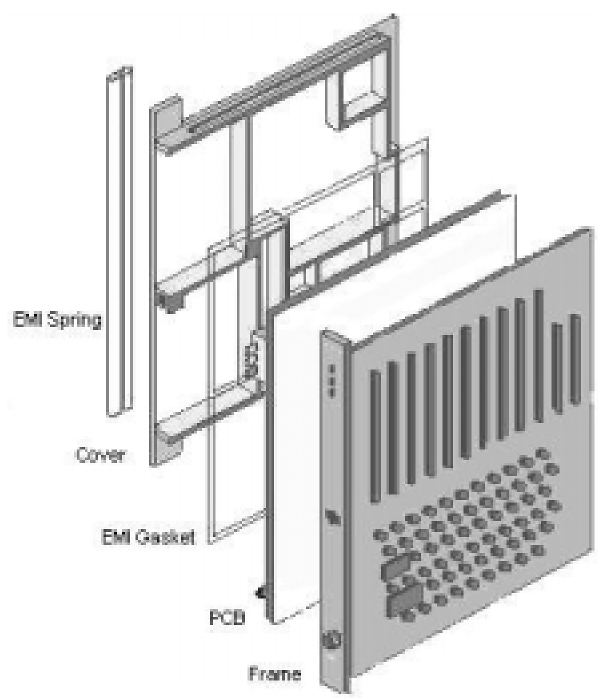
Table 4.2. Products Selected for Performance Measurement During the Experiment

T Series Electronic Modules Selected for Microfactory Conversion	
Designation	***Description***
T1-5	1.5 Watt, Single Board, Electronic Transceiver Module
T10	10 Watt, Single Board, Electronic Transceiver Module
T30	30 Watt, Single Board, Electronic Transceiver Module
D Series and LM Electronic Modules Not Converted to Microfactory Similar Products Control Group (Figure 4.2)	
Designation	***Description***
D10	10 Watt, Multiple Board, Electronic Transceiver Module
D50	50 Watt, Multiple Board, Electronic Transceiver Module
LM	Electronic Module for Signal Location Verification
Radio Base Station Cabinets Not Converted to Microfactory Dissimilar Products Control Group (Figure 4.2)	
Designation	***Description***
MAC-T	Radio Base Station Transceivers Cabinet
19-T	Radio Base Station Transceivers Cabinet
IN-MI	Radio Base Station Transceivers Cabinet

T1-5, T10, and T30 are electronic transceiver modules which are used as components in cellular telephony radio base stations. They are single board variants from the same product family. The production function that is selected for microfactory conversion is an electronic module assembly activity that manufactures these three electronic transceiver module variants. The production process entails the placement of components and input/output fixtures on a bare printed circuit board (PCB). The PCB is then housed in a mounting frame and sealed with an EMI (electromagnetic interference) gasket. The final product is a "plug in" module for a radio base station transceivers cabinet. A photograph of a T1-5 module is shown in Figure 4.5 (a) and an exploded view of the T1-5 module is illustrated in Figure 4.5 (b). As can be seen in the figure, the populated PCB is mounted between a frame and a cover which are sealed with an EMI gasket and an EMI tension spring.



a) Photograph of a T1-5 Electronic Transceiver Module with the Cover Plate Removed.



b) Exploded View of a T1-5 Electronic Transceiver Module.

Figure 4.5. An Electronic Transceiver Module Variant Designated T1-5

As listed in Table 4.2, products that are not converted to microfactory production, yet are assembled in the same manufacturing facility, consist of products (i.e., electronic modules) that are similar to products manufactured by the microfactory and products (i.e., transceivers cabinets) that are dissimilar to the electronic module products. These products comprise the similar and dissimilar product control groups illustrated in Figure 4.2. It is anticipated that the performance of these products indicate possible systemic, plant-wide, cost changes that are present during the microfactory evaluation period.

The products similar to the microfactory produced T1-5, T10, and T30 electronic transceiver modules are designated D10, D50, and LM. The D10 and D50 are from the "D series" family of electronic transceiver modules which are similar to the microfactory assembled T series of electronic transceiver modules. The LM is also an electronic module that functions as a plug in processing unit to determine signal location. The products which are dissimilar to both the selected "D series" and "T series" electronic transceiver modules and the LM electronic module are designated the MAC-T, the 19-T, and the IN-MI. The MAC-T and 19-T are radio base station transceivers cabinets containing a modem function, radio frequency and digital backplanes, data connection boards, and power and cooling units. The IN-MI is a reduced size version of a radio base station transceivers cabinet for indoor use. Figure 4.6 illustrates a typical radio base station transceivers cabinet showing the placement of each of the products selected for the experiment. As can be seen in this figure, the T series and D series electronic modules, as well as the LM electronic module, are units that are plugged directly into the backplane of the transceivers cabinet. The MAC-T, 19-T, and IN-MI are all designations for transceiver cabinet configurations that vary in size and power capabilities.

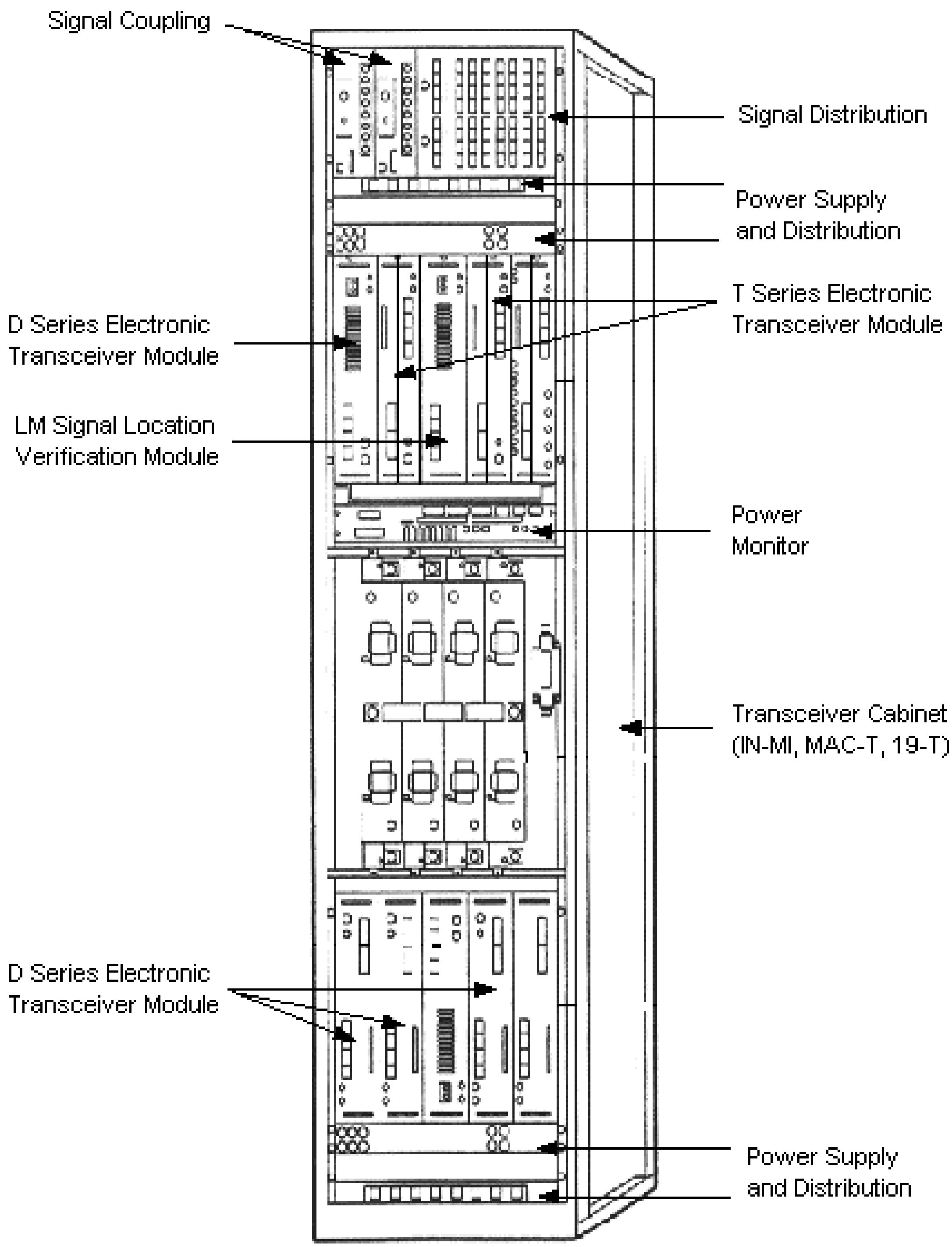


Figure 4.6. Illustration of a Typical Radio Base Station Transceivers Cabinet Showing the Placement of Each of the Products Selected for the Experiment

Chapter 5

Results of the Research

Chapter 5 addresses the completion of Research Objective 3: "Compare Microfactory Performance with Historical Pre-Microfactory Performance," which is discussed in Section 3.3. The performance parameters that are measured during the experiment are based on the goal of the research; namely, the acceptance or non-acceptance of the hypothesis stated in Section 1.1.2. Accordingly, the parameters of interest are throughput time, quality, and cost. The following sections present the data acquired during the completion of the experiment for each of these parameters. The first section presents throughput time in the context of changes to the value stream map. The second and third sections present quality and cost data, respectively, which are tabulated, graphed, and then analyzed using the Wilcoxon Signed Rank test.

5.1 Throughput Time

The throughput times for each element in the T series electronic transceiver module order to shipping VSM before the conversion to a microfactory are shown in Figure 5.1. As can be seen in Figure 5.1, five main organizational elements comprise the order to shipping value stream (i.e., Logistics Order, Shop Operations, Logistics Inventory, Base Operations, and Logistics Shipping). In addition, the Shop Operations organizational element, which represents the assembly of the T series modules, is further subdivided into six value stream elements (i.e., Shop Operations Order Processing and Planning, Surface Mount Assembly or SMA, In-Circuit Test, Buffer Stock, Module Assembly, and Test). The cumulative throughput time for the Shop Operations value stream element itself is 11 days and the cumulative throughput time from system order to shipping is 17 days.

ORGANIZATIONAL VALUE STREAM ELEMENT	THROUGHPUT TIME	CUMULATIVE TIME
Logistics Order	1 Day	1 Day
Shop Operations	11 Days	12 Days
Logistics Inventory	2 Days	14 Days
Base Operations	2 Days	16 Days
Logistics Shipping	1 Day	17 Days

MODULE ASSEMBLY VALUE STREAM ELEMENT	THROUGHPUT TIME	CUMULATIVE TIME
Shop Operations Order Processing and Planning	1 Day	1 Day
SMA	0.5 Days	1.5 Days
In-Circuit Test	0.5 Days	2 Days
Buffer Stock	4 Days	6 Days
Module Assembly	3 Days	9 Days
Test	2 Days	11 Days

Figure 5.1. Throughput Time From Order to Shipping for the T Series of Electronic Transceiver Modules Before Implementation of the Microfactory Concept (i.e., the Application of Automation, Decentralization, and Simplification)

The throughput time data were acquired by the Investigator in a series of meetings with the Program Manager for the T series electronic module production activity. During these meetings internal reports of throughput time were reviewed and compared against observed production process procedure. Furthermore, these process procedures were directly observed by the Investigator to verify accuracy. As can be seen in Figure 5.1, the unit of measurement for throughput time is the day. This is a result of a production process procedure that supports product transfers between process elements on a daily basis. Based on this, the throughput time data points before conversion to a microfactory as shown in Figure 5.1 were determined as follows:

- **Logistics Order Processing** – Logistics receives and processes product orders each day and passes the daily orders on to Shop Operations every evening. Shop Operations, in turn, receives the orders every morning. Consequently, it was determined the time required for Logistics to process and pass on a product order is 1 day (cumulative time = 1 day).

- **Shop Operations Order Processing and Planning** – Shop Operations receives Logistics product orders every morning. These orders are then processed during the day and passed on to Surface Mount Assembly in the evening. Surface Mount Assembly receives the orders every morning. Consequently, it was determined the time required for Shop Operations to process and pass on a product order is 1 day (cumulative time = 2 days).

- **Surface Mount Assembly and In-Circuit Test** – Surface Mount Assembly receives Shop Operations orders every morning. The ordered circuit boards are populated during the first part of the day and are function tested in the latter half of the day. Completed boards are sent to buffer stock at the end of the day. Consequently, it was determined the time required for Surface Mount Assembly and In-Circuit Test to build the boards ordered by Shop Operations is 0.5 day + 0.5 day = 1 day (cumulative time = 3 days).

- **Buffer Stock** – Four days of inventory are maintained in Buffer Stock to ensure continuous production even if disruptions occur in Surface Mount Assembly. Consequently, it was determined the throughput time for a product in Buffer Stock is 4 days (cumulative time = 7 days).

- **Module Assembly** – The module assembly process is based on a series of manual assembly and testing workstations. The first day, circuit boards are taken from buffer stock and input/output fixtures and components too large or too complex to be placed by the previous surface mount activity are manually soldered onto them. These boards are then passed onto assembly workstations. The second day these assembly workstations put together complete modules including mounting frames, EMI gaskets, and covers. The third day these completed modules are passed on to function test workstations where comprehensive signal and logic testing is conducted. Consequently, it was determined the throughput time for a product in Module Assembly is 3 days (cumulative time = 10 days).

- **Test** – The assembled and function tested modules are transferred to time test workstations where environmental and eight hour "burn in" testing is conducted. This process takes two days to complete. Consequently, it was determined the throughput time for a product in Test is 2 days (cumulative time = 12 days).

- **Logistics Inventory** – The assembled and tested modules are transferred to Logistics Inventory. Logistics Inventory maintains a two day inventory of product to ensure continuous production of radio base stations even if disruptions occur in Module Assembly or Test. Consequently, it was determined the throughput time for a product in Logistics Inventory is 2 days (cumulative time = 14 days).

- **Base Operations** – The first day Base Operations takes completed modules from Logistics Inventory and assembles radio base stations. The second day these stations are function tested and transferred to Logistics Shipping. Consequently, it was determined the throughput time for a product in Base Operations is 2 days (cumulative time = 16 days).

- **Logistics Shipping** – Logistics Shipping receives completed radio base stations from Base Operations and processes them for shipping the next day. Consequently, it was determined the throughput time for a product in Logistics Shipping is 1 day (cumulative time = 17 days).

Figure 5.2 illustrates the implementation of the microfactory concept in terms of throughput time reduction. As can be seen in the figure 5.2, automation and simplification of the six original electronic module assembly activity elements (i.e., Shop Operations Order Processing and Planning, Surface Mount Assembly, In-Circuit Test, Buffer Stock, Module Assembly, and Test) result in an interim value stream element, automated assembly. This element is then expanded into a microfactory through decentralization and simplification of the original organizational structure to encompass Logistics Order and Logistics Inventory. Moreover, decentralization and simplification result in additional throughput time reduction by integrating Base Operations and Logistics Shipping.

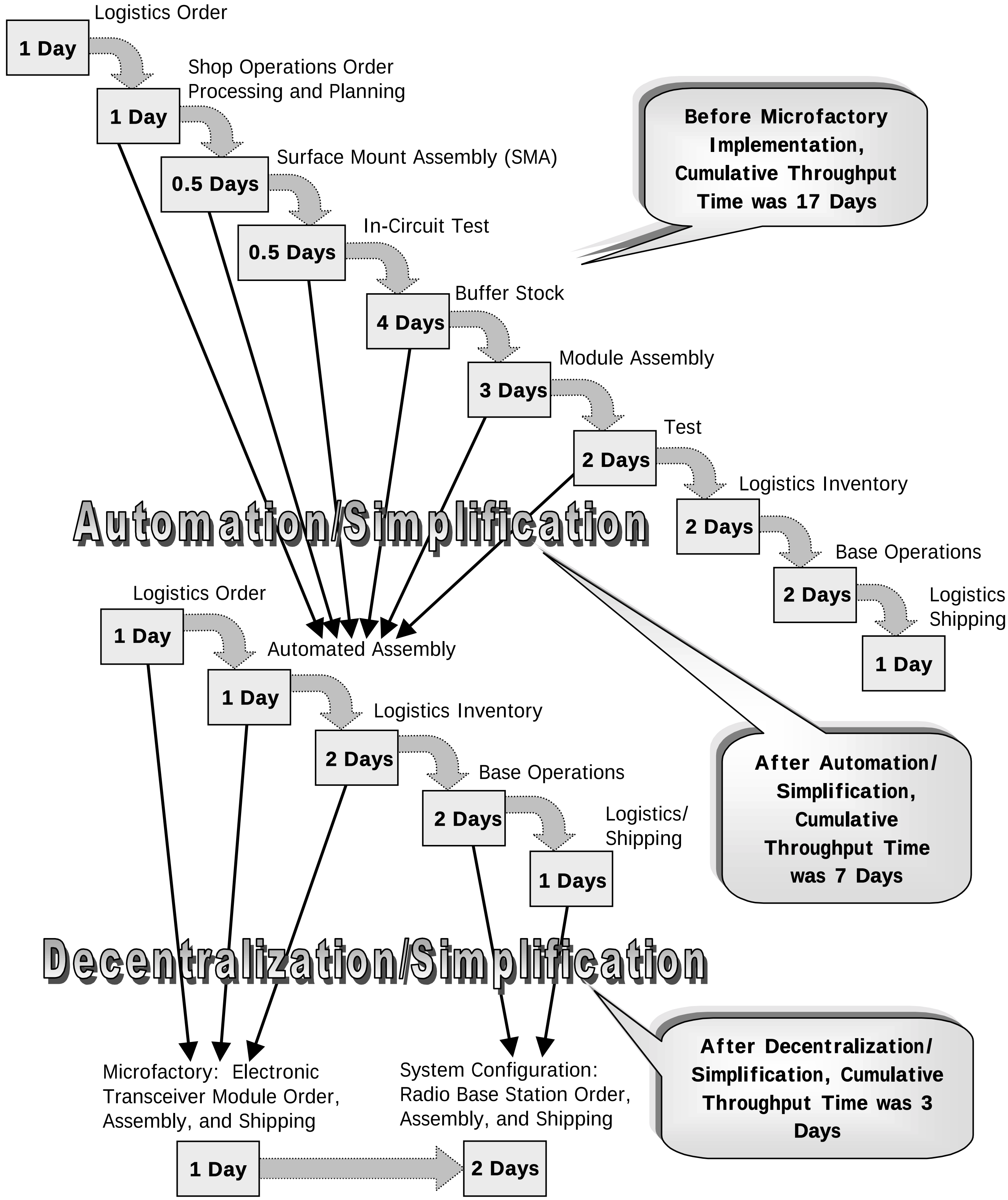


Figure 5.2. Throughput Time Before and After Microfactory Implementation (i.e., the Application of Automation, Decentralization, and Simplification)

The final value stream (illustrated in Figures 3.16, 3.17, and 5.2) is comprised of two elements, the Microfactory and System Configuration, with a total throughput time of three days. Product flow within this value stream is as follows:

- **Microfactory** – In an integrated process, the microfactory directly receives orders for products and builds, tests, and ships in one day. This process entails the receipt of orders, production planning, automated surface mount assembly, automated module assembly, automated function testing, automated four hour burn in testing, and shipping of completed modules (cumulative time = 1 day).

- **System Configuration** – System Configuration receives the completed modules the next morning and assembles the radio base stations that day. The next day, System Configuration tests the stations and ships by the end of the day. Accordingly, the throughput time required for System Configuration to assemble, test, and ship product is 2 days (cumulative time = 3 days).

5.1.1 Analysis of Throughput Time Data

Tabulated value stream element throughput times are shown in Figure 5.3. As can be seen in Figure 5.3, reductions in throughput times occurred after application of automation and simplification to the T series electronic transceiver module assembly process and after application of decentralization and simplification to the overall organizational structure of the order to shipping value stream. The microfactory production activity which resulted from the application of automation and simplification to the module assembly process demonstrated a reduction in throughput time from 11 days to 1 day. After the application of decentralization and simplification to the overall organizational structure and in conjunction with the implementation of the microfactory module assembly activity, the order to shipping throughput time is reduced from 17 days to 3 days.

5.2 Quality

Quality performance data are acquired both before and after the implementation of the microfactory concept to ascertain if, as stated in the hypothesis in Section 1.1.2, the implementation of the microfactory concept adversely effects production quality of the T series electronic transceiver modules. Because the microfactory concept does not directly address detailed process quality issues, the Investigator anticipates that the data will show no change in quality after the conversion. Quarterly (i.e., three month) quality performance data are acquired over a 10 quarter period (i.e., two and a half years) for five quarters before the microfactory conversion and for five quarters after the microfactory conversion, resulting in a small sample set of ten points (i.e., five pairs). In addition to the small sample size, the distribution of the before and after sample sets is not known. Given these characteristics of the data, the Wilcoxon Signed Rank test (discussed in Section 4.2) is chosen to test the null hypothesis stated in Section 1.1.2. The quality performance data are acquired by the Investigator from quarterly performance reports that provide failure rate data for the two quality tests run on the T series electronic transceiver modules during assembly; namely, function test and time test. Function failure rates and time failure rates are collected for each quarter from Q2 1997 to Q3 1999. Consequently, five pairs of function test failure rate data and five pairs of time test failure rate data are acquired.

Because the alternative hypothesis predicts that degradation in quality will not occur, a one-tailed test is conducted. As detailed in Section 4.2, a minimum of five data pairs are needed to ascertain a statistical significance level of $p = 0.03125$ using the Wilcoxon Signed Rank test for a one-tailed test which is less than the standard $p \leq 0.05$ level of significance widely recognized by researchers [64], [69]. Accordingly, this level of significance is reached when:

$$T^{+} = \boldsymbol{\Sigma}\,\mathbf{rank}|x_{i\text{-before}} - x_{i\text{-after}}| = \text{the sum of all ranks} = 1+2+3+4+5 = 15$$

and

$$T^{-} = \boldsymbol{\Sigma}\,\mathbf{rank}|x_{i\text{-before}} - x_{i\text{-after}}| = 0$$

ORGANIZATIONAL VALUE STREAM ELEMENT	THROUGHPUT TIME	CUMULATIVE TIME
Logistics Order	1 Day	1 Day
Shop Operations	11 Days	12 Days
Logistics Inventory	2 Days	14 Days
Base Operations	2 Days	16 Days
Logistics Shipping	1 Day	17 Days

MODULE ASSEMBLY VALUE STREAM ELEMENT	THROUGHPUT TIME	CUMULATIVE TIME
Shop Operations Order Processing and Planning	1 Day	1 Day
SMA	0.5 Days	1.5 Days
In-Circuit Test	0.5 Days	2 Days
Buffer Stock	4 Days	6 Days
Module Assembly	3 Days	9 Days
Test	2 Days	11 Days

Automation and Simplification

Decentralization and Simplification

VALUE STREAM ELEMENT	THROUGHPUT TIME	CUMULATIVE TIME
"T Series" Module Order, Assembly, and Shipping (Microfactory)	1 Day	1 Day
Radio Base Station Order, Assembly, and Shipping (System Configuration)	2 Days	3 Days

Figure 5.3. Tabulated Value Stream Element Throughput Times Showing Reductions from the Application of Automation and Simplification to the Module Assembly Process (i.e., the Microfactory) and from Decentralization and Simplification of the Organizational Structure

Furthermore, because the Wilcoxon test discards data pairs where $|x_{i\text{-before}} - x_{i\text{-after}}| = 0$, only data sets in which none of the $|x_{i\text{-before}} - x_{i\text{-after}}| = 0$ can show a significance level of $p \leq 0.05$. Moreover, to ensure a more rigorous determination of this level significance, the data pairs are ordered in opposed descending and ascending columns. This ensures that significance can only occur when every one of the $x_{i\text{-before}}$ data points are greater than the $x_{i\text{-after}}$ data points or when every one of the $x_{i\text{-before}}$ data points are less than the $x_{i\text{-after}}$ data points. Sections 5.2.1 and 5.2.2 present quality performance (i.e., test failure rate) data for function testing and time testing, respectively while Sections 5.2.1.1 and 5.2.1.2 detail the results of Wilcoxon Signed Rank testing on each data set. An analysis of these results is provided in Section 5.2.3.

5.2.1 Function Test

The function test is a comprehensive in-circuit test of signal and logic that is conducted after each electronic transceiver module is assembled. Function test failure rates for the T series electronic transceiver module assembly activity, acquired from quarterly performance reports, are tabulated in Table 5.1. In this table, quarters Q2-97 to Q2-98 represent failure rates before conversion to a microfactory and quarters Q3-98 to Q3-99 are failure rates after conversion to a microfactory.

Table 5.1. Function Test Failure Rates for T Series Electronic Transceiver Modules (Source: Company Quarterly Performance Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
T1-5	50.9%	46.1%	16.7%	19.5%	22.1%	19.8%	29.7%	21.4%	15.6%	13.8%
T10	62.6%	25.6%	20.6%	20.4%	19.7%	20.2%	23.5%	22.8%	16.9%	17.8%
T30	26.4%	20.7%	31.6%	24.0%	22.5%	20.7%	34.1%	25.7%	21.3%	23.8%

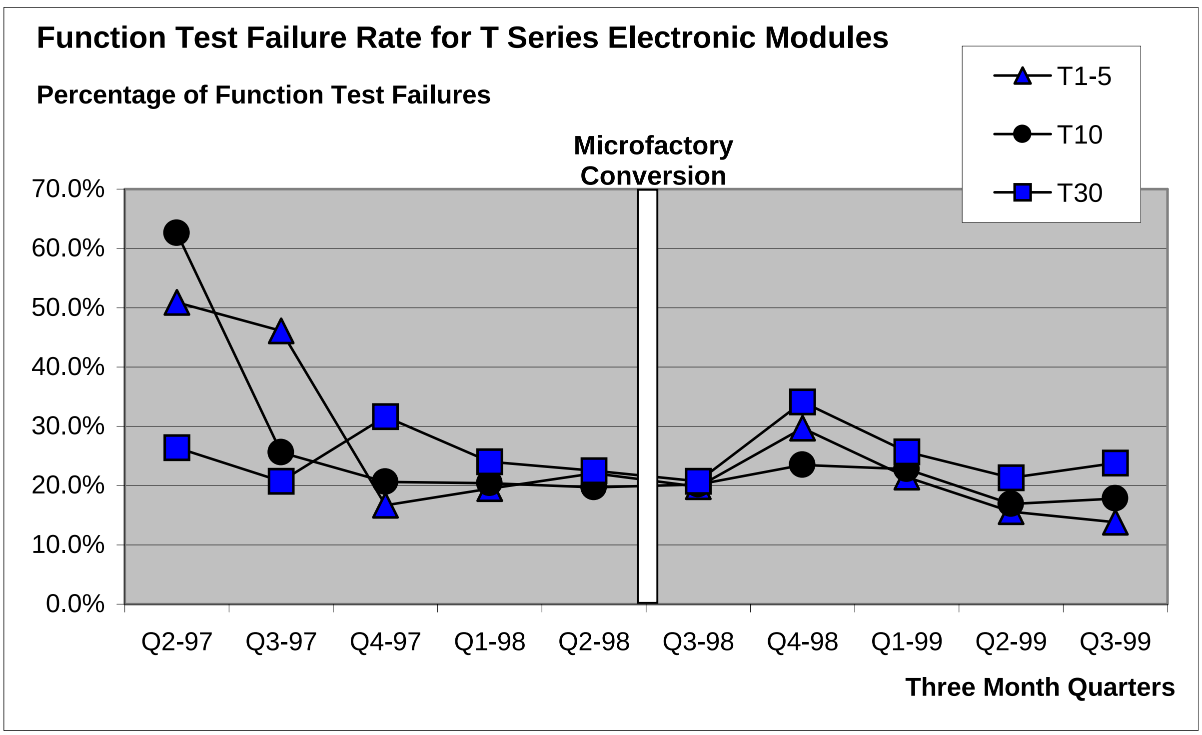


Figure 5.4. Graph of Function Test Failure Rates for T Series Electronic Transceiver Modules

5.2.1.1 Wilcoxon Signed Rank Test Results for Function Test Failure Rates of T Series Electronic Transceiver Modules

Product: T1-5

Quarter-Year	Failure Rate	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	50.9%	16.7%	29.7%	-13.0%		3
Q3-97	46.1%	19.5%	21.4%	-1.9%		1
Q4-97	16.7%	22.1%	19.8%	2.3%	2	
Q1-98	19.5%	46.1%	15.6%	30.5%	4	
Q2-98	22.1%	50.9%	13.8%	37.1%	5	
Q3-98	19.8%			**Σ Ranks :**	**11**	**4**
Q4-98	29.7%					
Q1-99	21.4%					
Q2-99	15.6%					
Q3-99	13.8%					

No Statistically Significant Difference Shown Between Means

Product: T10

Quarter-Year	Failure Rate	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	62.6%	19.7%	23.5%	-3.8%		3
Q3-97	25.6%	20.4%	22.8%	-2.4%		2
Q4-97	20.6%	20.6%	20.2%	0.4%	1	
Q1-98	20.4%	25.6%	17.8%	7.8%	4	
Q2-98	19.7%	62.6%	16.9%	45.7%	5	
Q3-98	20.2%			**Σ Ranks :**	**10**	**5**
Q4-98	23.5%					
Q1-99	22.8%					
Q2-99	16.9%					
Q3-99	17.8%					

No Statistically Significant Difference Shown Between Means

Product: T30

Quarter-Year	Failure Rate	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	26.4%	20.7%	34.1%	-13.4%		5
Q3-97	20.7%	22.5%	25.7%	-3.2%		2
Q4-97	31.6%	24.0%	23.8%	0.2%	1	
Q1-98	24.0%	26.4%	21.3%	5.1%	3	
Q2-98	22.5%	31.6%	20.7%	10.9%	4	
Q3-98	20.7%			**Σ Ranks :**	**8**	**7**
Q4-98	34.1%					
Q1-99	25.7%					
Q2-99	21.3%					
Q3-99	23.8%					

No Statistically Significant Difference Shown Between Means

5.2.2 Time Test

The time test is a "burn in" test entailing the full power operation of each assembled and function tested module in a simulated operating environment. The length of each time test was for eight hours before the T series electronic transceiver module production activity was converted to a microfactory and for four hours after the microfactory conversion. Time test failure rates for the module assembly activity, acquired from quarterly performance reports, are tabulated in Table 5.2. In this table, quarters Q2-97 to Q2-98 represent failure rates before conversion to a microfactory and quarters Q3-98 to Q3-99 are failure rates after conversion to a microfactory.

Table 5.2. Time Test Failure Rates for T Series Electronic Transceiver Modules (Source: Company Quarterly Performance Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
T1-5	3.0%	2.9%	3.1%	1.4%	1.9%	2.4%	2.1%	1.3%	2.2%	2.2%
T10	3.3%	4.3%	9.0%	4.5%	3.9%	3.9%	4.2%	3.0%	3.0%	3.5%
T30	5.6%	2.9%	12.5%	4.5%	2.9%	3.4%	3.8%	4.1%	4.2%	6.1%

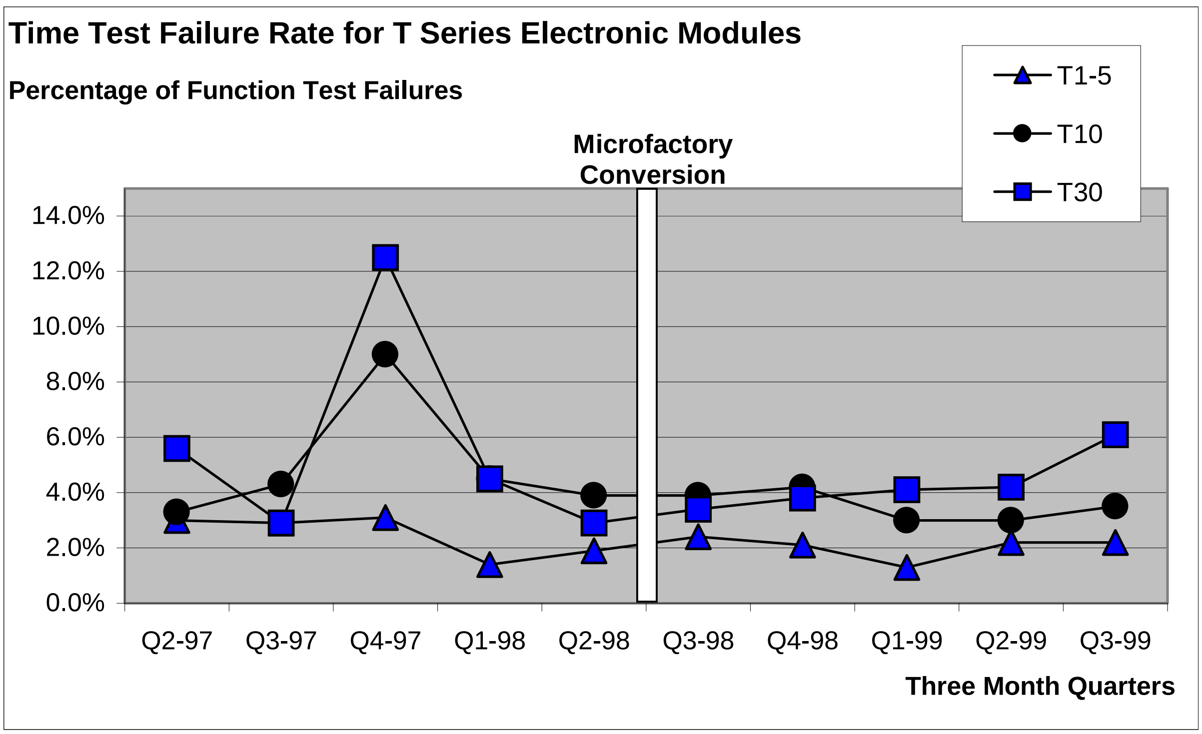


Figure 5.5. Graph of Time Test Failure Rates for T Series Electronic Transceiver Modules

5.2.2.1 Wilcoxon Signed Rank Test Results for Time Test Failure Rates of T Series Electronic Transceiver Modules

Product: T1-5

Quarter-Year	Failure Rate	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	3.0%	1.4%	2.4%	-1.0%		4
Q3-97	2.9%	1.9%	2.2%	-0.3%		1
Q4-97	3.1%	2.9%	2.2%	0.7%	2	
Q1-98	1.4%	3.0%	2.1%	0.9%	3	
Q2-98	1.9%	3.1%	1.3%	1.8%	5	
Q3-98	2.4%			**Σ Ranks :**	**10**	**5**
Q4-98	2.1%					
Q1-99	1.3%					
Q2-99	2.2%					
Q3-99	2.2%					

No Statistically Significant Difference Shown Between Means

Product: T10

Quarter-Year	Failure Rate	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	3.3%	3.3%	4.2%	-0.9%		2
Q3-97	4.3%	3.9%	3.9%	0.0%		
Q4-97	9.0%	4.3%	3.5%	0.8%	1	
Q1-98	4.5%	4.5%	3.0%	1.5%	3	
Q2-98	3.9%	9.0%	3.0%	6.0%	4	
Q3-98	3.9%			**Σ Ranks :**	**8**	**2**
Q4-98	4.2%					
Q1-99	3.0%					
Q2-99	3.0%					
Q3-99	3.5%					

No Statistically Significant Difference Shown Between Means

Product: T30

Quarter-Year	Failure Rate	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	5.6%	2.9%	6.1%	-3.2%		4
Q3-97	2.9%	2.9%	4.2%	-1.3%		2
Q4-97	12.5%	4.5%	4.1%	0.4%	1	
Q1-98	4.5%	5.6%	3.8%	1.8%	3	
Q2-98	2.9%	12.5%	3.4%	9.1%	5	
Q3-98	3.4%			**Σ Ranks :**	**9**	**6**
Q4-98	3.8%					
Q1-99	4.1%					
Q2-99	4.2%					
Q3-99	6.1%					

No Statistically Significant Difference Shown Between Means

5.2.3 Analysis of Failure Rate Data

Table 5.3 presents a summary of the Wilcoxon Signed Rank testing results detailed in Sections 5.2.1.1 and 5.2.2.1 of failure rates before the microfactory conversion (Q2 1997 to Q2 1998) and after the microfactory is implemented (Q3 1998 to Q3 1999). These results are used to ascertain if there exists a statistically significant (i.e., $p \leq 0.05$) difference between the before and after failure rates. If significance is found, then the data suggest degradation in quality has occurred after the microfactory is implemented. In Table 5.3, the letter "N" is used to indicate that the Wilcoxon Signed Rank test did not show a statistically significant difference between the before and after data.

Table 5.3. Results of Wilcoxon Signed Rank Testing for a One-Tailed Statistical Significance Level of $p \leq 0.05$ Between Test Failure Rates Before and After Microfactory Conversion

MODULE DESIGNATION	FUNCTION TEST	TIME TEST
T1-5	N	N
T10	N	N
T30	N	N

As can be seen in Table 5.3, the results of the Wilcoxon Signed Rank testing did not show a statistically significant difference between the before and after function test failure data and time test failure data for the T1-5, T10, and T30 electronic transceiver modules. A possible interpretation of these results is that the implementation of the microfactory based on automation, simplification, and decentralization did not result in degradation of production quality.

5.3 Cost

Cost data are acquired both before and after the implementation of the microfactory concept to ascertain if, as stated in the hypothesis in Section 1.1.2, the implementation of the microfactory concept would reduce the cost of the T series electronic transceiver modules. The Investigator anticipates that the data will show a reduction in the labor cost, the overhead cost, and the total product cost, after the conversion to a microfactory architecture. Quarterly (i.e., three month) cost data are collected over a 10 quarter period (i.e., two and a half years) for five quarters before the microfactory conversion and for five quarters after the microfactory conversion, resulting in a small sample set of ten points (i.e., five pairs). The cost data are acquired from company quarterly financial reports covering quarters from Q2 1997 to Q3 1999. As with the previously discussed quality data (Section 5.2), the statistical distribution of these small size before and after sample sets is not known. Accordingly, the Wilcoxon Signed Rank test (discussed in Section 4.2) is chosen to test the null hypothesis stated in Section 1.1.2. Furthermore, because the alternative hypothesis presented by the Investigator predicts a reduction in the labor cost, the overhead cost, and the total product cost, then a one-tailed test is conducted.

Canada et al. [71] note that accounting records of production costs are normally divided into three main categories: direct labor, direct material, and indirect overhead costs. In the case of this research, the company divides cost into four main categories, choosing to separate indirect costs into overhead and material burden. This being the case, cost per unit data are acquired in material cost, material burden, labor cost, and overhead cost. Furthermore, total cost and total cost excluding material cost and material burden are also included in the cost data to be analyzed.

Of the six categories of data to be collected, three categories are directly related to the research hypothesis presented in Section 1.1.2; labor cost, overhead cost, and total product cost. The microfactory concept does not directly address the reduction of material cost and the associated material burden. Once a product design is specified, then the cost of material is most directly effected by the abilities of both buyers at the production site who deal directly with vendors and corporate level contract negotiators who establish long term buying agreements with vendors. Changes in material cost and material burden can result in a change in the total product cost. Consequently, the Investigator acquired cost data for both total product cost and total product cost excluding material cost and material burden. A scenario in which total product cost excluding material cost and material burden does not change, yet the total product cost does change, would indicate changes had occurred in material cost and material burden. Since, as mentioned previously, the microfactory concept does not directly address these two cost parameters, this might suggest that performance changes had occurred that were unrelated to the microfactory implementation.

Because the cost is acquired over a ten quarter period, the data are adjusted for inflation to year 2000 U.S. Dollars. This is accomplished using inflation rates published in the U.S. Department of Labor, Bureau of Labor Statistics Consumer Price Index Report [72]. The average rate of inflation for 1997 to 2000 is given in Table 5.4.

Table 5.4. Rate of Inflation for 1997 to 2000 as Reported by the U.S. Department of Labor, Bureau of Labor Statistics Consumer Price Index

Year	Rate of Inflation
1997 to 1998	1.6 %
1998 to 1999	2.2 %
1999 to 2000	3.4 %

Sections 5.3.1 through 5.3.6 present the cost data for each quarter from Q2 1997 to Q3 1999 and detail the results of Wilcoxon Signed Rank testing on each data set. Based on the rates listed in Table 5.4, the adjustment for inflation of the cost data from 1997 U.S. Dollars to 2000 U.S. Dollars is 7.2%; from 1998 U.S. Dollars to 2000 U.S. Dollars is 5.6%; and from 1999 U.S. Dollars to 2000 U.S. Dollars is 3.4%. An analysis of the Wilcoxon Signed Rank testing of the cost data is given in Section 5.3.7.

5.3.1 Material Cost

The data in Table 5.5 represent the cost of material per unit produced. It is determined by dividing the total cost of material used by the number of units produced. In this table, quarters Q2-97 to Q2-98 represent material cost before conversion to a microfactory and quarters Q3-98 to Q3-99 represent material cost after conversion to a microfactory. Figure 5.6 charts the material cost data and Section 5.3.1.1 presents the results of Wilcoxon Signed Rank testing on the data.

Table 5.5. End of Quarter Material Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars (Source: Company Quarterly Financial Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
IN-MI	1579	1544	1580	1514	1488	1390	1435	1365	1396	1301
MAC-T	1433	1448	1434	1382	1397	1358	1317	1246	1078	1078
19-T	1240	1201	1141	1181	1194	1168	1139	1055	888	888
LM	908	864	846	732	760	743	720	688	688	688
D10	1508	1383	1369	1183	1124	1174	1138	1095	1095	1095
D50	1659	1536	1522	1328	1270	1320	1283	1236	1236	1236
T1-5	650	626	614	535	529	531	532	381	356	349
T10	697	656	644	563	555	557	558	404	377	372
T30	765	742	730	619	615	605	488	454	428	409

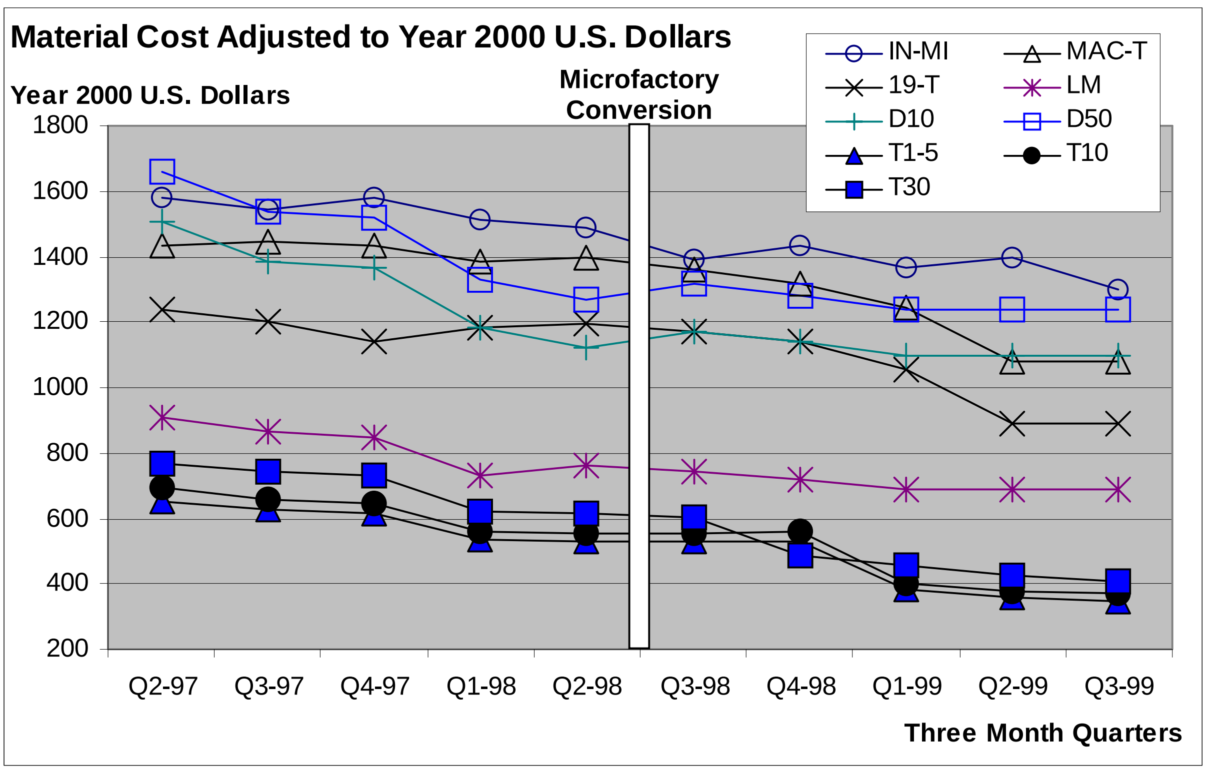


Figure 5.6. Graph of End of Quarter Material Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars

5.3.1.1 Wilcoxon Signed Rank Test Results for Material Cost (Adjusted to Year 2000 U.S. Dollars)

Product: IN-MI

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1579	1488	1435	53	1	
Q3-97	1544	1514	1396	118	2	
Q4-97	1580	1544	1390	154	3	
Q1-98	1514	1579	1365	214	4	
Q2-98	1488	1580	1301	279	5	
Q3-98	1390			**Σ Ranks :**	**15**	**0**
Q4-98	1435					
Q1-99	1365					
Q2-99	1396					
Q3-99	1301					

Second Mean Significantly (i.e., p ≤ 0.05) Smaller

Product: MAC-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1433	1382	1358	24	1	
Q3-97	1448	1397	1317	80	2	
Q4-97	1434	1433	1246	187	3	
Q1-98	1382	1434	1078	356	4	
Q2-98	1397	1448	1078	370	5	
Q3-98	1358			**Σ Ranks :**	**15**	**0**
Q4-98	1317					
Q1-99	1246					
Q2-99	1078					
Q3-99	1078					

Second Mean Significantly (i.e., p ≤ 0.05) Smaller

Product: 19-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1240	1141	1168	-27		1
Q3-97	1201	1181	1139	42	2	
Q4-97	1141	1194	1055	139	3	
Q1-98	1181	1201	888	313	4	
Q2-98	1194	1240	888	352	5	
Q3-98	1168			**Σ Ranks :**	**14**	**1**
Q4-98	1139					
Q1-99	1055					
Q2-99	888					
Q3-99	888					

No Statistically Significant Difference Shown Between Means

Product: LM

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	908	732	743	-11		1
Q3-97	864	760	720	40	2	
Q4-97	846	846	688	158	3	
Q1-98	732	864	688	176	4	
Q2-98	760	908	688	220	5	
Q3-98	743			**Σ Ranks :**	**14**	**1**
Q4-98	720					
Q1-99	688					
Q2-99	688					
Q3-99	688					

No Statistically Significant Difference Shown Between Means

Product: D10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1508	1124	1174	-50		2
Q3-97	1383	1183	1138	45	1	
Q4-97	1369	1369	1095	274	3	
Q1-98	1183	1383	1095	288	4	
Q2-98	1124	1508	1095	413	5	
Q3-98	1174			**Σ Ranks :**	**13**	**2**
Q4-98	1138					
Q1-99	1095					
Q2-99	1095					
Q3-99	1095					

No Statistically Significant Difference Shown Between Means

Product: D50

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1659	1270	1320	-50		2
Q3-97	1536	1328	1283	45	1	
Q4-97	1522	1522	1236	286	3	
Q1-98	1328	1536	1236	300	4	
Q2-98	1270	1659	1236	423	5	
Q3-98	1320			**Σ Ranks :**	**13**	**2**
Q4-98	1283					
Q1-99	1236					
Q2-99	1236					
Q3-99	1236					

No Statistically Significant Difference Shown Between Means

Product: T1-5

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	650	529	532	-3		1
Q3-97	626	535	531	4	2	
Q4-97	614	614	381	233	3	
Q1-98	535	626	356	270	4	
Q2-98	529	650	349	301	5	
Q3-98	531			**Σ Ranks :**	**14**	**1**
Q4-98	532					
Q1-99	381					
Q2-99	356					
Q3-99	349					

No Statistically Significant Difference Shown Between Means

Product: T10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	697	555	558	-3		1
Q3-97	656	563	557	6	2	
Q4-97	644	644	404	240	3	
Q1-98	563	656	377	279	4	
Q2-98	555	697	372	325	5	
Q3-98	557			**Σ Ranks :**	**14**	**1**
Q4-98	558					
Q1-99	404					
Q2-99	377					
Q3-99	372					

No Statistically Significant Difference Shown Between Means

Product: T30

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	765	615	605	10	1	
Q3-97	742	619	488	131	2	
Q4-97	730	730	454	276	3	
Q1-98	619	742	428	314	4	
Q2-98	615	765	409	356	5	
Q3-98	605			**Σ Ranks :**	**15**	**0**
Q4-98	488					
Q1-99	454					
Q2-99	428					
Q3-99	409					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

5.3.2 Material Burden

As discussed in Section 5.3, the company separates indirect overhead cost into overhead cost and material burden. Material burden encompasses all costs associated with the purchasing and handling of material for production including both associated indirect labor and indirect material and excluding the direct cost of the material. The material burden category is comprised of procurement, freight, duty, receiving, incoming inspection, and component warehousing costs. The data in Table 5.6 represent the material burden per unit produced. In this table, quarters Q2-97 to Q2-98 represent material burden before conversion to a microfactory and quarters Q3-98 to Q3-99 represent material burden after conversion to a microfactory. Figure 5.7 charts the material burden data and Section 5.3.2.1 presents the results of Wilcoxon Signed Rank testing on the data.

Table 5.6. End of Quarter Material Burden per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars (Source: Company Quarterly Financial Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
IN-MI	126	123	126	98	97	93	93	70	70	65
MAC-T	115	116	115	90	91	89	86	62	54	54
19-T	100	77	75	77	77	76	74	49	44	44
LM	73	69	68	48	49	49	46	34	34	34
D10	121	110	109	77	73	76	74	55	55	55
D50	133	122	122	87	82	86	83	62	62	62
T1-5	51	50	49	35	35	35	36	19	18	18
T10	56	53	51	37	36	36	37	21	19	19
T30	61	60	59	40	40	39	32	23	22	21

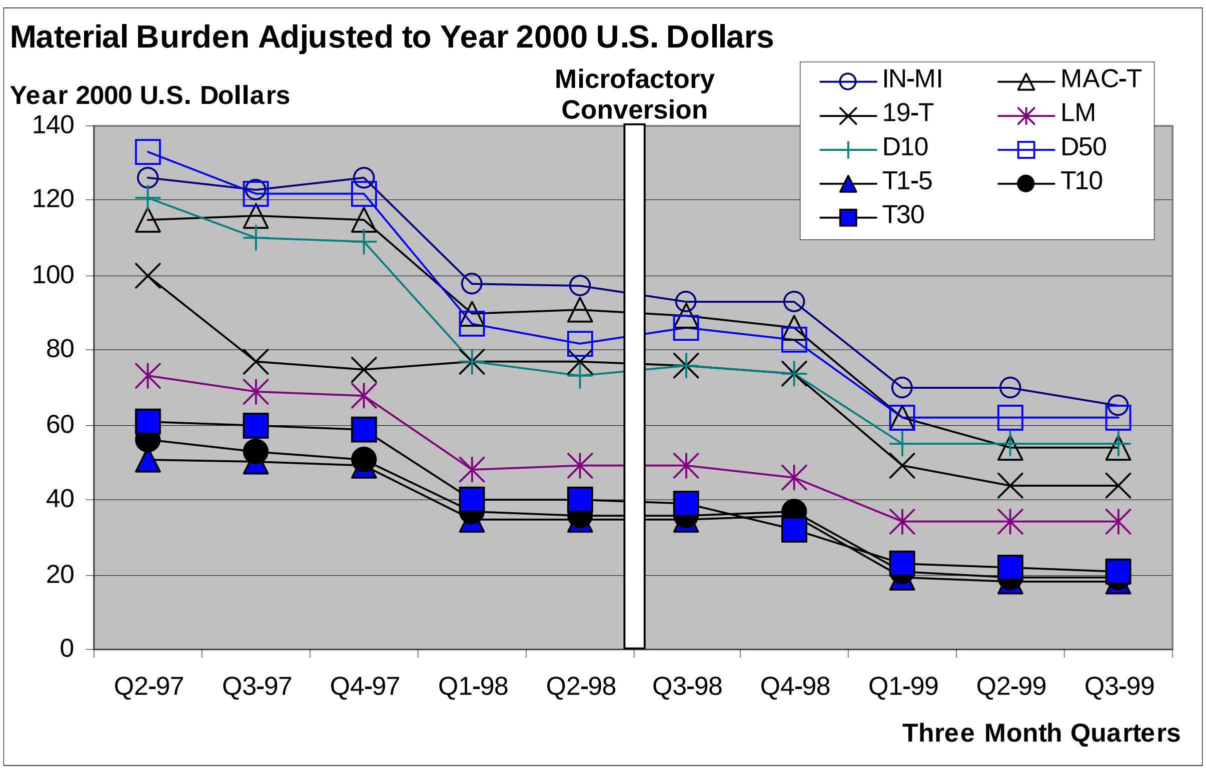


Figure 5.7. Graph of End of Quarter Material Burden per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars

5.3.2.1 Wilcoxon Signed Rank Test Results for Material Burden (Adjusted to Year 2000 U.S. Dollars)

Product: IN-MI

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	126	97	93	4	1	
Q3-97	123	98	93	5	2	
Q4-97	126	123	70	53	3	
Q1-98	98	126	70	56	4	
Q2-98	97	126	65	61	5	
Q3-98	93			**Σ Ranks:**	**15**	**0**
Q4-98	93					
Q1-99	70					
Q2-99	70					
Q3-99	65					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: MAC-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	115	90	89	1	1	
Q3-97	116	91	86	5	2	
Q4-97	115	115	62	53	3	
Q1-98	90	115	54	61	4	
Q2-98	91	116	54	62	5	
Q3-98	89			**Σ Ranks:**	**15**	**0**
Q4-98	86					
Q1-99	62					
Q2-99	54					
Q3-99	54					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: 19-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	100	75	76	-1		1.5
Q3-97	77	77	74	3	1.5	
Q4-97	75	77	49	28	3	
Q1-98	77	77	44	33	4	
Q2-98	77	100	44	56	5	
Q3-98	76			**Σ Ranks:**	**13.5**	**1.5**
Q4-98	74					
Q1-99	49					
Q2-99	44					
Q3-99	44					

No Statistically Significant Difference Shown Between Means

Product: LM

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	73	48	49	-1		1
Q3-97	69	49	46	3	2	
Q4-97	68	68	34	34	3	
Q1-98	48	69	34	35	4	
Q2-98	49	73	34	39	5	
Q3-98	49			**Σ Ranks:**	**14**	**1**
Q4-98	46					
Q1-99	34					
Q2-99	34					
Q3-99	34					

No Statistically Significant Difference Shown Between Means

Product: D10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	121	73	76	-3		1.5
Q3-97	110	77	74	3	1.5	
Q4-97	109	109	55	54	3	
Q1-98	77	110	55	55	4	
Q2-98	73	121	55	66	5	
Q3-98	76			**Σ Ranks:**	**13.5**	**1.5**
Q4-98	74					
Q1-99	55					
Q2-99	55					
Q3-99	55					

No Statistically Significant Difference Shown Between Means

Product: D50

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	133	82	86	-4		1.5
Q3-97	122	87	83	4	1.5	
Q4-97	122	122	62	60	3.5	
Q1-98	87	122	62	60	3.5	
Q2-98	82	133	62	71	5	
Q3-98	86			**Σ Ranks:**	**13.5**	**1.5**
Q4-98	83					
Q1-99	62					
Q2-99	62					
Q3-99	62					

No Statistically Significant Difference Shown Between Means

Product: T1-5

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	51	35	36	-1		1
Q3-97	50	35	35	0		
Q4-97	49	49	19	30	2	
Q1-98	35	50	18	32	3	
Q2-98	35	51	18	33	4	
Q3-98	35			**Σ Ranks:**	**9**	**1**
Q4-98	36					
Q1-99	19					
Q2-99	18					
Q3-99	18					

No Statistically Significant Difference Shown Between Means

Product: T10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	56	36	37	-1		1.5
Q3-97	53	37	36	1	1.5	
Q4-97	51	51	21	30	3	
Q1-98	37	53	19	34	4	
Q2-98	36	56	19	37	5	
Q3-98	36			**Σ Ranks:**	**13.5**	**1.5**
Q4-98	37					
Q1-99	21					
Q2-99	19					
Q3-99	19					

No Statistically Significant Difference Shown Between Means

Product: T30

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	61	40	39	1	1	
Q3-97	60	40	32	8	2	
Q4-97	59	59	23	36	3	
Q1-98	40	60	22	38	4	
Q2-98	40	61	21	40	5	
Q3-98	39			**Σ Ranks:**	**15**	**0**
Q4-98	32					
Q1-99	23					
Q2-99	22					
Q3-99	21					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

5.3.3 Labor Cost

The data in Table 5.7 represent the cost of direct labor per unit produced. It is determined by dividing the total cost of direct labor used by the number of units produced. In this table, quarters Q2-97 to Q2-98 represent labor cost before conversion to a microfactory and quarters Q3-98 to Q3-99 represent labor cost after conversion to a microfactory. Figure 5.8 charts the labor cost data and Section 5.3.3.1 presents the results of Wilcoxon Signed Rank testing on the data.

Table 5.7. End of Quarter Labor Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars (Source: Company Quarterly Financial Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
IN-MI	59	54	53	54	54	56	53	52	53	53
MAC-T	42	31	31	31	33	33	33	35	38	38
19-T	30	31	30	30	31	31	32	31	32	32
LM	20	21	21	22	22	22	22	23	23	23
D10	50	50	50	51	52	52	52	52	52	52
D50	54	54	54	55	55	56	55	55	56	56
T1-5	11	11	10	11	12	6	6	4	6	6
T10	11	12	11	11	12	6	6	4	6	6
T30	10	10	10	11	12	6	6	4	6	6

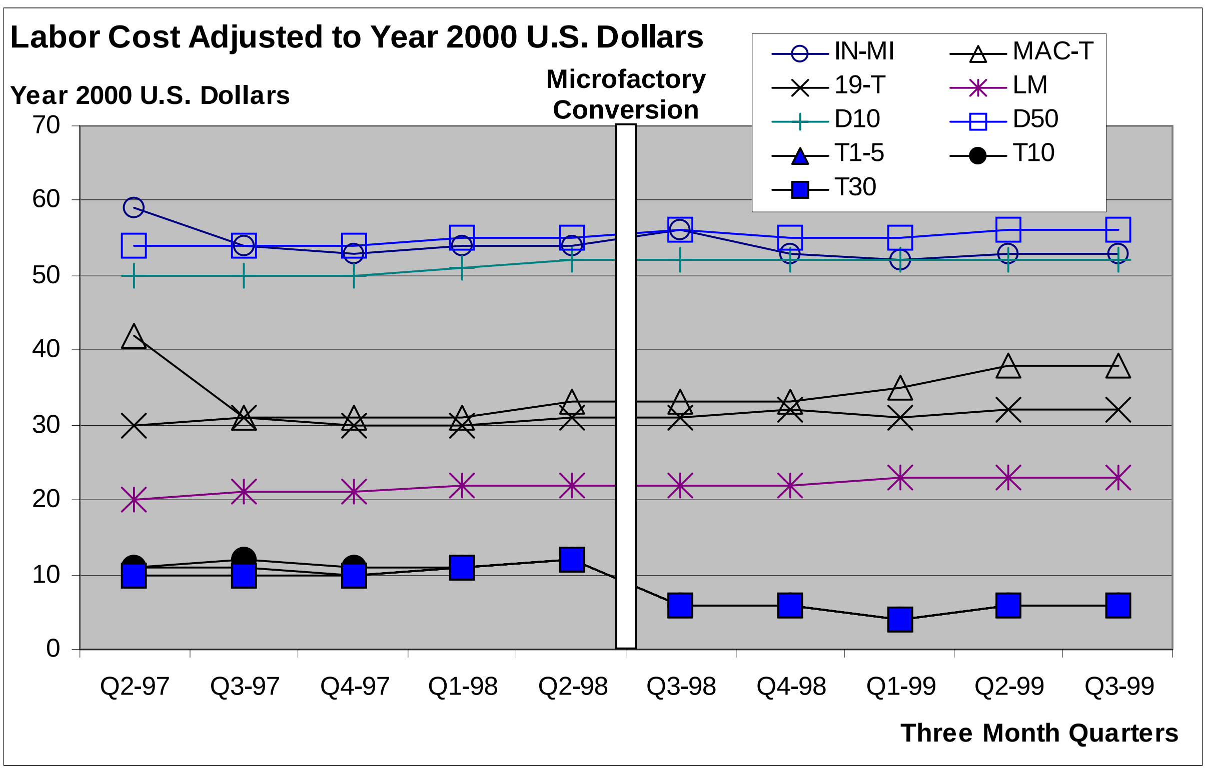


Figure 5.8. Graph of End of Quarter Labor Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars

5.3.3.1 Wilcoxon Signed Rank Test Results for Labor Cost (Adjusted to Year 2000 U.S. Dollars)

Product: IN-MI

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	59	53	56	-3		4
Q3-97	54	54	53	1	2	
Q4-97	53	54	53	1	2	
Q1-98	54	54	53	1	2	
Q2-98	54	59	52	7	5	
Q3-98	56			**Σ Ranks:**	**11**	**4**
Q4-98	53					
Q1-99	52					
Q2-99	53					
Q3-99	53					

No Statistically Significant Difference Shown Between Means

Product: MAC-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	42	31	38	-7		2.5
Q3-97	31	31	38	-7		2.5
Q4-97	31	31	35	-4		1
Q1-98	31	33	33	0		
Q2-98	33	42	33	9	4	
Q3-98	33			**Σ Ranks:**	**4**	**6**
Q4-98	33					
Q1-99	35					
Q2-99	38					
Q3-99	38					

No Statistically Significant Difference Shown Between Means

Product: 19-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	30	30	32	-2		2
Q3-97	31	30	32	-2		2
Q4-97	30	30	32	-2		2
Q1-98	30	31	31	0		
Q2-98	31	31	31	0		
Q3-98	31			**Σ Ranks:**	**0**	**6**
Q4-98	32					
Q1-99	31					
Q2-99	32					
Q3-99	32					

No Statistically Significant Difference Shown Between Means

Product: LM

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	20	20	23	-3		3
Q3-97	21	21	23	-2		1.5
Q4-97	21	21	23	-2		1.5
Q1-98	22	22	22	0		
Q2-98	22	22	22	0		
Q3-98	22			**Σ Ranks:**	**0**	**6**
Q4-98	22					
Q1-99	23					
Q2-99	23					
Q3-99	23					

No Statistically Significant Difference Shown Between Means

Product: D10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	50	50	52	-2		3
Q3-97	50	50	52	-2		3
Q4-97	50	50	52	-2		3
Q1-98	51	51	52	-1		1
Q2-98	52	52	52	0		
Q3-98	52			**Σ Ranks:**	**0**	**10**
Q4-98	52					
Q1-99	52					
Q2-99	52					
Q3-99	52					

No Statistically Significant Difference Shown Between Means

Product: D50

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	54	54	56	-2		2
Q3-97	54	54	56	-2		2
Q4-97	54	54	56	-2		2
Q1-98	55	55	55	0		
Q2-98	55	55	55	0		
Q3-98	56			**Σ Ranks:**	**0**	**6**
Q4-98	55					
Q1-99	55					
Q2-99	56					
Q3-99	56					

No Statistically Significant Difference Shown Between Means

Product: T1-5

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	11	10	6	4	1	
Q3-97	11	11	6	5	3	
Q4-97	10	11	6	5	3	
Q1-98	11	11	6	5	3	
Q2-98	12	12	4	8	5	
Q3-98	6			**Σ Ranks:**	**15**	**0**
Q4-98	6					
Q1-99	4					
Q2-99	6					
Q3-99	6					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	11	11	6	5	2	
Q3-97	12	11	6	5	2	
Q4-97	11	11	6	5	2	
Q1-98	11	12	6	6	4	
Q2-98	12	12	4	8	5	
Q3-98	6			**Σ Ranks:**	**15**	**0**
Q4-98	6					
Q1-99	4					
Q2-99	6					
Q3-99	6					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T30

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	10	10	6	4	2	
Q3-97	10	10	6	4	2	
Q4-97	10	10	6	4	2	
Q1-98	11	11	6	5	4	
Q2-98	12	12	4	8	5	
Q3-98	6			**Σ Ranks:**	**15**	**0**
Q4-98	6					
Q1-99	4					
Q2-99	6					
Q3-99	6					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

5.3.4 Overhead Cost

As discussed in Section 5.3, the company separates indirect overhead cost into overhead cost and material burden. Material burden (Section 5.3.2) encompasses all costs associated with the purchasing and handling of material for production including both associated indirect labor and indirect material and excluding the direct cost of the material. Overhead cost accounts for all other indirect costs including both indirect costs charged to the production activity and a share of facility-wide indirect costs. The overhead cost category is comprised of administration, finance, manufacturing technology, human resources, quality, and information technology costs. The data in Table 5.8 represent the overhead cost per unit produced. In this table, quarters Q2-97 to Q2-98 represent overhead cost before conversion to a microfactory and quarters Q3-98 to Q3-99 represent overhead cost after conversion to a microfactory. Figure 5.9 charts the overhead cost data and Section 5.3.4.1 presents the results of Wilcoxon Signed Rank testing on the data.

Table 5.8. End of Quarter Overhead Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars (Source: Company Quarterly Financial Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
IN-MI	487	438	433	731	732	757	718	424	419	410
MAC-T	375	288	283	363	404	403	418	331	341	341
19-T	382	343	344	338	378	378	393	290	292	292
LM	202	214	214	229	232	246	246	206	206	206
D10	500	500	500	518	536	536	536	447	447	447
D50	533	533	533	550	578	578	578	482	482	482
T1-5	109	109	109	119	132	94	95	59	68	68
T10	108	107	108	116	130	94	96	58	68	68
T30	102	102	102	116	132	95	95	58	68	68

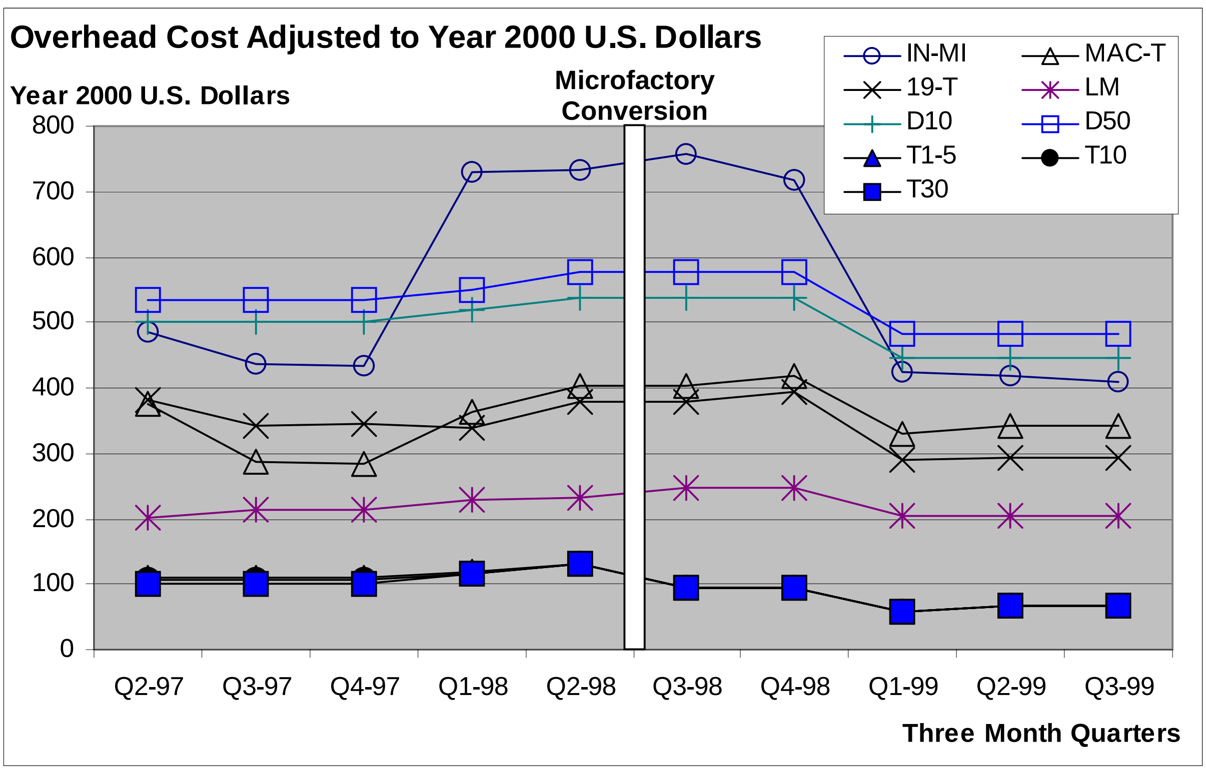


Figure 5.9. Graph of End of Quarter Overhead Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars

5.3.4.1 Wilcoxon Signed Rank Test Results for Overhead Cost (Adjusted to Year 2000 U.S. Dollars)

Product: IN-MI

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	487	433	757	-324		5
Q3-97	438	438	718	-280		2
Q4-97	433	487	424	63	1	
Q1-98	731	731	419	312	3	
Q2-98	732	732	410	322	4	
Q3-98	757			**Σ Ranks:**	**8**	**7**
Q4-98	718					
Q1-99	424					
Q2-99	419					
Q3-99	410					

No Statistically Significant Difference Shown Between Means

Product: MAC-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	375	283	418	-135		5
Q3-97	288	288	403	-115		4
Q4-97	283	363	341	22	1	
Q1-98	363	375	341	34	2	
Q2-98	404	404	331	73	3	
Q3-98	403			**Σ Ranks:**	**6**	**9**
Q4-98	418					
Q1-99	331					
Q2-99	341					
Q3-99	341					

No Statistically Significant Difference Shown Between Means

Product: 19-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	382	338	393	-55		3
Q3-97	343	343	378	-35		1
Q4-97	344	344	292	52	2	
Q1-98	338	378	292	86	4	
Q2-98	378	382	290	92	5	
Q3-98	378			**Σ Ranks:**	**11**	**4**
Q4-98	393					
Q1-99	290					
Q2-99	292					
Q3-99	292					

No Statistically Significant Difference Shown Between Means

Product: LM

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	202	202	246	-44		5
Q3-97	214	214	246	-32		4
Q4-97	214	214	206	8	1	
Q1-98	229	229	206	23	2	
Q2-98	232	232	206	26	3	
Q3-98	246			**Σ Ranks:**	**6**	**9**
Q4-98	246					
Q1-99	206					
Q2-99	206					
Q3-99	206					

No Statistically Significant Difference Shown Between Means

Product: D10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	500	500	536	-36		1.5
Q3-97	500	500	536	-36		1.5
Q4-97	500	500	447	53	3	
Q1-98	518	518	447	71	4	
Q2-98	536	536	447	89	5	
Q3-98	536			**Σ Ranks:**	**12**	**3**
Q4-98	536					
Q1-99	447					
Q2-99	447					
Q3-99	447					

No Statistically Significant Difference Shown Between Means

Product: D50

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	533	533	578	-45		1.5
Q3-97	533	533	578	-45		1.5
Q4-97	533	533	482	51	3	
Q1-98	550	550	482	68	4	
Q2-98	578	578	482	96	5	
Q3-98	578			**Σ Ranks:**	**12**	**3**
Q4-98	578					
Q1-99	482					
Q2-99	482					
Q3-99	482					

No Statistically Significant Difference Shown Between Means

Product: T1-5

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	109	109	95	14	1	
Q3-97	109	109	94	15	2	
Q4-97	109	109	68	41	3	
Q1-98	119	119	68	51	4	
Q2-98	132	132	59	73	5	
Q3-98	94			**Σ Ranks:**	**15**	**0**
Q4-98	95					
Q1-99	59					
Q2-99	68					
Q3-99	68					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	108	107	96	11	1	
Q3-97	107	108	94	14	2	
Q4-97	108	108	68	40	3	
Q1-98	116	116	68	48	4	
Q2-98	130	130	58	72	5	
Q3-98	94			**Σ Ranks:**	**15**	**0**
Q4-98	96					
Q1-99	58					
Q2-99	68					
Q3-99	68					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T30

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	102	102	95	7	1.5	
Q3-97	102	102	95	7	1.5	
Q4-97	102	102	68	34	3	
Q1-98	116	116	68	48	4	
Q2-98	132	132	58	74	5	
Q3-98	95			**Σ Ranks:**	**15**	**0**
Q4-98	95					
Q1-99	58					
Q2-99	68					
Q3-99	68					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

5.3.5 Total Cost

The data in Table 5.9 tabulate the total cost per unit produced. Total cost includes all direct (i.e., material cost and labor cost) and indirect (i.e., material burden and overhead cost) costs. In this table, quarters Q2-97 to Q2-98 represent total cost per unit before conversion to a microfactory and quarters Q3-98 to Q3-99 represent total cost per unit after conversion to a microfactory. Figure 5.10 charts the total cost per unit data and Section 5.3.5.1 presents the results of Wilcoxon Signed Rank testing on the data.

Table 5.9. End of Quarter Total Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars
(Source: Company Quarterly Financial Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
IN-MI	2251	2159	2192	2397	2371	2296	2299	1911	1938	1829
MAC-T	1965	1884	1862	1867	1925	1883	1853	1674	1512	1512
19-T	1752	1652	1590	1625	1681	1653	1638	1424	1256	1256
LM	1203	1168	1149	1031	1063	1060	1035	950	950	950
D10	2179	2043	2028	1829	1785	1838	1800	1648	1648	1648
D50	2379	2245	2231	2020	1985	2039	1999	1834	1835	1835
T1-5	821	796	783	700	708	666	670	462	448	442
T10	872	828	815	727	733	693	697	487	470	465
T30	938	913	900	786	798	746	621	539	524	505

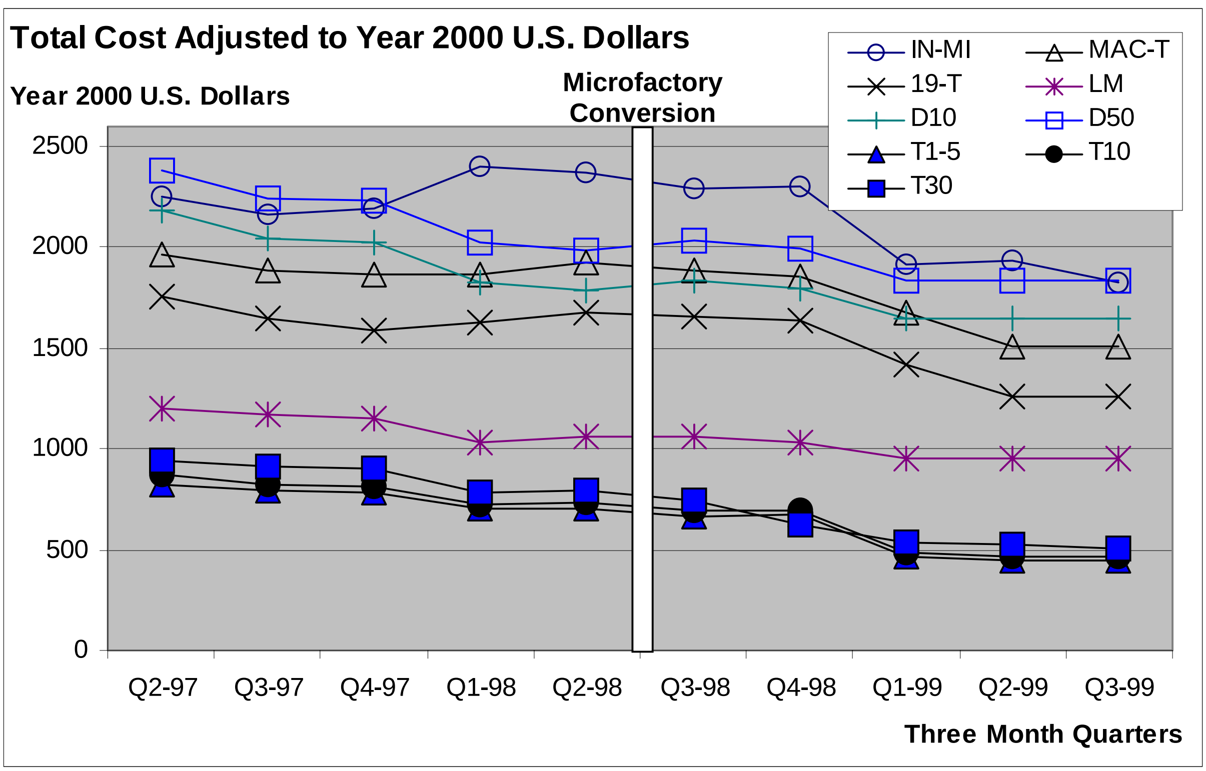


Figure 5.10. Graph of End of Quarter Total Cost per Unit for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars

5.3.5.1 Wilcoxon Signed Rank Test Results for Total Cost (Adjusted to Year 2000 U.S. Dollars)

Product: IN-MI

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	2251	2159	2299	-140		2
Q3-97	2159	2192	2296	-104		1
Q4-97	2192	2251	1938	313	3	
Q1-98	2397	2371	1911	460	4	
Q2-98	2371	2397	1829	568	5	
Q3-98	2296			**Σ Ranks:**	**12**	**3**
Q4-98	2299					
Q1-99	1911					
Q2-99	1938					
Q3-99	1829					

No Statistically Significant Difference Shown Between Means

Product: MAC-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1965	1862	1883	-21		2
Q3-97	1884	1867	1853	14	1	
Q4-97	1862	1884	1674	210	3	
Q1-98	1867	1925	1512	413	4	
Q2-98	1925	1965	1512	453	5	
Q3-98	1883			**Σ Ranks:**	**13**	**2**
Q4-98	1853					
Q1-99	1674					
Q2-99	1512					
Q3-99	1512					

No Statistically Significant Difference Shown Between Means

Product: 19-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1752	1590	1653	-63		2
Q3-97	1652	1625	1638	-13		1
Q4-97	1590	1652	1424	228	3	
Q1-98	1625	1681	1256	425	4	
Q2-98	1681	1752	1256	496	5	
Q3-98	1653			**Σ Ranks:**	**12**	**3**
Q4-98	1638					
Q1-99	1424					
Q2-99	1256					
Q3-99	1256					

No Statistically Significant Difference Shown Between Means

Product: LM

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	1203	1031	1060	-29		2
Q3-97	1168	1063	1035	28	1	
Q4-97	1149	1149	950	199	3	
Q1-98	1031	1168	950	218	4	
Q2-98	1063	1203	950	253	5	
Q3-98	1060			**Σ Ranks:**	**13**	**2**
Q4-98	1035					
Q1-99	950					
Q2-99	950					
Q3-99	950					

No Statistically Significant Difference Shown Between Means

Product: D10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	2179	1785	1838	-53		2
Q3-97	2043	1829	1800	29	1	
Q4-97	2028	2028	1648	380	3	
Q1-98	1829	2043	1648	395	4	
Q2-98	1785	2179	1648	531	5	
Q3-98	1838			**Σ Ranks:**	**13**	**2**
Q4-98	1800					
Q1-99	1648					
Q2-99	1648					
Q3-99	1648					

No Statistically Significant Difference Shown Between Means

Product: D50

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	2379	1985	2039	-54		2
Q3-97	2245	2020	1999	21	1	
Q4-97	2231	2231	1835	396	3	
Q1-98	2020	2245	1835	410	4	
Q2-98	1985	2379	1834	545	5	
Q3-98	2039			**Σ Ranks:**	**13**	**2**
Q4-98	1999					
Q1-99	1834					
Q2-99	1835					
Q3-99	1835					

No Statistically Significant Difference Shown Between Means

Product: T1-5

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	821	700	670	30	1	
Q3-97	796	708	666	42	2	
Q4-97	783	783	462	321	3	
Q1-98	700	796	448	348	4	
Q2-98	708	821	442	379	5	
Q3-98	666			**Σ Ranks:**	**15**	**0**
Q4-98	670					
Q1-99	462					
Q2-99	448					
Q3-99	442					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	872	727	697	30	1	
Q3-97	828	733	693	40	2	
Q4-97	815	815	487	328	3	
Q1-98	727	828	470	358	4	
Q2-98	733	872	465	407	5	
Q3-98	693			**Σ Ranks:**	**15**	**0**
Q4-98	697					
Q1-99	487					
Q2-99	470					
Q3-99	465					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T30

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	938	786	746	40	1	
Q3-97	913	798	621	177	2	
Q4-97	900	900	539	361	3	
Q1-98	786	913	524	389	4	
Q2-98	798	938	505	433	5	
Q3-98	746			**Σ Ranks:**	**15**	**0**
Q4-98	621					
Q1-99	539					
Q2-99	524					
Q3-99	505					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

5.3.6 Total Cost Excluding Material Cost and Material Burden

As discussed in Section 5.3, changes in material cost and material burden can result in a change in the total product cost. The microfactory concept does not directly address the reduction of material cost and the associated material burden. A scenario can be envisioned in which total product cost changes, yet the total product cost excluding material cost and material burden does not change. This would suggest performance changes had occurred that were unrelated to the microfactory implementation. Consequently, the Investigator acquired cost data for both total product cost and total product cost excluding material cost and material burden.

The data in Table 5.10 tabulate the total cost excluding material cost and material burden per unit produced. This includes labor cost and overhead cost and excludes material cost and material burden. In this table, quarters Q2-97 to Q2-98 represent total cost excluding material cost and material burden per unit before conversion to a microfactory, and quarters Q3-98 to Q3-99 represent total cost excluding material cost and material burden per unit after conversion to a microfactory. Figure 5.11 charts the data and Section 5.3.6.1 presents the results of Wilcoxon Signed Rank testing on the data.

Table 5.10. End of Quarter Total Cost per Unit Excluding Material Cost and Material Burden for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars (Source: Company Quarterly Financial Reports)

MODULE DESIGNATION	Q2-97	Q3-97	Q4-97	Q1-98	Q2-98	Q3-98	Q4-98	Q1-99	Q2-99	Q3-99
IN-MI	546	491	485	785	786	813	771	476	472	463
MAC-T	417	319	313	394	437	436	451	366	379	379
19-T	412	374	374	367	410	409	425	321	324	324
LM	222	235	235	251	254	268	268	229	229	229
D10	550	550	550	569	588	588	588	498	498	498
D50	586	586	586	605	633	634	633	537	538	538
T1-5	120	120	119	130	144	100	101	63	74	74
T10	119	119	119	127	142	100	102	62	74	74
T30	111	111	111	127	144	101	101	62	74	74

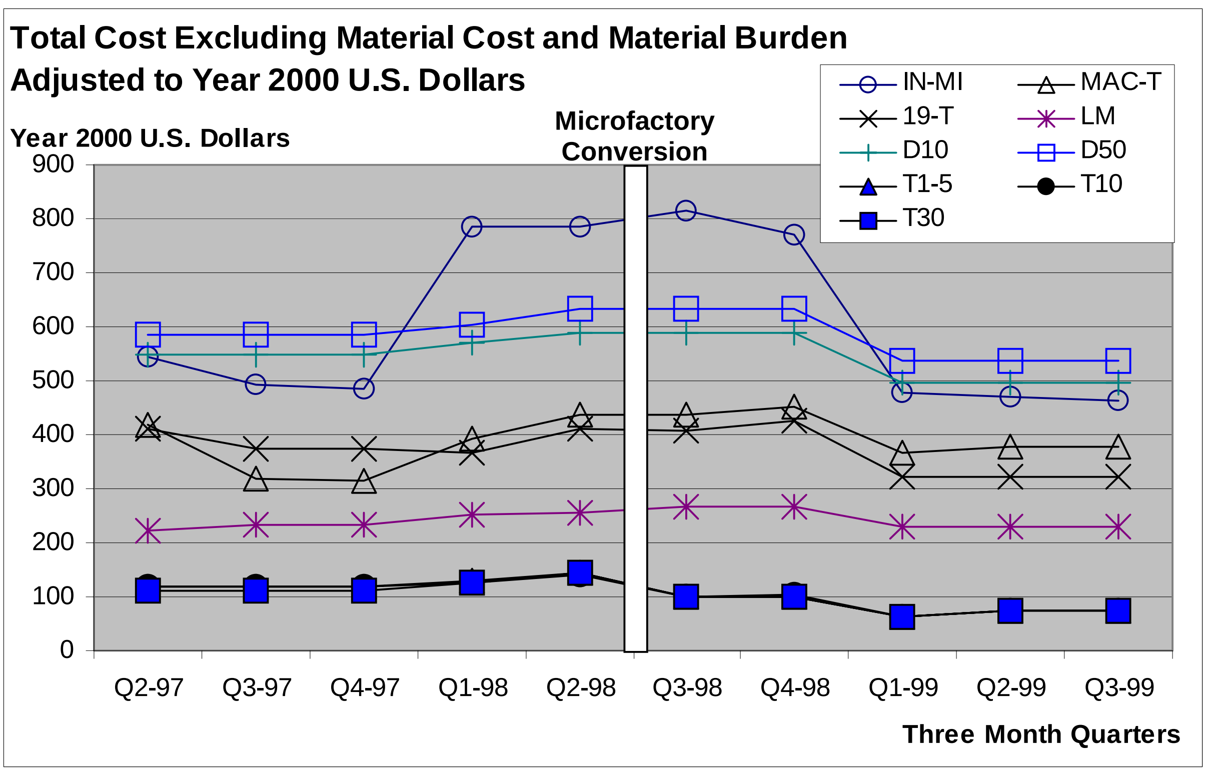


Figure 5.11. Graph of End of Quarter Total Cost per Unit Excluding Material Cost and Material Burden for Selected Products Including the T Series of Electronic Modules Adjusted to Year 2000 U.S. Dollars

5.3.6.1 Wilcoxon Signed Rank Test Results for Total Cost Excluding Material Cost and Material Burden (Adjusted to Year 2000 U.S. Dollars)

Product: IN-MI

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	546	485	813	-328		5
Q3-97	491	491	771	-280		2
Q4-97	485	546	476	70	1	
Q1-98	785	785	472	313	3	
Q2-98	786	786	463	323	4	
Q3-98	813			**Σ Ranks:**	**8**	**7**
Q4-98	771					
Q1-99	476					
Q2-99	472					
Q3-99	463					

No Statistically Significant Difference Shown Between Means

Product: MAC-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	417	313	451	-138		5
Q3-97	319	319	436	-117		4
Q4-97	313	394	379	15	1	
Q1-98	394	417	379	38	2	
Q2-98	437	437	366	71	3	
Q3-98	436			**Σ Ranks:**	**6**	**9**
Q4-98	451					
Q1-99	366					
Q2-99	379					
Q3-99	379					

No Statistically Significant Difference Shown Between Means

Product: 19-T

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	412	367	425	-58		3
Q3-97	374	374	409	-35		1
Q4-97	374	374	324	50	2	
Q1-98	367	410	324	86	4	
Q2-98	410	412	321	91	5	
Q3-98	409			**Σ Ranks:**	**11**	**4**
Q4-98	425					
Q1-99	321					
Q2-99	324					
Q3-99	324					

No Statistically Significant Difference Shown Between Means

Product: LM

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	222	222	268	-46		5
Q3-97	235	235	268	-33		4
Q4-97	235	235	229	6	1	
Q1-98	251	251	229	22	2	
Q2-98	254	254	229	25	3	
Q3-98	268			**Σ Ranks:**	**6**	**9**
Q4-98	268					
Q1-99	229					
Q2-99	229					
Q3-99	229					

No Statistically Significant Difference Shown Between Means

Product: D10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	550	550	588	-38		1.5
Q3-97	550	550	588	-38		1.5
Q4-97	550	550	498	52	3	
Q1-98	569	569	498	71	4	
Q2-98	588	588	498	90	5	
Q3-98	588			**Σ Ranks:**	**12**	**3**
Q4-98	588					
Q1-99	498					
Q2-99	498					
Q3-99	498					

No Statistically Significant Difference Shown Between Means

Product: D50

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	586	586	634	-48		2.5
Q3-97	586	586	633	-47		1
Q4-97	586	586	538	48	2.5	
Q1-98	605	605	538	67	4	
Q2-98	633	633	537	96	5	
Q3-98	634			**Σ Ranks:**	**11.5**	**3.5**
Q4-98	633					
Q1-99	537					
Q2-99	538					
Q3-99	538					

No Statistically Significant Difference Shown Between Means

Product: T1-5

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	120	119	101	18	1	
Q3-97	120	120	100	20	2	
Q4-97	119	120	74	46	3	
Q1-98	130	130	74	56	4	
Q2-98	144	144	63	81	5	
Q3-98	100			**Σ Ranks:**	**15**	**0**
Q4-98	101					
Q1-99	63					
Q2-99	74					
Q3-99	74					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T10

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	119	119	102	17	1	
Q3-97	119	119	100	19	2	
Q4-97	119	119	74	45	3	
Q1-98	127	127	74	53	4	
Q2-98	142	142	62	80	5	
Q3-98	100			**Σ Ranks:**	**15**	**0**
Q4-98	102					
Q1-99	62					
Q2-99	74					
Q3-99	74					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

Product: T30

Quarter-Year	Cost Per Unit	Before Treatment	After Treatment	Difference	Rank +	Rank -
Q2-97	111	111	101	10	1.5	
Q3-97	111	111	101	10	1.5	
Q4-97	111	111	74	37	3	
Q1-98	127	127	74	53	4	
Q2-98	144	144	62	82	5	
Q3-98	101			**Σ Ranks:**	**15**	**0**
Q4-98	101					
Q1-99	62					
Q2-99	74					
Q3-99	74					

Second Mean Significantly (i.e., $p \leq 0.05$) Smaller

5.3.7 Analysis of Cost Data

As detailed in previous sections, cost data are acquired to ascertain if, as stated in the hypothesis in Section 1.1.2, the implementation of the microfactory concept would reduce the cost of T series electronic transceiver module production. Toward this end, quarterly (i.e., three month) cost per unit data are acquired in six categories; material cost, material burden, labor cost, overhead cost, total cost, and total cost excluding material cost and material burden. The acquired data span a five quarter period before the microfactory conversion and a five quarter period after the microfactory conversion. Consequently, five data pairs are available for Wilcoxon Signed Rank testing. Because the alternative hypothesis presented by the Investigator postulates a reduction in the labor cost, the overhead cost, and the total product cost, then a one-tailed test is conducted.

Table 5.11 presents a summary of the results of the Wilcoxon Signed Rank testing for cost before the microfactory conversion (Q2 1997 to Q2 1998) and after the microfactory is implemented (Q3 1998 to Q3 1999) using cost data adjusted to year 2000 U.S. Dollars. The results presented in Table 5.11 are determined by using the Wilcoxon Signed Rank test to ascertain if there exists a statistically significant (i.e., $p \leq 0.05$) difference between the before and after cost data. If statistical significance is found, then the data suggest a reduction in cost occurs once the microfactory is implemented. In Table 5.11, the letter "N" is used to indicate that the Wilcoxon Signed Rank test did not show a statistically significant difference and the letter "S" is used to indicate that the Wilcoxon Signed Rank test did show a statistically significant difference.

Table 5.11. Results of Wilcoxon Signed Rank Testing of Cost for a One-Tailed Statistical Significance Level of $p \leq 0.05$ Before and After Microfactory Implementation

	Non-Microfactory Products						Microfactory Products		
COST CATEGORY	**IN-MI**	**MAC-T**	**19-T**	**LM**	**D10**	**D50**	**T1-5**	**T10**	**T30**
Material Cost	S	S	N	N	N	N	N	N	S
Material Burden	S	S	N	N	N	N	N	N	S
Labor Cost	N	N	N	N	N	N	S	S	S
Overhead Cost	N	N	N	N	N	N	S	S	S
Total Cost	N	N	N	N	N	N	S	S	S
Total Cost Excluding Material and Burden Costs	N	N	N	N	N	N	S	S	S

S = Statistical Significance ($p \leq 0.05$) Shown
N = Statistical Significance Not Shown

The null hypothesis detailed in Section 1.1.2, states that, along with throughput time and production quality, no change occurs in the labor cost, overhead cost, and total cost when the microfactory concept (i.e., automation, simplification, and decentralization) is implemented. As can be seen in Table 5.11, the results of the Wilcoxon Signed Rank testing did not show a statistically significant difference between the before and after cost data for non-microfactory products (i.e., IN-MI, MAC-T, 19-T, LM, D10, and D50) in the cost categories of labor cost, overhead cost, total cost, and total cost excluding material and burden costs. However, a statistically significant difference between before and after cost data is shown for the microfactory products (i.e., T1-5, T10, and T30) in these same cost categories (i.e., labor cost, overhead cost, total cost, and total cost excluding material and burden costs).

In the two remaining cost categories, material cost and material burden, a statistically significant difference between before and after cost data is shown for the non-microfactory IN-MI and MAC-T and the microfactory produced T30. As discussed in Section 5.3, even though the microfactory concept does not address the cost of material and the associated material burden, the Investigator chose to acquire both to ascertain if any changes in the total product cost might be the result of changes in material cost and material burden instead of the implementation of the microfactory concept. As can be seen in Table 5.11, a statistically significant difference between the before and after total cost and total cost excluding material and burden cost is shown only for microfactory products (i.e., T1-5, T10, and T30). A possible interpretation of this result is that the implementation of the microfactory concept based on automation, simplification, and decentralization did result in a reduction in the labor cost, overhead cost, and total product cost.

5.3.8 Attendance

In addition to the throughput time, quality, and cost data that are measured during the research, employee attendance data are also acquired and are tabulated in Table 5.12. These data are collected to ascertain if a Hawthorne Effect may have been present during the implementation of the microfactory concept. The Hawthorne Effect was first reported through a series of socioeconomic experiments conducted with employees of the Western Electric Hawthorne Works in Chicago from 1924 to 1932 where "…the central idea is that behavior during the course of an experiment can be altered by a subject's awareness of participating in the experiment." [73]. The results found in experiments investigating the effects on productivity from changes in room lighting were that productivity in both existing lighting and increased illumination groups improved regardless of changes in illumination [64].

In the case of the microfactory implementation, the question arises as to whether performance gains are due to the microfactory or are due to increased interest in the changes in process and practice and the increased attention that employees feel as part of their involvement in a new technology introduction. To address this issue, attendance is measured as an indicator of Hawthorne Effect, the presence of which would tend to reduce absenteeism. Out of approximately 30 employees involved in the microfactory implementation, the attendance history of ten employees is tracked from the first quarter of 1998 to the first quarter of 1999. The resulting absentee data are given in Table 5.12 and graphed in Figure 5.12.

Table 5.12. Total Absentee Hours per Quarter for Ten Employees Involved in the Transition to Microfactory Production

QUARTER	TOTAL ABSENTEE HOURS DURING THE QUARTER
Q1-98	695
Q2-98	655
Q3-98	598
Q4-98	547
Q1-99	658

The data tabulated in Table 5.12 and graphically illustrated in Figure 5.12 suggest the Hawthorne Effect is present during the transition to microfactory production. The microfactory implementation occurs between Q2-98 and Q3-98 during which time it can be seen in Figure 5.12 that absenteeism is reduced from earlier pre-microfactory levels. This extended into the fourth quarter of 1998; however, with the return of absentee hours to earlier levels by Q1-99, the effect appears to no longer be present by the first quarter of 1999. Accordingly, it is surmised by the Investigator that any Hawthorne Effect is transitory and does not remain after the microfactory is fully implemented.

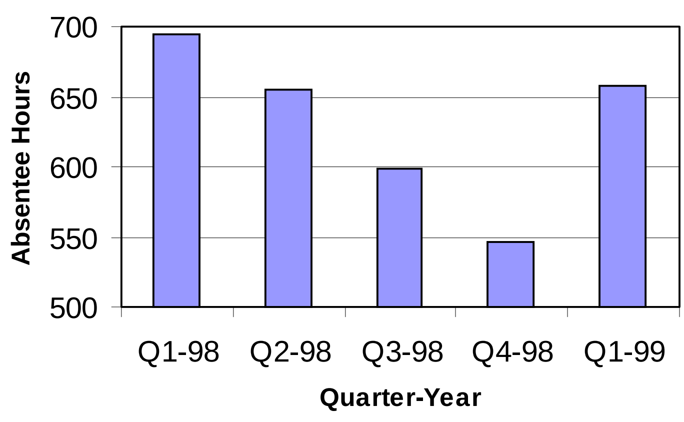


Figure 5.12. Total Absentee Hours per Quarter for Ten Employees Involved in the Transition to Microfactory Production

Chapter 6

Conclusions and Recommendations

Chapter 6 presents statements of fact that can be deduced from the results detailed in Chapter 5 and argues against the acceptance of the null hypothesis. In addition, the Investigator suggests areas of investigation that might be pursued in future research and lessons learned during the conduct of the research.

6.1 Overview of the Research Goal

The goal of the research is twofold. First and foremost, the goal is to investigate the acceptability of the null hypothesis presented in Section 1.1.2. Secondly, the goal is the accomplishment of an actual field implementation of the microfactory concept through the automation, simplification, and decentralization of a targeted product series (i.e., the T series) of electronic transceiver modules and the overall value stream in which the T series module production resides. The results of the research are organized in terms of the three research objectives presented in Section 1.1.3. The first objective encompasses the development of a microfactory and supporting multiple-microfactory architecture based on automation, simplification, and decentralization. The second objective is the demonstration of the microfactory concept as a prototype in a real world production environment. The third objective entails the performance comparison of the deployed microfactory with pre-microfactory performance. Each of these objectives is accomplished during the research and a comparison of performance as required by the third objective is completed.

6.2 Performance Data and the Research Hypothesis

The hypothesis, detailed in Section 1.1.2, which forms the basis for the research conducted is as follows:

IF an electronics module assembly activity is altered in the following ways:

- Comprehensive automation of assembly processes
- Simplification of production practice through a minimization of operator interaction and a reduction of assembly transaction points requiring operator intervention
- Restructuring of organizational functions through decentralization and simplification of a centralized configuration to provide organizational and operational autonomy to the assembly activity

THEN will the following parameters change:

- Throughput Time – The time from receipt of order to shipping of product
- Labor Cost – The cost of labor to produce the product
- Overhead Cost – The cost of associated overhead activities comprised of administration, finance, manufacturing technology, human resources, quality, and information technology costs
- Total Product Cost – The total cost of producing a product
- Production Quality – The failure rates for functional tests and time tests

The hypotheses are as follows:

H_0: The parameters (throughput time, labor cost, overhead cost, total product cost, and production quality) do not change.

H_1: The parameters (throughput time, labor cost, overhead cost, and total product cost) decrease without degrading production quality (i.e., production quality does not change).

The two hypotheses represent: 1) no change (i.e., the null hypothesis, H_0); and 2) throughput time and cost performance improvement without degrading production quality (i.e., the alternative hypothesis, H_1). If the null hypothesis is successfully rejected, then it would be shown that the implementation of the microfactory concept through automation, simplification, and decentralization results in an enhancement of production performance (i.e., a reduction in throughput time, labor cost, overhead cost, and total product cost) without degrading production quality. As discussed previously, each of the change ("IF") conditions (i.e., automation, simplification, and decentralization) are implemented during the research. Before and after performance data are acquired that indicate the following performance changes in the "THEN" parameters:

- *Throughput Time*
  - Decreases from 17 days to 3 days.

- *Labor Cost*
  - When analyzed using Wilcoxon Signed Rank testing for one-tailed statistical significance, a statistically significant (i.e., $p \leq 0.05$) reduction is shown in labor cost data after implementation of the microfactory.

- *Overhead Cost*
  - When analyzed using Wilcoxon Signed Rank testing for one-tailed statistical significance, a statistically significant (i.e., $p \leq 0.05$) reduction is shown in overhead cost data after implementation of the microfactory.

- *Total Product Cost and Total Product Cost Excluding Material Cost and Material Burden*
  - When analyzed using Wilcoxon Signed Rank testing for one-tailed statistical significance, a statistically significant (i.e., $p \leq 0.05$) reduction is shown in total product cost data and total product cost excluding material cost and material burden cost data after implementation of the microfactory.

- *Production Quality*
  - When analyzed using Wilcoxon Signed Rank testing for one-tailed statistical significance (i.e., $p \leq 0.05$), no statistically significant difference is shown in test failure rate data after implementation of the microfactory.

A possible interpretation of these results is that the implementation of the microfactory concept based on automation, simplification, and decentralization did result in a reduction in the labor cost, overhead cost, and total product cost and did not result in a degradation in production quality. Based on this, the **null hypothesis is *successfully rejected*** and it is maintained that the data suggest the implementation of the microfactory concept through automation, simplification, and decentralization have resulted in enhanced performance and the **alternative hypothesis is *accepted***.

The Investigator believes this result supports work conducted by other researchers in the field. Eversheim et al. [74] are addressing issues of product design and process planning and have proposed decentralized autonomous production cells (APC's) as a possible solution to shorten order processing cycles. In a manner similar to the microfactory concept, these APC's are self-reliant production activities that can function over long production periods without external intervention. Van Assen et al. [75] are also studying decentralized architectures to increase agility with emphasis on manufacturing planning and control. In the Van Assen et al. [75] model, the production organizational structure is based on a series of decentralized systems which are comprised of similar modules spanning order processing through production activity control. Cochran et al. [76] have conducted research into production system decentralization in which the production architecture is decentralized into organizational sub-units dedicated to integrated processes. In a manner similar to the microfactory model and associated supporting resources, the Cochran et al. [76] archetype is distinguished by indirect functional sub-units that support production sub-units.

6.3 Future Research Opportunities

As discussed in Section 2.7: "Basis for the Research," the microfactory draws on holonic, fractal, and focused factory concepts to demonstrate an NGMS implementation in a real world manufacturing environment. The microfactory is a facility-level, self-managed, autonomous production activity that receives strategic direction from higher level corporate management elements. McDonald [77] observes, "A self managing organization is quickly becoming the new paradigm of business." The Investigator believes methods and architectures for implementing this concept of autonomous self-management is a promising area of future research and suggests an analysis of the extent to which the technical chain of command reflects (i.e., tracks) the administrative bureaucracy.

Such research would be based on the postulation that in any production organization there are, in essence, two chains of command, administrative and technical. The administrative chain of command would be a formalized, documented series of executive positions in order of authority. Invariably (and unintentionally), the administrative organizational structure may spawn a secondary "technical" chain of command as a more expedient counterbalance to the official administrative bureaucracy. This technical hierarchy, which may never be formally documented, would exist as a shadowy organizational structure that may circumvent administrative aegis. To illustrate this concept, consider the technical information flow shown in Figure 6.1.

One would normally think that the problem-solving process shown in Figure 6.1 would be well documented. The Investigator believes that the need to rapidly respond to issues that impact production performance (and associated financial performance) requires such extensive flexibility that the process is not easily formalized. Spear and Bowen [78] suggest the Toyota Production System has succeeded using a similar dichotomy, stating:

> So why has it been so difficult to decode the Toyota Production System? The answer, we believe, is that observers confuse the tools and practices they see on their plant visits with the system itself. That makes it impossible for them to resolve an apparent paradox of the system -- namely, that activities, connections, and production flows in a Toyota factory are rigidly scripted, yet at the same time Toyota's operations are enormously flexible and adaptable. Activities and processes are constantly being challenged and pushed to a higher level of performance, enabling the company to continually innovate and improve.

As an example of this paradox between rigid administration and unformalized technical actions, during the research the Investigator observed that when a process issue halts production, all available resources may become focused on resolving the issue regardless of administrative allegiance. Plonka [38] notes that such a response is considered an integral part of lean and agile enterprises (Sections 2.4.3 and 2.4.4), observing that, "Workers have to look beyond loading parts in machines. They will need to be continually involved with the process and to intervene when required."

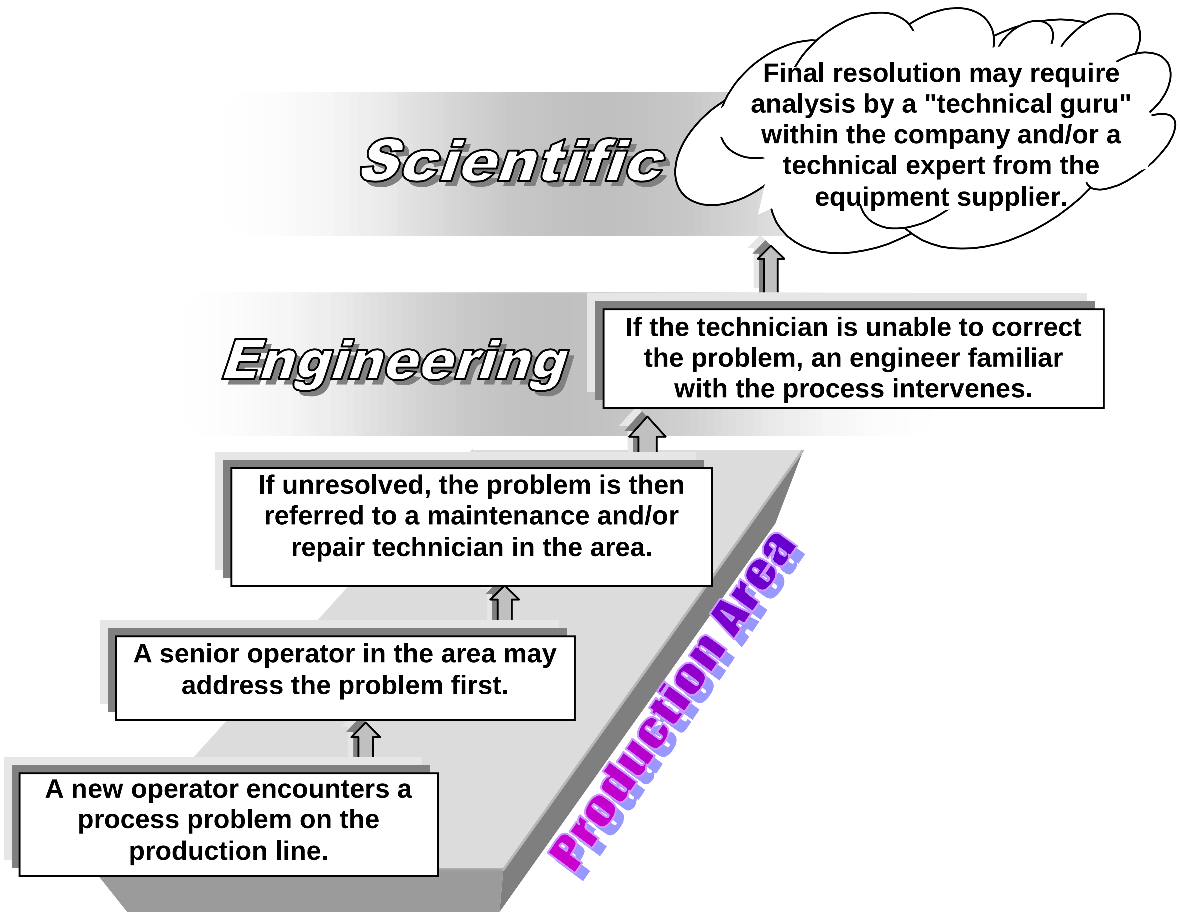


Figure 6.1. Example of Technical Information Flow

This need for rapid response may be the key driver for any manifestation of a technical counterbalance. Vertically, the technical chain of command may often follow the chain of administrative authority, because one may surmise that technical issues tend to move up administrative levels. However, it may be that the more bureaucratic and lethargic the administrative hierarchy, the more the technical chain of command deviates from the administrative hierarchy. Furthermore, a highly efficient administrative hierarchy may assist rather than hinder a rapid technical response to production issues, thus remediating the need for the response to "short circuit" the formal bureaucracy.

A further area of investigation is indirectly suggested by Figure 6.1. Usually, operators and technicians must be physically present on the line during a production run to operate and maintain machinery. On the other hand, the actual production process does not require the physical attendance of engineering staff unless a process issue that requires physical intervention by engineering occurs. Also, an engineer may be able to access electronically near real time production performance information through an Internet connection. In essence, he or she can monitor near real time production performance from almost anywhere in the world using a laptop computer, wireless modem, videoconferencing software, and a cellular telephone. The nature of the engineering function and the availability of remote data access form the basis for an investigation into the development of a working environment contributing to off-site interaction with production activities. As part of such an investigation, future research could consider a work shift for engineering staff that integrates a balance between telecommuting and more traditional attendance-based employment practice. A scheduling policy that recognizes three levels of work shift attendance might be envisioned.

- On-Site: The engineer is required to be physically present in the plant for periodic meetings, research and development issues requiring physical interaction, and production matters that require physical intervention by engineering.

- On-Call: The engineer is remotely linked, but can be present at the plant within 30 minutes of notification. On-call engineers would be available to support all production activities as needed.

- Telecommute: The engineer is remotely linked off-site with no location restrictions. Telecommuting is valid for computer-based tasks that can be accomplished with remote data access and videoconferencing.

It is anticipated that the integration of telecommuting into engineering staff scheduling will result in increased employee satisfaction and an associated increase in job performance.

However, it should be emphasized that the successful integration of telecommuting may require the prudent application of this option since the appropriate level of off-site activity may be found to be largely dependent upon the individual employee. The researcher should consider that remote site activities lack the social interaction and the general camaraderie of an office environment. Accordingly, it may be found that telecommuting implementations should support periodic on-site meetings and set a minimum on-site attendance requirement. In addition, the research should investigate the advantages of required seminars that discuss issues associated with telecommuting and provide a suggested framework for accomplishing off-site activities.

The internal validity of an experiment refers to the confidence with which one can conclude that, in fact, the independent variable did indeed produce the performance enhancements that were observed. To increase the internal validity of the microfactory performance comparison experiment, a control group/treatment group experimental design (as described in Section 4.1) was used. External validity, on the other hand, refers to what extent the findings of the study can be generalized to a larger set of applications. If the results can be generalized to an entire range of manufacturing environments, then the experimental results can be said to have a high external validity. In general, one can investigate the level of external validity through repetition of the experiment (i.e., implementation of the microfactory concept) across a wide range of manufacturing environments. This being the case, another area for future research is the study of external validity or generalizability of the microfactory concept in manufacturing environments other than the electronic module assembly application investigated in this research.

As discussed in Section 1.1.1, the Investigator believes that the generalizability of the microfactory is limited to manufacturing environments experiencing rapid technological change resulting in significant market fluctuations and associated shortened (i.e., less than two year) product lifecycles. The need for rapid response to such change requires an ability to approach a single product unit, build-to-order capability, a requirement that is directly addressed by the strengths of the microfactory concept. However, the Investigator anticipates the small, decentralized manufacturing elements which make up the microfactory concept will not be able to compete on a cost basis in industrial environments characterized by incremental technological change, slowly changing markets, and long lifecycle products such as the basic paper industry where small incremental changes in technology are introduced to the market almost entirely on the basis of reduced production cost. In such environments, the Investigator believes that centralized, highly integrated production processes will prove to be more cost effective than a microfactory architecture.

The crux of the research was the implementation of the microfactory concept in a real world manufacturing environment, during which time, several lessons were learned about the practicality of conducting research in such an environment. In a real world situation, the Investigator must first work to resolve the basic conflict between the desire to conduct research in a "laboratory-like" manner and the business requirements of the company hosting the research. As a research project, whether for a thesis or a dissertation, a student will need to connect with a "champion" within the company who can smooth and expedite the business arguments for the research. The student must also realize that a considerable portion of the work needed to conduct the research will be preliminary groundwork requiring significant effort before the actual research can be started.

In addition to making a business case for the research, the researcher will need to work within the measurement constraints of the company bureaucracy. In general, detailed customized measurement by a single researcher at the machine level is relatively easy to implement and will be allowed by the company as long as it does not impact production flow. However, for higher level organizational research by a single student, a practical plan will need to utilize existing measurement resources. In the case of the microfactory implementation, the utilization of existing measurement resources was an acceptable solution. The Investigator made the argument to company management that the implementation of a microfactory will improve business for the company. The evidence for this would be a reduction in cost and throughput time, both parameters already being measured by the company and recognized as indicators of business performance. However, once the case was made, the company wanted to implement the microfactory across all production activities leaving the Investigator with no control group products. Fortunately, the Investigator was able to delay the introduction of the microfactory concept to the control group products long enough to allow treatment group and control group data to be collected.

As a result, enough data were acquired to allow a Wilcoxon Signed Rank test for statistical significance. The conclusions reached from this statistical test (as detailed in Section 6.2) are that the implementation of the microfactory did indeed improve the business performance of the company. Furthermore, even though quantification of the cost savings resulting from the microfactory implementation was beyond the scope of the research effort, a Return-on-Investment analysis completed before the implementation of the microfactory estimated that a $2.9 million investment would be required with a positive return by the end of the first year of operation. In actuality, implementation of the microfactory required an investment of approximately $2.3 million which was recovered within the first three quarters of operation. In addition, company financial reports have indicated that during the first three years of operation the microfactory remained the low cost leader internally within the company and externally in the marketplace for its product family.

Bibliography

[1] C. Terwiesch and R. E. Bohn, "Learning and Process Improvement During Production Ramp-Up," *International Journal of Production Economics*, vol. 70, no. 1, pp. 1-19, Mar. 2001.

[2] M. A. Hitt, "Transformation of Management for the New Millennium," *Organizational Dynamics*, vol. 28, no. 3, pp. 6-17, Winter 2000.

[3] R. J. Calantone and C. A. Di Benedetto, "Performance and Time to Market: Accelerating Cycle Time with Overlapping Stages," *IEEE Trans. Eng. Manage.*, vol. 47, no. 2, pp. 232-244, May 2000.

[4] C. H. St. John, A. R. Cannon, and R. W. Pouder, "Change Drivers in the New Millennium: Implications for Manufacturing Strategy Research," *Journal of Operations Management*, vol. 19, no. 2, pp. 143-160, Feb. 2001.

[5] G. Stalk, Jr., "Time – The Next Source of Competitive Advantage," *Harvard Business Review*, vol. 66, no. 4, pp. 41- 51, Jul./Aug. 1988.

[6] R. G. Askin and C. R. Standridge, *Modeling and Analysis of Manufacturing Systems*. New York: John Wiley & Sons, Inc., 1993.

[7] S. Ashley, "Manufacturing Firms Face the Future," *Mechanical Engineering*, vol. 119, no. 6, pp. 70-74, Jun. 1997.

[8] L. Wang, " Integrated Design-To-Control Approach for Holonic Manufacturing Systems," *Robotics and Computer Integrated Manufacturing*, vol. 17, no. 1-2, pp. 159-167, 2001.

[9] C. S. Osborn, "Systems for Sustainable Organizations: Emergent Strategies, Interactive Controls and Semi-Formal Information, *Journal of Management Studies*, vol. 35, no. 4, pp. 481-509, Jul. 1998.

[10] C. Y. Baldwin and K. B. Clark, "Managing in an Age of Modularity," *Harvard Business Review*, vol. 75, no. 5, pp. 84-93, Sep./Oct. 1997.

[11] K. Hitomi, *Manufacturing Systems Engineering*. London: Taylor & Francis, 1996.

[12] U. Rembold, B. O. Nnaji, and A. Storr, *Computer Integrated Manufacturing and Engineering*. New York: Addison-Wesley Publishing Company, 1993.

[13] J. Pereira and B. Paulre, "Flexibility in Manufacturing Systems: A Relational and a Dynamic Approach," *European Journal of Operational Research*, vol. 130, no. 1, pp. 70-82, Apr. 2001.

[14] J. L. Sampler and J. E. Short, "Sustainability of New Organizational Arrangements," *Journal of Management Studies*, vol. 35, no. 4, pp. 413-415, Jul. 1998.

[15] D. Lerner, *The Passing of Traditional Society*. Glencoe, Illinois: The Free Press, 1958.

[16] D. Bell, *The Coming of the Post-Industrial Society*. New York: Basic Books, Inc., 1973.

[17] H. T. Amrine, J. A. Ritchey, C. L. Moodie, and J. F. Kmec, *Manufacturing Organization and Management*. Englewood Cliffs, New Jersey: Prentice Hall, 1993.

[18] J. B. Sorensen and T. E. Stuart, "Aging, Obsolescence, and Organizational Innovation," *Administrative Science Quarterly*, vol. 45, no. 1, pp. 81-112, Mar. 2000.

[19] R. Pascale, M. Millemann, and L. Gioja, "Changing the Way We Change," *Harvard Business Review*, vol. 75, no. 6, pp. 126-139, Dec. 1997.

[20] M. Hammer and J. Champy, *Reengineering the Corporation: A Manifesto for Business Revolution*. New York: Harper Business, 1993.

[21] C. L. Berrington and R. L. Oblich, "Translating Business Reengineering Into Bottom-Line Results," *Industrial Engineering*, vol. 27, no. 1, pp. 24-27, Jan. 1995.

[22] J. Champy, *Reengineering Management: The Mandate for New Leadership*. New York: Harper Business, 1995.

[23] V. Grover, "From Business Reengineering to Business Process Change Management: A Longitudinal Study of Trends and Practices," *IEEE Trans. Eng. Manage.*, vol. 46, no. 1, pp. 36-46, Feb. 1999.

[24] L. V. Orman, "A Model Management Approach to Business Process Reengineering," *Journal of Management Information Systems*, vol. 15, no. 1, pp. 187-212, Summer 1998.

[25] N. N. Mitev, "Empowerment, Change, and Information Technology: Socio-Technical Design and Business Process Reengineering," *Personnel Review*, vol. 25, no. 4, pp. 56-66, Jun. 1996.

[26] S. H. Appelbaum, "Socio-Technical Systems Theory: An Intervention Strategy for Organizational Development," *Management Decision*, vol. 35, no. 5-6, pp. 452-463, May/Jun. 1997.

[27] W. Skinner, "The Focused Factory," *Harvard Business Review*, vol. 52, no. 3, pp. 113-121, May/Jun. 1974.

[28] G. F. Tannous and P. M. Mangiameli, "A Microeconomic Model for the Focused Factory-Vertical Integration Strategic Decision Problem," *Decision Sciences*, vol. 24, no. 1, pp. 209-217, Jan./Feb. 1993.

[29] K. Ueda, "A Concept for Bionic Manufacturing Systems Based on DNA-Type Information," *Human Aspects in Computer Integrated Manufacturing: Proceedings of the Eighth International PROLAMAT Conference*, Tokyo, pp. 853-863, Jun. 24-26, 1992.

[30] R. McCormack, "Biological Concepts Make Their Way Into Manufacturing," *Manufacturing News*, vol. 4, no. 27, Dec. 1997.

[31] A. Tharumarajah, A. J. Wells, and L. Nemes, "Comparison of the Bionic, Fractal and Holonic Manufacturing System Concepts," *International Journal of Computer Integrated Manufacturing*, vol. 9, no. 3, pp. 217-226, May/Jun. 1996.

[32] H. Warnecke, *The Fractal Company: A Revolution in Corporate Culture*. New York: Springer-Verlag, 1993.

[33] U. Venkatadri, R. L. Rardin, and B. Montreuil, "A Design Methodology for Fractal Layout Organization," *IIE Trans.*, vol. 29, no. 10, pp. 911-924, Oct. 1997.

[34] W. A. Spivey, J. M. Munson, and J. H. Wolcott, "Improving the New Product Development Process: A Fractal Paradigm for High-Technology Products," *Journal of Product Innovation Management*, vol. 14, no. 3, pp. 203-218, May 1997.

[35] J. P. Womack, D. T. Jones, and D. Roos, *The Machine that Changed the World*. New York: Simon & Schuster, Inc., 1990.

[36] J. P. Womack and D. T. Jones, *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. New York: Simon & Schuster, Inc., 1996.

[37] H. Noori and F. Mavaddat, "Enterprise Integration: Issues and Methods," *International Journal of Production Research*, vol. 36, no. 8, pp. 2083-2097, Aug. 1998.

[38] F. E. Plonka, "Developing a Lean and Agile Workforce," *Human Factors and Ergonomics in Manufacturing*, vol. 7, no. 1, pp. 11-20, Winter 1997.

[39] G. H. Lee, "Designs of Components and Manufacturing Systems for Agile Manufacturing," *International Journal of Production Research*, vol. 36, no. 4, pp. 1023-1044, Apr. 1998.

[40] R. DeVor, R. Graves, and J. J. Mills, "Agile Manufacturing Research: Accomplishments and Opportunities," *IIE Trans.*, vol. 29, no. 10, pp. 813-823, Oct. 1997.

[41] A. Gunasekaran, "Agile Manufacturing: Enablers and an Implementation Framework," *International Journal of Production Research*, vol. 36, no. 5, pp. 1223-1247, May 1998.

[42] C. Forsythe, "Human Factors in Agile Manufacturing: A Brief Overview with Emphasis on Communications and Information Infrastructure," *Human Factors and Ergonomics in Manufacturing*, vol. 7, no. 1, pp. 3-10, Winter 1997.

[43] M. Jung, M. K. Chung, and H. Cho, "Architectural Requirements for Rapid Development of Agile Manufacturing Systems," *Computers & Industrial Engineering: Proceedings of the 19th International Conference on Computers and Industrial Engineering*, vol. 31, no. 3/4, pp. 551-554, Dec. 1996.

[44] R. H. Weston, "Integration Infrastructure Requirements for Agile Manufacturing Systems," *Journal of Engineering Manufacture: Proceedings of the Institution of Mechanical Engineers, Part B*, vol. 212, no. B6, pp. 423-437, 1998.

[45] M. D. Reimann and J. Sarkis, "An Infrastructure for Agile Enterprise Product Development Systems," *Flexible Automation and Intelligent Manufacturing 1996: Proceedings of the Sixth International FAIM Conference*, Atlanta, pp. 57-66, May 13-15, 1996.

[46] A. Koestler, *The Ghost in the Machine*. New York: The Macmillan Company, 1967.

[47] H. Sun and P. K. Venuvinod, "The Human Side of Holonic Manufacturing Systems," *Technovation*, vol. 21, no. 6, pp. 353-360, 2001.

[48] IMS International, *IMS Annual Progress Report 2000*. Tokyo: IMS International, 2000.

[49] J. Cselenyi and T. Toth, "Some Questions of Logistics in the Case of Holonic Production Systems," *Journal of Intelligent Manufacturing*, vol. 9, no. 2, pp. 113-118, Apr. 1998.

[50] P. Valckenaers, H. Van Brussel, J. Wyns, L. Bongaerts, and P. Peeters, "Designing Holonic Manufacturing Systems," *Robotics and Computer-Integrated Manufacturing*, vol. 14, no. 5/6, pp. 455-464, Oct./Dec. 1998.

[51] R. W. Bagshaw and S. T. Newman, "Production Code Generation and Manufacturing Analysis within a Holonically Enhanced Small Manufacturing Enterprise," *Proceedings of the 10th International Conference on Flexible Automation and Intelligent Manufacturing*, College Park, Maryland, pp. 1056-1065, Jun. 26-28, 2000.

[52] V. Sambamurthy and L. J. Kirsch, "An Integrative Framework of the Information Systems Development Process," *Decision Sciences*, vol. 31, no. 2, pp. 391-411, Spring 2000.

[53] F. K. Sen and W. G. Egelhoff, "Innovative Capabilities of a Firm and the Use of Technical Alliances," *IEEE Trans. Eng. Manage.*, vol. 47, no. 2, pp. 174-183, May 2000.

[54] J. B. Quinn, "Outsourcing Innovation: the New Engine of Growth," *Sloan Management Review*, vol. 41, no. 4, pp. 13-27, Summer 2000.

[55] L. Ming, Y. Xiaohong, M. M. Tseng, and Y. Shuzi, "A COBRA-Based Agent-Driven Design for Distributed Intelligent Manufacturing Systems," *Journal of Intelligent Manufacturing*, vol. 9, no. 5, pp. 457-465, Oct. 1998.

[56] L. Wang, S. Balasubramanian, D. H. Norrie, and R. W. Brennan, "Agent-Based Control System for Next Generation Manufacturing," *Proceedings of the 1998 IEEE International Symposium on Intelligent Control (ISIC)*, Gaithersburg, Maryland, pp. 78-83, Sep. 14-17, 1998.

[57] J. F. Rockart, "Towards Survivability of Communication-Intensive New Organization Forms," *Journal of Management Studies*, vol. 35, no. 4, pp. 417-420, Jul. 1998.

[58] S. Kalpakjian, *Manufacturing Engineering and Technology*. New York: Addison-Wesley Publishing Company, 1995.

[59] J. Harrington, Jr., *Understanding the Manufacturing Process*. New York: Marcel Dekker, Inc., 1984.

[60] N. Singh, *Systems Approach to Computer Integrated Design and Manufacturing*. New York: John Wiley & Sons, Inc., 1996.

[61] M. Rother and J. Shook, *Learning to See*. Brookline, Massachusetts: Lean Enterprise Institute, Inc., 2000.

[62] U. S. Bititci, P. Suwignjo, and A. S. Carrie, "Strategy Management Through Quantitative Modelling of Performance Measurement Systems," *International Journal of Production Economics*, vol. 69, no. 1, pp. 15-22, Jan. 2001.

[63] A. M. Ghalayini, J. S. Noble, and T. J. Crowe, "An Integrated Dynamic Performance Measurement System for Improving Manufacturing Competitiveness," *International Journal of Production Economics*, vol. 48, no. 3, pp. 207-225, Feb. 1997.

[64] D. W. Martin, *Doing Psychology Experiments*. New York: Brooks/Cole Publishing Company, 1996.

[65] C. H. Kraft and C. Van Eeden, *A Nonparametic Introduction to Statistics*. New York: The Macmillan Company, 1968.

[66] H. L. Alder and E. B. Roessler, *Probability and Statistics*. San Francisco: W. H. Freeman and Company, 1977.

[67] J. E. Freund and R. E. Walpole, *Mathematical Statistics*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1980.

[68] J. V. Bradley, *Distribution-Free Statistical Tests*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1968.

[69] D. Salvatore, *Theory and Problems of Statistics and Econometrics*. New York: McGraw-Hill, Inc., 1982.

[70] R. A. Fisher, *Statistical Methods and Scientific Inference*. New York: Hafner Press, 1973.

[71] J. R. Canada, W. G. Sullivan, and J. A. White, *Capital Investment Analysis for Engineering and Management*. Upper Saddle River, New Jersey: Prentice Hall, Inc., 1996.

[72] Bureau of Labor Statistics, U. S. Department of Labor, *Consumer Price Index Report*. Washington, D. C.: Office of Publications, Bureau of Labor Statistics, 2001.

[73] S. R. G. Jones, "Was There a Hawthorne Effect?," *American Journal of Sociology*, vol. 98, no. 3, pp. 451-468, Nov. 1992.

[74] W. Eversheim, A. Haufe, W. Kolcheid, M. Walz, and N. Michaias, "Integrative Structure for Flexible Product Design and Manufacturing Planning," *Human Factors and Ergonomics in Manufacturing*, vol. 10, no. 3, pp. 343-353, Summer 2000.

[75] M. F. Van Assen, E. W. Hans, and S. L. Van de Velde, "An Agile Planning and Control Framework for Customer-Order Driven Discrete Parts Manufacturing Environments," *International Journal of Agile Management Systems*, vol. 2, no. 1, pp. 16-23, 2000.

[76] D. S. Cochran, W. Eversheim, G. Kubin, and M. L. Sestermenn, "The Application of Axiomatic Design and Lean Management Principles in the Scope of Production System Segmentation," *International Journal of Production Research*, vol. 38, no. 6, pp. 1377-1396, Apr. 2000.

[77] T. McDonald, "Beyond Empowerment," *Successful Meetings*, vol. 47, no. 2, Feb. 1998.

[78] S. Spear and H. K. Bowen, "Decoding the DNA of the Toyota Production System," *Harvard Business Review*, vol. 77, no. 5, p. 97, Sep./Oct. 1999.

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