Impact of Manufacturing System Design, Organizational Processes and Leadership on Manufacturing System change and Implementation

by

Abhinav Shukla

Bachelor of Technology, Mechanical Engineering
Indian Institute of Technology, Bombay, 1999

Submitted to the Massachusetts Institute of Technology
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 2001

Signature of Author ______________________________
Department of Mechanical Engineering
May 11, 2001

Certified by ______________________________
David S. Cochran
Assistant Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ______________________________
Professor Ain Sonin
Chairman, Committee on Graduate Studies

Impact of Manufacturing System Design, Organizational Processes and Leadership on Manufacturing System change and Implementation

by

Abhinav Shukla

Submitted to the Department of Mechanical Engineering on May 11, 2000
in Partial Fulfillment of the Requirements for the Degree of
Master of Science

ABSTRACT

Manufacturing system design methodologies often ignore the importance of enterprise related issues that affect the implementation and improvement efforts. Systems Engineering provides a rigorous approach to system design and coupled with a decomposition approach can result in effective system design. Manufacturing system design must be linked to the strategy and objectives of the firm. The decomposition ensures that low-level design decisions are related to the higher-level objectives of the firm. Manufacturing system design is a complicated process that involves all sections of the manufacturing organization; systems engineering provides the rigor to guide the design and implementation process through various phases and ensures that the design is comprehensive.

However, the manufacturing organization cannot function independent of the enterprise. Often projects aimed at implementing effective system designs fail as the organizational processes are not aligned and the system is not prepared for the change. Leadership owns the responsibility for aligning interfaces and processes to facilitate change.

The thesis is aimed at providing a case study based illustration of the above discussion that highlights certain causes of poor systemic performance. Finally the thesis proposes a methodology that combines some of the pioneering research at the Production System design Laboratory in the area of manufacturing system design to the systems engineering approach and relates these to issues of strategy, organizational processes and alignment of enterprise interfaces.

Thesis Supervisor: Professor David S. Cochran

Acknowledgements

I am grateful to Ford Motor Co. and Visteon Automotive Systems for supporting my education at MIT and giving me the opportunity to work at their plants. I would specifically like to thank Mark Winters and Victor Carillo of the Mexican plants as well as Bart Hogarth and Al Tervalon, Director (Quality), Visteon Automotive Systems.

The thesis and indeed my graduate studies are greatly indebted to Prof. David S. Cochran whose approach to production system design and his keen insights to business implications of the former have greatly influenced my thinking. Going forward, I hope I would have more opportunities to interact with you at a professional level. Your faith and conviction in my abilities and continuous support and guidance has been the cornerstone of my studies at MIT. The emphasis on decomposing objectives into requirements and separating them from the means is an interesting way of thinking that I have learnt from you.

The ambition to graduate from MIT was one that I shared with my mother since I was in secondary school and she was always there to extend her support and keep me focused. I know my graduation brings her great joy and that makes it even more special for me. It has always been so easy to relate to you; from corny jokes to my love life there has never been anything hidden from you. Papa, the times that I turned to you for advice always made me feel that there was so much more that I could learn from you; your incredible maturity and sensitivity had the effect of inspiring me to achieve more and every time I did you would always be so pleasantly surprised. Like you did not expect it, and the fact that it happened made you feel so happy. I am so glad you did, it always made every thing so special. I am sure you must have actually felt blessed when I first walked and talked, which I did quite soon, did'nt I?

Gaurav, 'Bhaiya' and as the South Indians say 'Anna', you have consistently graduated from being older loving brother, to bully bro, to sporting rival and now to great friend. From common dislike for girls in our early days to shared passion for bikes and sports cars and everything that is fast and hot, we have come a long way as friends. I never have to remind myself that you are an older brother. I love it that way.

A strong contribution to preparing me for graduate studies at the world's best technical institution comes from Asia's best, the MIT of the East, the Indian Institute of Technology, Bombay. I have often felt it took the life energy out of me to prepare for those manic like problems in vector calculus and ethereal chemistry and clear the Joint Entrance Examination. When I did, and two times over (one time later for kicks) at that, I felt confident that I could prepare for any examination on the face of the earth, so long as it involved analytical thinking and problem solving. The emotional maturity that I developed staying in a hostel with 300 incredibly intelligent guys for four years and still manage to retain both top grades and my self-confidence made me feel ready for most challenges in life. It also made me wiser about my self and I realized that it was not realistic to expect to be great at everything. One must discover one's niche and be comfortable with it. The friends that I made at school, I am sure would in years to come rank as one of my life's most significant gains.

All organizations that I have worked for have had a role in shaping me. Marketing and advertising projects during internships at MARG and HTA, made me first experience financial independence. And it increased my appetite for more. Work at Schlumberger Inc. as field engineer, was a test in physical endurance and mental abilities. Surviving in 120 degree, 99% humidity off shore conditions for 72 hours at a stretch without sleep and still being able to think sharply, quickly and decisively makes me feel confident that if I did dose off at meetings ever, I could blame it on the speaker. Ford and Visteon provided great opportunities for work in production system design that laid the foundation for my studies at MIT. Four months as Summer Associate with McKinsey & Co. have convinced me that Management Consulting was the right place for me after graduation. Their professionalism on the projects and the mentoring and learning I received will surely help me later in my career. Refusing their offer for work has been a very tough personal decision for me.

I would like to thank all my friends at MIT, from those I knew from IIT-B, Mahesh, Chaitanya, Shyam etc. to those whom I developed close ties with here. Raj, I knew you from secondary school and you have made my stay so much more enjoyable. You have been my fashion advisor, club guide, hangout buddy and friend. David Estrada, whom I worked with on the Coclisa project, would always be a special friend to me. Not only is his contribution to this Thesis invaluable but he has also been one of my first few friends in the USA. The time spent with him and his family and friends at El Paso would be especially memorable for me. The Production System Design Laboratory has allowed me the opportunity to interact with some of the brightest minds and warmest souls. Jorge, Jim, Jose and Jochen as senior members were always there for advice. The rest of the gang from Ania, Brandon, Cesar, Carlos, Deny, Guillermo, Jongyoon, Jey, Keith, Kola, Quinton, Yong Suk to Zhenwei have all at different times done so many special things for me that its hard for me to thank them enough. Jacqueline although not a formal member of the Lab, her presence this semester has been very special for me. Spanish lessons received from you will help me remember you forever. And for once I could abuse Cesar in Spanish. Pinche' Cesar!

My other friends at MIT and I would honestly need to publish another thesis to be able to cover all names and anecdotes, but you know who you are. From buddies who have accompanied me to Frat parties in the UG party scene at MIT and parties in Boston to those whom I have collaborated with on course projects and those that I just happen to know because we bumped into each other quite often, you have all made distinct impressions on me that would be hard to replace. Gemma, Ralph and Lauren the England trip was great; the next destination is India. Jim, Bukola, Miriam, Mark, Tamara, Gaurav, Gokul, Anurag, Damien, Anne, Joe, Laura, Jeff, Liev, Ayla, Ben, Nicky….I am so going to be sued for leaving friends out.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AGV: Automated Guided Vehicle

AHP: Analytic Hierarchy Procedure

CI: Consistency Index

CNC: Computer Numerically Controlled

CR: Consistency Ratio

DP: Design Parameter

FMS: Flexible Manufacturing System

FR: Functional Requirement

IDEF: Integrated computer-aided manufacturing DEFinition

JIT: Just-In-Time

MRP: Manufacturing Resource Planning

MSD: Manufacturing System Design

MSDD: Manufacturing System Design Decomposition

MTTF: Mean Time to Fail

MTTR: Mean Time to Repair

PM: Performance Measure

QFD: Quality Function Deployment

ROI: Return On Investment

SPC: Statistical Process Control

TPS: Toyota Production System

TQM: Total Quality Management

Chapter 1 Introduction

The 'beer game' first developed in the 1960's at the Massachusetts Institute of Technology's Sloan School of Management is a laboratory replica that allows separation of disruptions from their causes more acutely than is possible in organizations. By placing participants in a widely prevalent but not so extensively understood production/distribution situation of consumer commercial goods [Peter Senge, 1990], it helps reveal problems that originate in systemic thinking of participants and their mental models than highlight peculiarities of organization structure or policy.

The beer game has been widely played all across the world since its inception by individuals in a diverse spectrum of age, education, culture, language and business experience, yet they produce qualitatively very similar results. The cycle of growing demand, followed by creation of large orders in the face of depleting inventories and growing backlogs slowly transitioning to en masse arrival of beer that coincides with diminishing orders and high inventory levels at the end. Peter Senge argues that if thousands of diverse individuals produced the same qualitative behavior patterns, then the cause of the behavior has to lie outside the individuals and within the structure of the system itself.

In the late 80's, General Motors, Ford and Chrysler were all producing more cars than they could sell with surges in demand and inventory over adjustments, due to what economists call the 'inventory accelerator' theory of business cycles. The path breaking five-year research by the IMVP program at the Massachusetts Institute of Technology in early 1980's on the future of the automobile, uncovered the secrets of the Japanese system of production that they chose to term *lean production system*. It demonstrated for the first time that reasons for the Japanese success in automobile production management lay with the design of their systems. These widely experienced dynamics of production-distribution systems illustrate a basic principle in systems thinking: Systems similar in structure produce similar responses in individuals and hence identical results. More succinctly, structure of systems influences its behavior. Almost as a corollary, system designers have potential leverage that they often do not exercise.

A manufacturing system can be defined as a collection of components (machines, equipment, people, etc.) bound by common material and information flow and working together to transform raw materials into marketable goods (adapted from Chryssolouris, 1992 and Wu, 1992). Integrating a variety of operations into one unified system that is capable of meeting all of the required demands requires effective communication among multiple disciplines and a methodology that enables the system designers to understand how design details interact and affect overall system performance.

1.1 Thesis Motivation

In the preceding passages, an argument has been made for the importance of system structure in influencing behavior and affecting performance. At the highest level, the structure of the system should influence behavior that supports the objectives of the firm. Two things become crucial here; translation of the business or corporate vision into objectives and coherent strategy for manufacturing that influences low level design decisions in accordance with high level objectives and finally a way to separate the objectives from the means of their achievement. This requires an understanding of the inter-relationship between the different elements of a system and effective communication of information across a manufacturing organization. Since system structure is a function of the design process, manufacturing system design becomes crucial to system performance. Unsatisfactory manufacturing system performance often evolves as the result of a system design focus that is too localized, that is too narrow in scope, that is overly simplistic, that is on the means and not the ends, or that is otherwise not aligned to the firm's overall manufacturing strategy.

Manufacturing systems have traditionally been designed in an ad-hoc and non-holistic manner with parts being designed independently of others. The system design is often not linked to firm objectives that are defined through the manufacturing strategy. Even when the strategy is well defined and linked to the system design there are problems in keeping the objectives separate from the means. This separation is essential as the converse leads to systems copying 'tools' from successful manufacturing philosophies like the TPS without an appreciation of the systemic requirements for successful implementation. Thus there are instances of systems trying to achieve JIT by slashing inventories or installing Kanban systems between successive pairs of processes in 15 minutes [Schonberger, 1990]. Although a Kanban system can be installed in short time, designing the manufacturing system in such a way that would allow the Kanban system to produce desired results is more crucial [Hopp and Spearman, 1996, James Duda, 2000, Cochran, 1999].

Based on a pattern identified in its research projects particularly during the implementation phase, a hypothesis of the crucial elements involved in successful 'lean' manufacturing design implementation and operation is proposed. These elements have at their foundation, effective system design philosophies and methodologies an area where the PSD has contributed the axiomatic design based decomposition approach. This approach proposes high-level system/business objectives and their subsequent decomposition to functional requirements at lower levels, until implementation in the physical domain to satisfy these requirements is possible.

This Thesis highlights the dynamic interplay of these factors through a Case Study discussion. The case study describes the re-design and implementation of a manufacturing system. During the pilot phase of the project, significant benefits were achieved on all relevant measures of performance. The benefits and impact of change were extensive in scope and covered both fabrication and assembly areas; material handling and information flow aspects of production but were limited in scale. The limitation of scale was not a function of the system design but the implementation process that was hindered by organizational issues of leadership and inert processes that were ingrained in the system from poor design and practice. The external environment provided a further incentive for the system to remain inert and unresponsive to changes in manufacturing practices.

From the above discussion the connection between system design, strategy and performance becomes apparent. The leadership is responsible for communicating the strategy to the line managers who in turn communicate the system requirements to the system designers and manufacturing engineers. The manufacturing strategy of the company should influence both the manufacturing system design as well as the set of organizational processes that measure and/or influence system performance. Alignment of performance measurement and management processes with system design helps to generate feedback loops that help take corrective measures as well as standardize system improvements. The information and control action communicated through these feedback loops thus becomes crucial. To ensure that the information is accurate and aligned towards meeting objectives from system performance, it is necessary that a) the system is designed such that low level design decisions are related to higher level objectives b) system operation and implementation reflects the system design c) performance measurement process highlights problem areas with the system design d) the system is designed to incorporate feedback for change and e) improvements and changes taking place in the system get standardized. Thus system design becomes essentially an iterative process with a planning, measuring, implementing and operating loop. Four elements crucial for the success of the production system can be identified. These are:

- Effective manufacturing system design methodology with implementation and decision support to system designers and engineers
- Favorable external environment – business climatic conditions that communicate changing business needs through manufacturing strategy, do not impose severe constraints on system design
- Organizational Processes especially of management accounting and performance measurement systems aligned towards objectives
- Organizational leadership that identifies strategy and also facilitates removal of obstacles by eliminating subjective constraints, misconceptions and re-aligning processes.

The thesis builds on this framework of thinking about the challenges in the manufacturing system design process and attempts to illustrate these observations in the context of a case discussion. Finally, an integrated methodology for designing systems is presented that addresses not only pure design aspects but also organizational and enterprise issues that relate to manufacturing system design.

1.2 Problem Statement

This thesis seeks to answer the following questions:

- What are the principal issues that surround the process of designing and implementing a manufacturing system? What does the actual implementation and operation process involve?
- What are important milestones in the process of designing, operating and improving a manufacturing system? How does the Manufacturing System Design Decomposition developed at the PSD, MIT fit into the design process vis a vis traditional system engineering approaches to design? Is there a comprehensive methodology to guide the design process?
- What is the role of the enterprise in the design of manufacturing systems? How can designers and managers ensure enterprise co-operation in the design process?

- What is the role-played by the leadership both at enterprise and plant level towards the re-design of manufacturing systems? What aspects of their role can help stabilize the system and prove beneficial to the change process?
- What are the Organizational Issues that prevent putting a stable manufacturing system in place? What are these barriers and how can they be removed?

Chapter 2 Classification of System Design Literature and Methodologies

Systemic structure is concerned with the key interrelationships that influence behavior over time. In a production system, this may include processing times, information transfer delays and reliability rates. "It is very important to understand that when we use the term 'systemic structure' we do not just mean structure outside the individual. The nature of structure in human systems is subtle because we are part of the structure. This means that we often have the power to alter structures within which we are operating." [Senge, 1990]. The last chapter identified the need for designing systemic structures that achieve business objectives by producing desired behavior and output from resources both human and physical. . Leverage often comes from new ways of thinking, [Senge, 1990]. These new ways of thinking about how to design and operate production systems will provide greater advancements than trying to optimize existing faulty system design.

The need for a structured approach to designing systems is significant as production system plays a significant and increasingly intensive role in the business, the industry and market, and society. At the same time the production system is a complex engineering system that is composed of technical elements of all natures, both human and mechanical. Every decision in production system design, implementation and control involves an interaction of objectives and solutions. There exist several frameworks and methods that classify a complete set of system objectives, from which a subset can be derived that describe the specific goals of a particular production system [Hayes, Pisano, 1996].

2.1 Definitions of System, Manufacturing System and Production System

A system is generally defined as a set of elements embodying specific characteristics. Between the elements are relations representing the functional connections of the elements. The system has a defined boundary to its environment and all elements exist within this boundary. Each element itself might be a subsystem.

A manufacturing system is a group of physical objects arranged to transform raw material into finished product. [Black, 1991] These physical objects include machines, tools, material handling equipment and people. Along with the raw material, a manufacturing system also requires information (customer orders, current system status), capital (money, equipment, fixed assets) and energy (labor, power, support resources) as inputs. The total output includes finished product, information, waste and profit. Manufacturing systems are affected by internal and external disturbances, and can be evaluated by measuring its intrinsic parameters (cost, time, quantity, area). A production flow value stream is a way of mapping a manufacturing system. "A value stream is all the actions (both value-added and non-value-added) currently required to bring a product through the main flows essential to every product: the production flow from raw material into the arms of the customer." [Rother, Shook, 1998]. The customers of the manufacturing system are those who receive finished product from the system [Carrus, 2000]. Depending on how the system boundaries are defined, the customer of the manufacturing system value stream may be a retailer, a distribution channel, a processing plant, or a downstream function in the same plant.

The production system includes the manufacturing system and all functions required for the support, operation and control of the manufacturing system. Maintenance, engineering, human resources, accounting, sales and marketing are examples of resources that are part of the production system. Figure 2-1 shows a graphical representation of production systems. [adapted from Cochran, 1994].

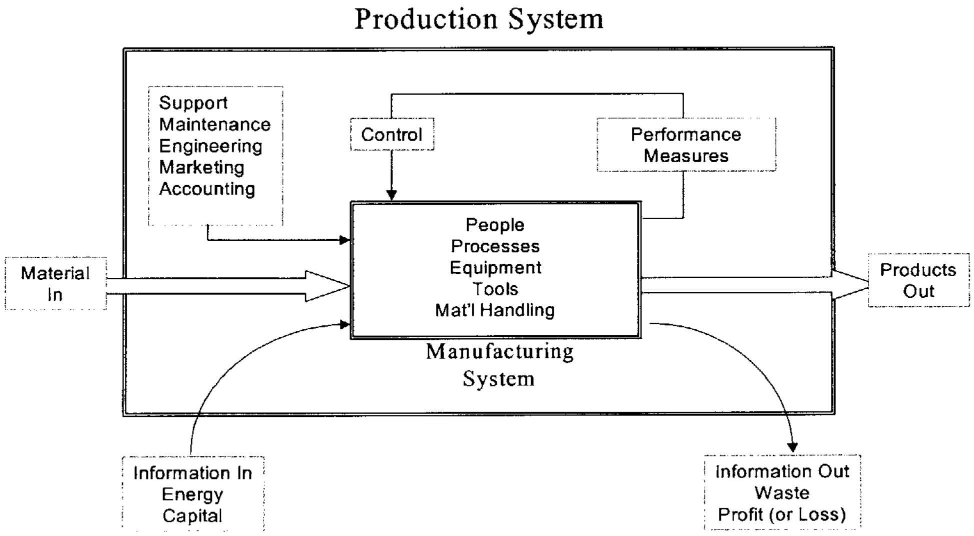


Figure 2-1: A graphical representation of Production systems [Cochran, 1994]

2.2 Introduction to Systems Engineering

Some researchers identify two basic categories of design approaches that relate to the five phases of the engineering system design process are design by philosophy and systems engineering [James Duda, 2000]. The former is design based on general high level philosophy that is widely understood and effectively communicated resulting in a holistic impact on all stages of design while the latter is a more rigorous approach to applying systems engineering principles in designing complex systems. The principle obstacle in creating a shared philosophy lies not only with changing attitudes of people but also convincing them of the new objectives being sought and the relation of the proposed means to achieving these objectives. While potentially powerful as an approach design by philosophy requires a deep understanding of underlying objectives and means for achieving them, reflected in decisions that reinforce enterprise ideals. More often, the design of systems evolves to reflect the design choices made in order to achieve high-level objectives. The design by philosophy approach does not reflect this concept of designing systems based on enterprise objectives.

Most traditional design methods are bottom up where the system is created as an aggregation of existing elements and evaluated in relation to requirements that provides feedback for refinements. The synthesis-analysis-evaluation approach is unsuitable for designing large systems. In such cases, a systems engineering approach is needed to define requirements as they relate to customer needs and strategy as well as consider the system hierarchy and interactions among elements at different levels as well as provide a structures rigorous approach to design, implementation and operation. It is believed that manufacturing system design must apply systems engineering methods to manage the complexity of manufacturing systems [Wu, 1992, Hitomi, 1996]. A review of systems engineering and its application to manufacturing system design is discussed in the next section. Existing frameworks and methodologies of manufacturing system design are then reviewed and related to the systems engineering process. The system engineering process itself is shown to be part of a larger framework for the Manufacturing System Design that is proposed in the next chapter. A pyramid view of the literature and methodologies for manufacturing system design is presented and the systems engineering approach is mapped with respect to the pyramid to demonstrate its extent of influence and the areas for further integration.

2.3 *Review of Systems Engineering and Related Approaches*

Systems engineering is basically a structured approach to think about and work with systems. Hitomi depicts four characteristics of systems engineering commonly found in literature [Blanchard, Fabrycky, 1998, p.23].

- Top-down approach and hierarchical view of systems: The approach considers how system elements work together and influence the overall system performance. Bottom-up approaches are complementary in that they deal with the individual elements.
- Life-cycle orientation: To address all phases of a system from conceptualization, rough design, detailed design, operation to phase out.
- Definition of system requirements: The definition of requirements forms the starting point of system design, relating these requirements to design decisions, and performing system evaluations relative to the requirements.
- Interdisciplinary approach: The interdisciplinary approach helps understand and handle the system complexity.

Figure 2-2 illustrates the activities in each phase of the systems engineering process as depicted from Blanchard & Fabrycky [1998, p.26] and applied to manufacturing system design [Linck, 2001]. The progression is iterative from left to right and not sequential.

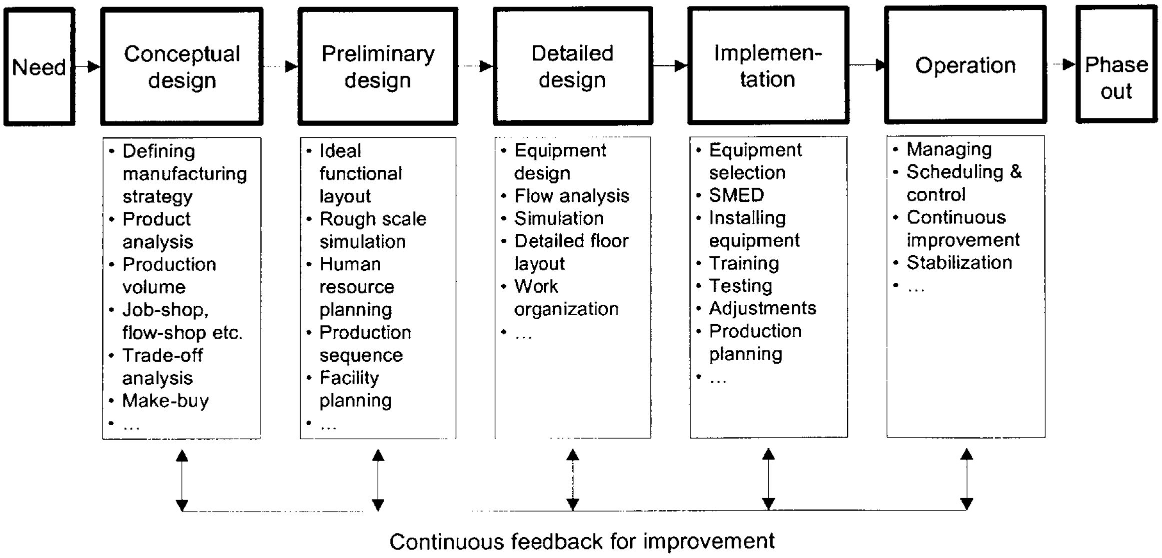


Figure 2-2: Systems Engineering Process applied to Manufacturing System Design [Linck 2001]

In the next few sections, various system design researchers and their frameworks and methodologies are classified according to the system design phases outlined above and discussed in connection with their particular relevance to each phase. A portion of the next few sections is adapted from the PhD Thesis (2001) of Jochen Linck.

2.3.1 Conceptual Design Frameworks

The purpose of conceptual design frameworks is to clarify the system requirements at an abstract level. The frameworks define manufacturing strategy criteria and translate those criteria into requirements for the conceptual and preliminary system design phases. With respect to system engineering, the frameworks support the first two phases as illustrated in Figure 2-3 [Linck 2001].

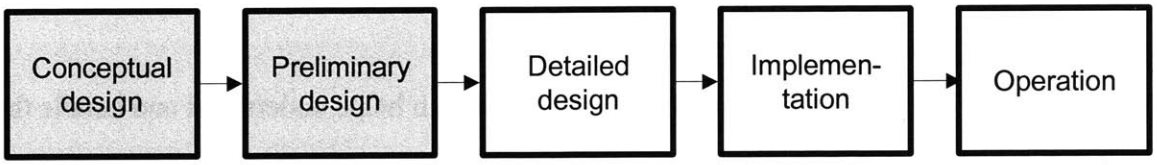


Figure 2-3: Positioning of conceptual design frameworks relative to systems engineering process.

The literature distinguishes general types of manufacturing system configurations. A manufacturing system configuration may be defined as manufacturing subsystem at a general, conceptual level [Duda, 2000, p.163]. A configuration is the result of general decisions about equipment selection and arrangement, material flow, and control. The most commonly cited configurations are: project shop, job shop, FMS, manufacturing cells, transfer lines, continuous flow [e.g. Hayes and Wheelwright, 1979, Kettner et al., 1984, Black, 1992, Askin, 1993, Miltenburg, 1995]. Hayes and Wheelwright [1979] developed the well-known product-process matrix showing the relationship between production volume and mix with the general manufacturing system structures.

Other authors offer similar correlations between production volume, mix and system configuration [e.g. Black, 1992, Reinhardt, 2000]. The relationships are only useful for a very high-level selection of possible configurations as there is significant overlap between the different configurations. Moreover, it assumes a myopic view that production volume and product variety are the main determinants for the system configuration. Chryssolouris [1992] discusses the advantages and disadvantages of each configuration not only in terms of production volume and mix, but includes factors such as inventory, scheduling, and flexibility. The selection of a configuration is just a starting point for the rest of the manufacturing system design process.

Miltenburg [1995] extended the process-product matrix by strategic objectives (delivery, cost, quality etc.), manufacturing levers (human resources, organization structure etc.) to support the selection of system configurations as shown in Figure 2-4.

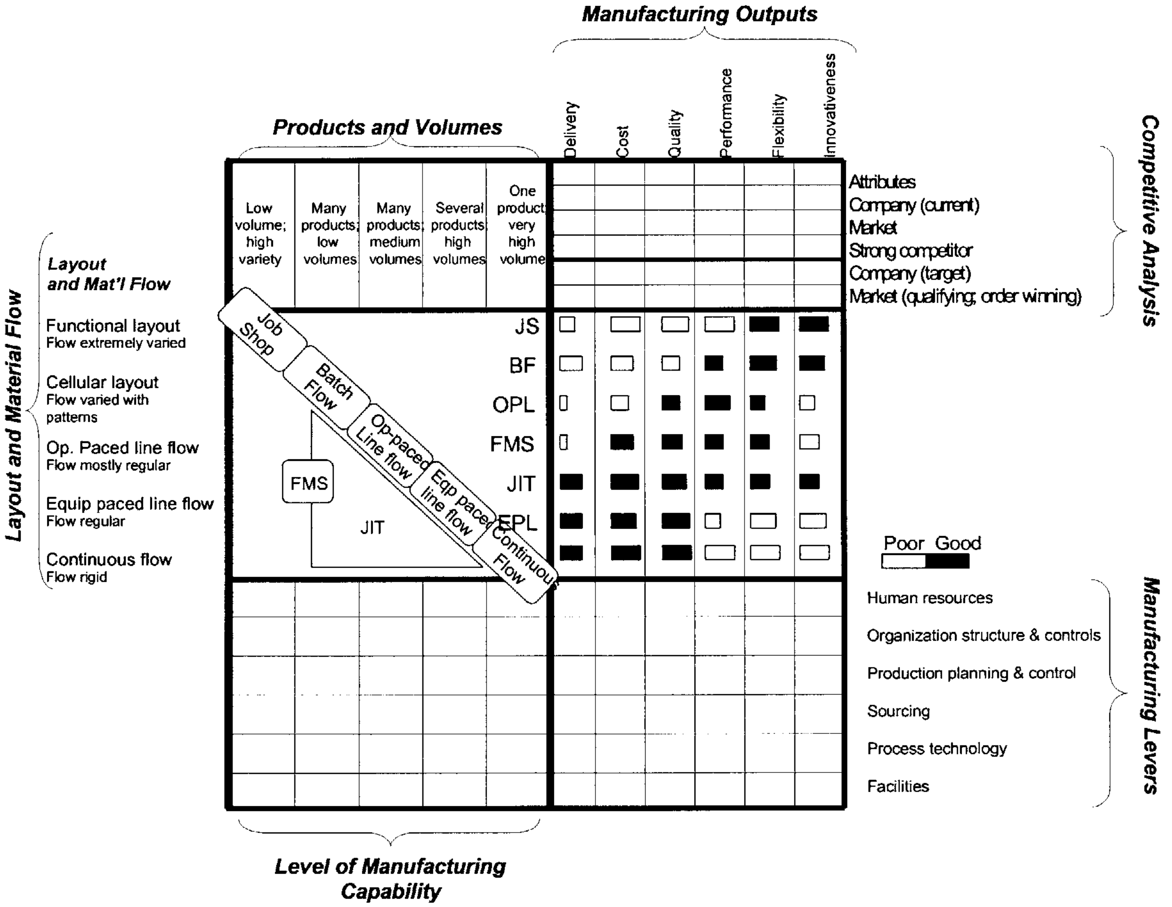


Figure 2-4: Framework for selecting a manufacturing strategy [Miltenburg, 1995]

The framework is very useful in analyzing the present position of a company and to derive an improvement strategy. It shows the impact of strategic decisions such as increasing production volume or changing production technology on the manufacturing system design and performance. However, the framework treats configurations as discrete choices and does not guide the actual design of the system. The impact is limited to high-level strategic choices.

2.3.2 Frameworks for Detailed Planning and Operation

2.3.2.1 Toyota Production System

The Toyota Production System (TPS) has greatly influenced the research of manufacturing system design over the couple of decades. The book "The Machine that Changed the World " [Womack, Jones, Ross, 1990] coined the term "lean production" in describing TPS and another term frequently used to describe TPS is Just-In-Time production [Sakakibara, 1993]. Lean production describes a broad set of management and manufacturing methods commonly used at Toyota. A tendency is to categorize "lean" tools into best practices such as Kanban, SMED, U-shaped manufacturing cells, which could then be implemented [e.g. Sekine, Laraia et al., 1999]. As pointed out earlier, there is a great necessity to view the practices in the context of the whole system. The following paragraphs review TPS related research with respect to the systems engineering process.

- **Sakakibara et al. [1993]** developed a framework and measurement instrument for Just-in-Time (JIT) manufacturing. The framework shown in Figure 2-5 shows how manufacturing strategy, management, and organizational aspects interrelate with each other. The main focus of the framework however is on continuous improvement and problem solving activities.

- **Monden** provides a bottom-up approach and relates basic methods and concepts observed at Toyota into a sequence in which those elements should be implemented. The intent of the framework is to show systemized relationships between system goals and means. The idea is to start with the means at the bottom and to move upward to achieve the ultimate goal of increasing profits. The framework clearly shows that single elements cannot be implemented in isolation of their prerequisites. The framework is useful in clarifying the interrelationships of those concepts. However, the distinction between means and goals is unclear as all lower-level elements appear as means to achieve the ultimate goal of increasing profits. In terms of system engineering, Monden's framework focuses on detailed design and operational aspects of system design by taking Toyota's conceptual design as given. Blanchard et al. point out that bottom-up methodologies are based on known elements that can be physically implemented. However, bottom-up methodologies cannot guarantee that high-level system requirements are being met once the known elements are implemented [Blanchard, Fabrycky, 1998, p. 28]. Therefore, it is unclear how well Monden's framework can support a systemic design of manufacturing systems as it lacks the clear definition of requirements.

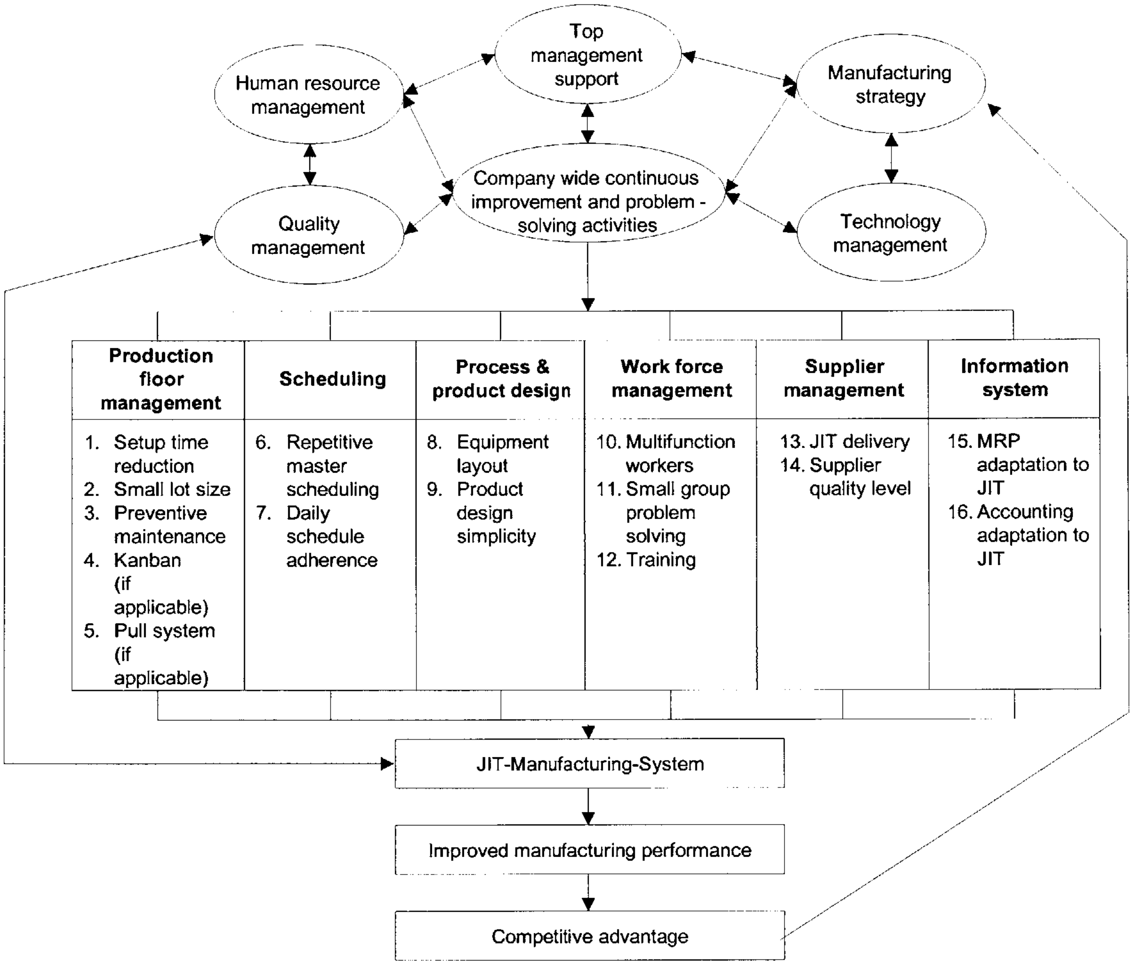


Figure 2-5: Core Just-In-Time manufacturing framework [Sakabibara et al., 1993].

- **Suzuki** created a lean production framework to better understand the relationships between the tools associated with TPS. Suzuki followed a bottom-up approach by categorizing the TPS tools and deriving three higher-level objectives supported by the tools of cost control, delivery control, and quality control. The framework shown in Figure 2-6 enables a better understanding of why particular tools should be used. The approach underlines the importance to state system requirements and state how means help achieving the requirements. Therefore, the framework extends towards early phases of the systems engineering process.

- **Spear & Bowen** researched the Toyota Production System from the organizational point of view. Spear concluded that "the Toyota production system can be codified as Rules-in-Use that guide the design, operation, and improvement of activities, connections, and flow paths" [Spear, 1999, p.105].
  1. All work shall be highly specified as to content, sequence, timing, and outcome.
  2. Every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses.
  3. The pathway for every product and service must be simple and direct.
  4. Any improvement must be made in accordance with the scientific method, under the guidance of a teacher, at the lowest possible level in the organization.

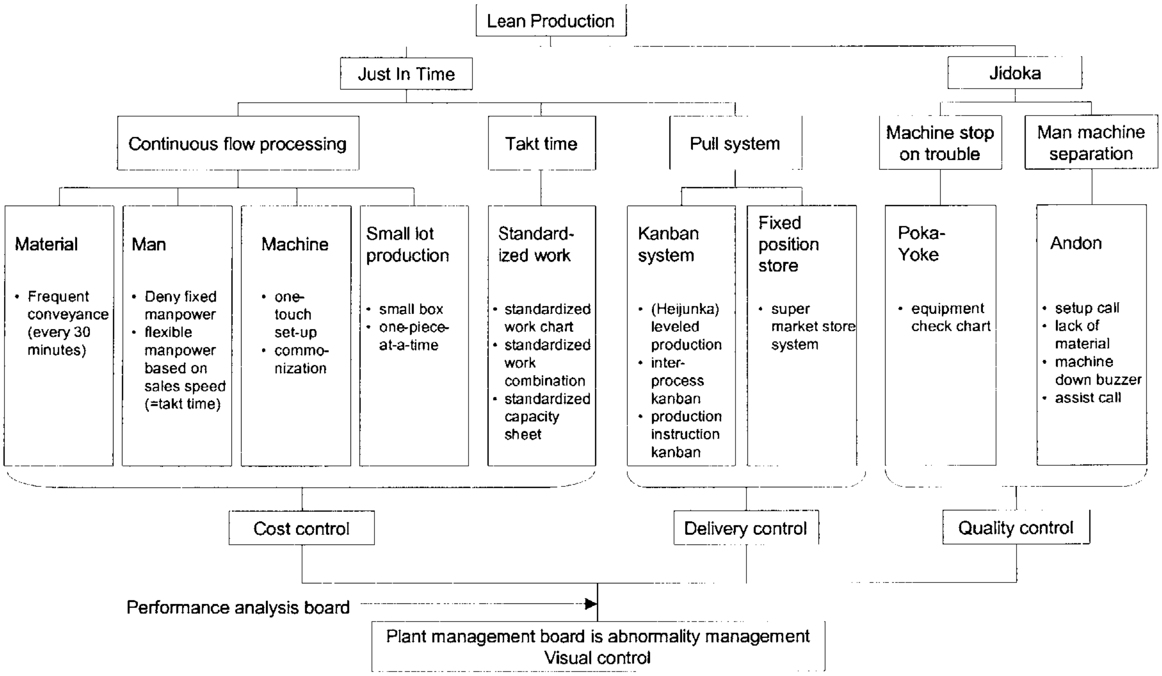


Figure 2-6: Lean production framework [Suzuki, 1999]

The elements usually associated with TPS (kanban, manufacturing cells, leveling) are considered visual manifests of applying the four rules. An emphasis on tacit knowledge inherent in the Toyota organizations explains why implementing merely physical design solutions do not lead to the same effect results as within Toyota. From the system engineering perspective, the rules are mostly related to the operational phase with only limited interaction to earlier phases. The rules do not guide the design of manufacturing systems, but rather provide a framework for continuous improvement once the system is implemented.

- **Summary of TPS Related Frameworks**

In terms of systems engineering, the focus of the frameworks is on operational aspects of system design including some considerations of detailed planning as illustrated in Figure 2-7 [Linck, 2001]. The frameworks build upon tools and concepts associated with Toyota and do not necessarily relate those tools to system requirements. Conceptual designs are considered as a given based on the Toyota's approach.

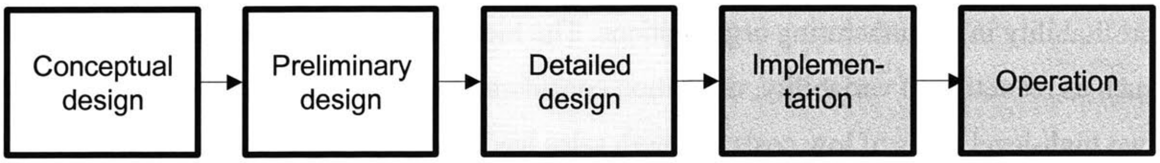


Figure 2-7: TPS related research and frameworks relative to systems engineering process.

2.3.2.2 Other Approaches

- **Value Stream Mapping (VSM)** consists of set of symbols and steps to illustrate material and information flow in manufacturing systems and to derive improvement activities. "Value stream mapping is a qualitative tool by which you describe in detail how your facility should operate in order to create flow" [Rother, Shook, 1998, p. 4]. A value stream encompasses all processes and steps - both value added and non-value added - to produce a final product from raw material to the outside customer. The information flow illustrates the coordination of the material flow.

Creating a value stream map facilitates cross-departmental discussions, since all participants of the value stream must express how their activities tie into the conversion flow. The main focus is on illustrating relationships between processes in terms of material and information flow. VSM is a very valuable and useful tool to support manufacturing system design particular during the early design phases, when general relationships between sub-systems are defined. In terms of systems engineering, VSM covers a broad range of tasks with the main focus on preliminary design as shown in Figure 2-8. It influences detailed design and operational phases in so far as it is used to derive recommendations and improvement activities, but VSM does not provide a formal process for the physical design [Linck 2001].

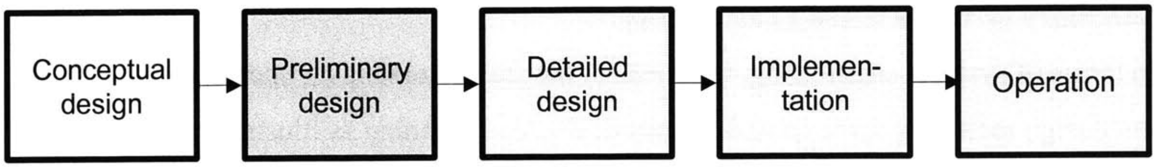


Figure 2-8: The focus of value stream mapping is on defining relationships between subsystems [Linck 2001].

- **Hopp and Spearman** generated a hierarchy of manufacturing objectives to achieve high profitability in manufacturing organizations. The hierarchy focuses on operational practices such as reduction of variability, utilization considerations, service rate, and inventory. The two high-level goals of low costs and high sales lead to conflicting practices at lower levels. For example: low inventory is desirable to reduce costs, while high inventory ensures delivery to achieve high sales. Large number of different products is supportive for high sales, but low number of products reduces costs. The hierarchy is not intended to be a manufacturing system design framework but rather illustrates how core operations management tools relate to overall manufacturing system objectives. Furthermore, the hierarchy points out the necessity of trade-offs in the operation of manufacturing systems.

- **Kettner** provides a detailed step-by-step guide for factory design. The goal of the procedure is to provide a logical and time sequence of main planning steps for designing a factory. Kettner subdivides the tasks into six phases as shown in Figure 2-9 and describes supportive tools for each phase such as organization charts, layout-planning tools, and workstation design. The procedure is comprehensive and covers all systems engineering phases except the operational phase. The general structure is intuitive and splits the complex task of factory design into different phases with an increasing level of detail. However, the procedure does not provide linkages between the phases. It is difficult to understand how decisions at later design phases affect the achievement of requirements from earlier phases.

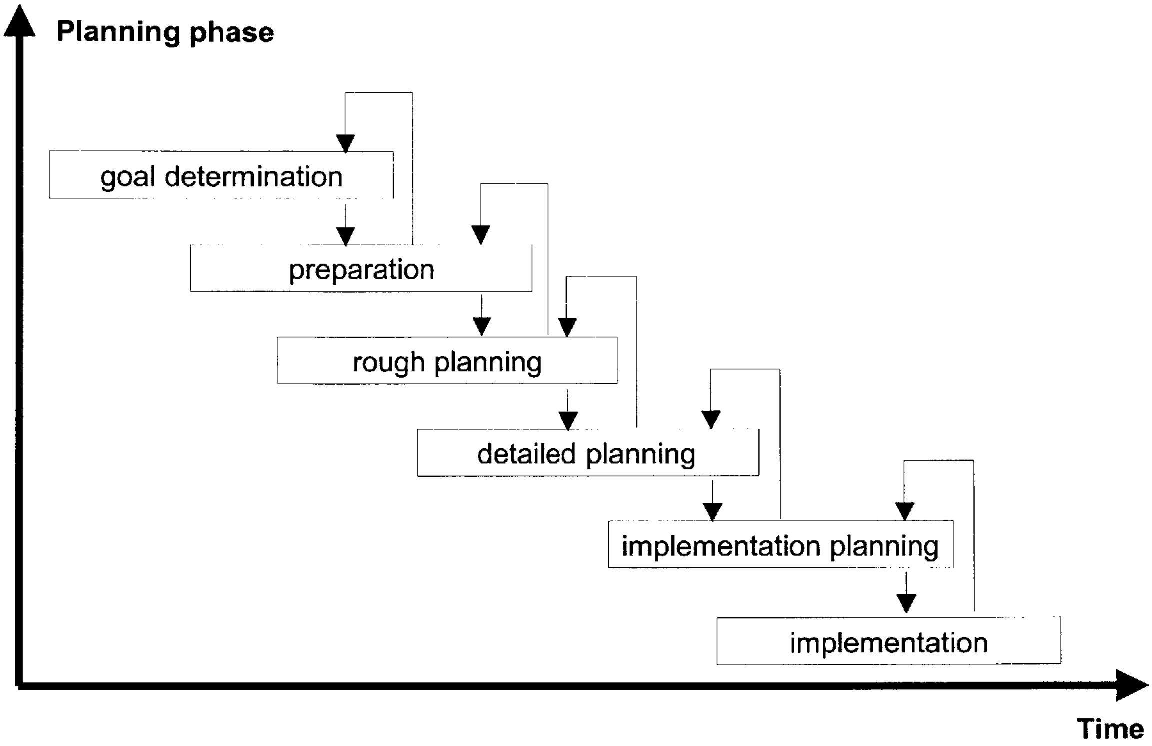


Figure 2-9: Factory design procedure [Kettner et al., 1984]

2.3.3 Conclusions

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

2.4 MSDD, PSDI Path and other Contributions from PSD, MIT

Much of the discussion in this section represents prior work in the development of the Production System Design and Deployment (PSDD) Framework. Some of the text here has been adapted from [Suh, Cochran, Lima, 1998], [Cochran 1999] and [Carrus, 2000].

2.4.1 Production System Design and Deployment Framework

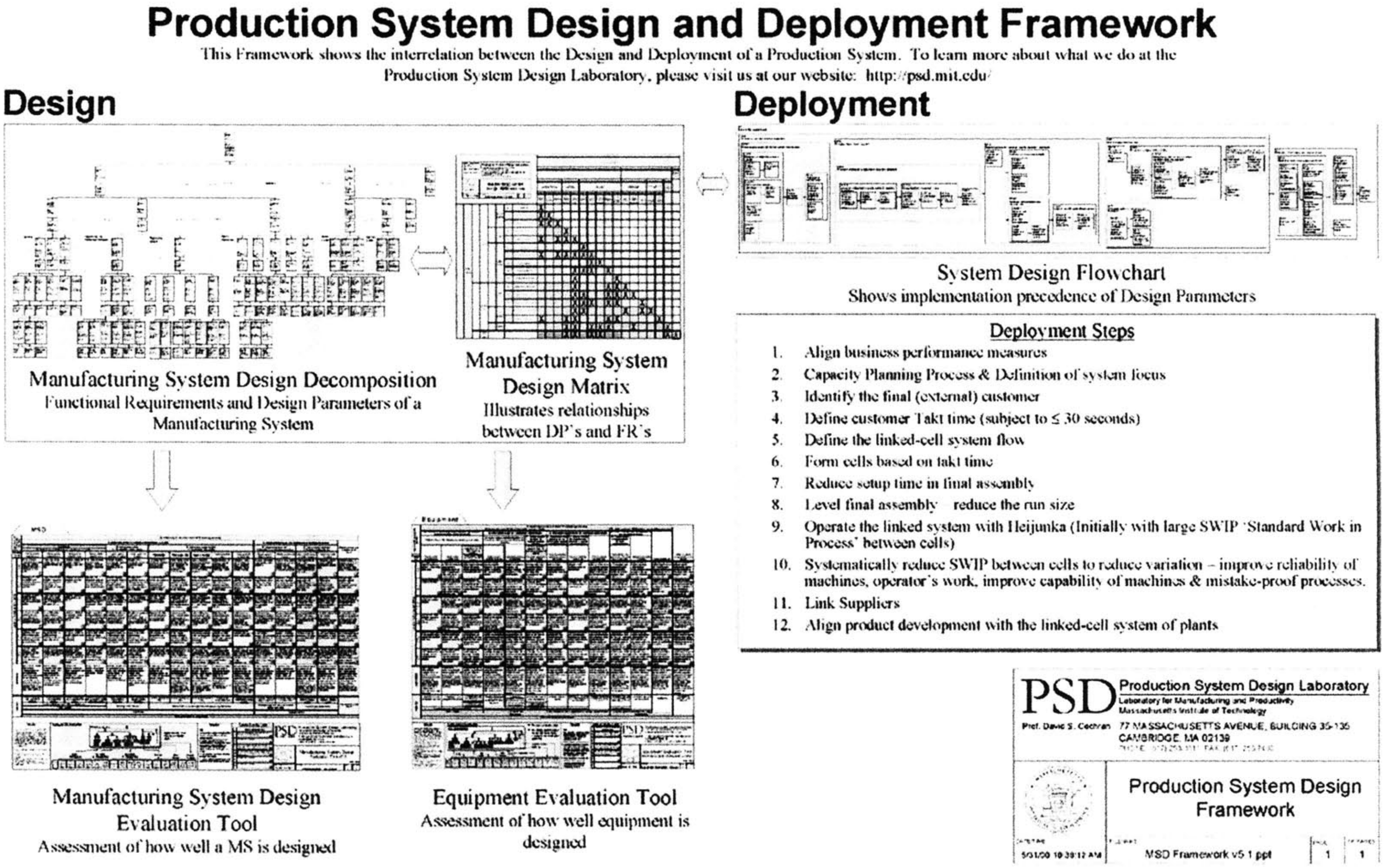
The Production System Design and Deployment (PSDD) Framework, along with the Production System Design Implementation Path (PSDI), create an approach for translating the strategic manufacturing objectives into a real production system on the manufacturing floor. Several authors have shown that success in manufacturing system design and implementation can only arise from complete "systems-thinking;" all actions involved in the design and control, implementation and improvement of these complex systems must be made with the entire system in mind. Any design component or improvement initiative for manufacturing systems must be traceable to both (1) the functional objective it was mapped from and (2) the higher level functional objectives it was decomposed from. [Cochran, 1994] [Monden, 1983] [Black, 1991] [Shingo, 1989] [Senge, 1990]. The PSDD Framework is shown in Figure 2-10. The elements of the PSDD Framework include:

- Manufacturing System Design Decomposition (MSDD)
- Production System Design Matrix
- Production System Design Flowchart
- Production System Design System Evaluation Tool
- Production System Design Equipment Evaluation Tool
- Production System Deployment Steps

2.4.1.1 MSDD

The MSDD Design serves as a map of the design hierarchy in the functional and physical domains. The relationship between high-level design objectives and low-level design solutions are clearly shown. During design process, the decomposition helps identify the complete hierarchy of functional requirements to be met. Other benefits include [Cochran, 1999]:

1. Concretely describes a production system design concept
2. Adaptable to different product and manufacturing environments
3. Ability to create new system designs to meet new FRs
4. Applicable across industries
5. Indicates the impact of lower-level design decisions on total system performance
6. Provides the foundation for developing performance measures from a system-design perspective.
7. Connects machine design requirements to system objectives.



Production System Design and Deployment Framework

This Framework shows the interrelation between the Design and Deployment of a Production System. To learn more about what we do at the Production System Design Laboratory, please visit us at our website: http://psd.mit.edu/

Design

Manufacturing System Design Decomposition
Functional Requirements and Design Parameters of a Manufacturing System

Manufacturing System Design Matrix
Illustrates relationships between DP's and FR's

Manufacturing System Design Evaluation Tool
Assessment of how well a MS is designed

Equipment Evaluation Tool
Assessment of how well equipment is designed

Deployment

System Design Flowchart
Shows implementation precedence of Design Parameters

Deployment Steps

1. Align business performance measures
2. Capacity Planning Process & Definition of system focus
3. Identify the final (external) customer
4. Define customer Takt time (subject to ≤ 30 seconds)
5. Define the linked-cell system flow
6. Form cells based on takt time
7. Reduce setup time in final assembly
8. Level final assembly – reduce the run size
9. Operate the linked system with Heijunka (Initially with large SWIP 'Standard Work in Process' between cells)
10. Systematically reduce SWIP between cells to reduce variation – improve reliability of machines, operator's work, improve capability of machines & mistake-proof processes.
11. Link Suppliers
12. Align product development with the linked-cell system of plants

PSD Production System Design Laboratory
Laboratory for Manufacturing and Productivity
Massachusetts Institute of Technology
Prof. David S. Cochran
77 MASSACHUSETTS AVENUE, BUILDING 35-135
CAMBRIDGE, MA 02139

Production System Design Framework

5/31/00 10:39:12 AM
MSD Framework v5 1 ppt
1
1

Figure 2-10: The Production System Design and Deployment Framework (version 5.1, 2000)

- The 7 Branches of the MSD Decomposition are listed below.

1. Quality
2. Identifying and Resolving Problems
3. Predictable Output
4. Delay Reduction
5. Direct Labor
6. Indirect Labor
7. Investment

2.4.1.2 Interrelationships in the MSDD

Design Matrix

During the development of the MSDD, functional requirements were mapped to design parameters across several levels of the design hierarchy. Each time a mapping from the functional to physical domain takes place, a design matrix is created. The design matrix defines the interrelationship between the design parameters and functional requirements.

Flowchart

The PSD Flowchart provides a different way of visualizing the PSD Design Matrix. In the Flowchart, path-dependent design information is displayed as a sequence of design parameters. The core DPs of the design decomposition that are prerequisite to other FRs/DPs of the design are shown in the internal modules of the Flowchart. Assuming that the innermost DPs of the Flowchart have been integrated in the production system design, the outer DP modules can be successfully implemented.

2.4.1.3 Performance Measurement and Evaluation

Performance Measures (PM)

Every functional requirement (FR) in the PSD Decomposition has an associated performance measure (PM) that can be measured based on the current state of the system, used in the feedback control of the system. The PMs of the system describe how well the FRs of the system design are being achieved at each level of the design hierarchy. To ensure proper control of the production system, the performance measurement system of the organization, from the plant management to the shop-floor operations must be aligned with the PMs of the production system design [Cochran, Kim, Kim, 2000].

Evaluation Tools

As the performance measures of the design (PMs) are intended to measure how well the functional requirements (FRs) are achieved, the evaluation tool is intended to quickly determine how well the design parameters (DPs) of the design have been implemented. The evaluation tool is an alternative way of measuring the performance of the system in terms of the physical domain. In the PSD Framework, evaluation tools exist for the entire manufacturing system and for the equipment in the manufacturing system. [Chu, 2000] [Gomez, Dobbs, Cochran, 2000]. The evaluation tool describes the degree to which a real-world system has implemented the design parameters. A six-level scale is used, where a rating of 1 represents poor systems thinking in implementation and a rating of 6 represents an ideal manifestation of a manufacturing system or equipment.

2.4.1.4 The PSDI Path

Figure 2-11 is a map of the path of production system design from design to implementation. On the left side of the diagram, the *design path* is shown. The highest-level objectives are mapped and decomposed into a detailed system design. From the manufacturing objectives, the system focus is defined and the conceptual flow design is created, showing the movement of material and information through the manufacturing system. The detailed physical elements of the system are then designed based on this system flow strategy, including the standard work-in-process buffers (SWIP), cells (equipment design, standard work routines), material handling routines and information transfer methods. The design can then be implemented.

On the right side of the diagram, the *implementation path* is shown. The physical components of the system are created. As the physical elements are placed on the manufacturing floor, the flow is buffered with SWIP at first. Each element is improved and controlled using tools to solve fundamental system problems. Direct material and information links between system elements are made. As each element is improved, the inventory buffers are reduced. The first stage of improvements and the associated reductions in inventory involve setup (changeover time) reduction, leveling and pacing production, and establishing predictable quality and time output. The elements can then be linked with pull replenishment. Once the proper flow is established, the suppliers can be linked to the system. Finally, the product design function can be integrated into the manufacturing system. The notion of flow is a theme during this entire process; the system will be designed and implemented with material and information flow in mind.

Early in the PSDI Path, production system designs begin as strategic initiatives. Manufacturing is a sub-function of the overall business structure, and therefore the manufacturing objectives are drawn from the objectives that are identified by the business. The upper-left most area of the PSDI Path is concerned with identifying manufacturing strategy from business strategy. Depending on several decision factors such as market, industry, process, product and customer attributes, the set of manufacturing strategic objectives are identified. Depending on these decision factors, the importance of cost, quality, flexibility, delivery performance and innovativeness is identified and used as the driver for the selection of high-level manufacturing system design alternatives.

The PSDI path however does not provide guidance on how the process of manufacturing system design can be integrated with the enterprise. The focus is on the design and implementation aspects of manufacturing system change and is thus similar to the systems engineering approach in terms of its impact. Moreover, there is a need for greater rigor in the implementation process and towards the training and education of the people in the system.

2.5 Main Observations from Literature Review

Recently, several authors emphasized the need for better integration among various disciplines to create a comprehensive manufacturing system design methodology [Meller, Gau, 1996; Wu, 2000; Hopp & Spearman, 1996, Hitomi, 1996]. Specifically the observations were:

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

There is thus a need for a comprehensive manufacturing system design methodology that integrates the various approaches and fosters the definition of design requirements. The methodology must relate design solutions to requirements and help communicate requirements and design solutions throughout the organization. Finally it must reflect how low-level decisions affect the achievement of high-level requirements and support a structured step-by-step design procedure.

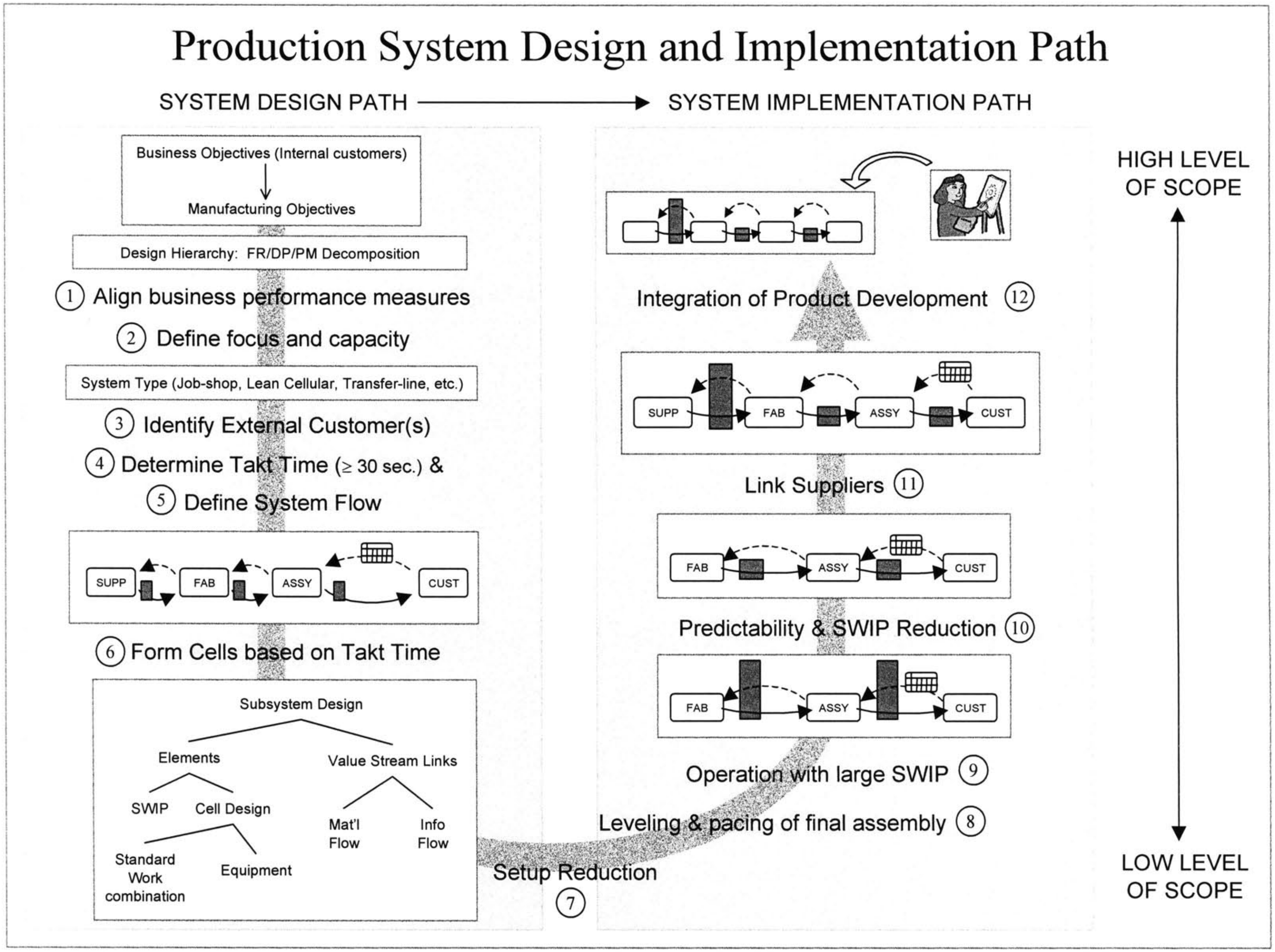


Figure 2-11: Production System Design and Implementation Path

2.6 *Pyramid Classification and Evaluation of Design Literature*

The above discussion leads to the following classification of system designs and methodologies in literature shown in Figure 2-12. Further, to summarize and illustrate the areas of emphasis in different design methodologies with respect to the two design categories, Figure 2-13 shows the spread in the area of impact across different levels of system design that the different methodologies and the general body of systems engineering spans. Finally, the blank base of the pyramid indicates that very few design methodologies address enterprise issues simultaneously with rigorous implementation support based on well-understood organizational thinking, separating objectives from means and providing assistance in continuously improving the system.

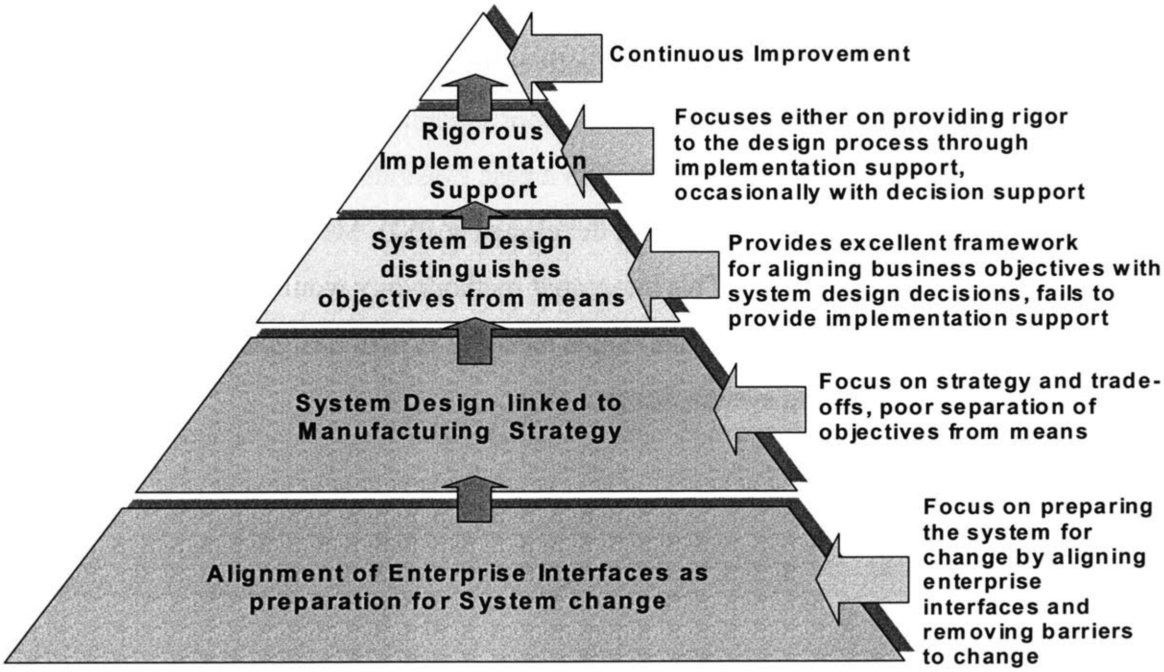


Figure 2-12: Pyramid classification of design methodologies

Through this thesis we wish to illustrate that the ideal methodology for system design would span across all levels of the design pyramid model. Conversely stated the success of system design is contingent not only on the success of the design but also its implementation and operation as part of an enterprise. Most of the system design methodologies address 3 out of the 5 levels and hence there are at least two key aspects of the manufacturing design process that they fail to incorporate. The system design pyramid also helps to indicate probable causes of frequent failure in achieving enterprise objectives through the design and implementation of manufacturing systems. The poor performance of systems could be a function of the design process and methodology, or a set of enterprise issues such as business environmental conditions, poor leadership and ill-designed organizational processes and misalignment of manufacturing with other parts of the enterprise. This appreciation leads to the following hypotheses on system design and performance.

Hypothesis 1 Production systems have poor operational performance due to poor design or implementation.

Hypothesis 2 Poor MSD is a result of mental models for manufacturing performance improvement based on minimizing unit operation costs.

Hypothesis 3 Financial Performance measures do not always reflect the true operational performance of a Manufacturing System or the effectiveness of its design.

Hypothesis 4 Poor organizational leadership sets poor organizational processes.

This thesis will discuss these hypotheses through a case illustration and ultimately propose a combination of approaches being researched and developed at PSD, MIT in the form of a serial yet iterative approach to system design. This integrated methodology would provide a means of addressing the enterprise issues and other challenges faced by system designers and engineers in producing change in manufacturing system design.

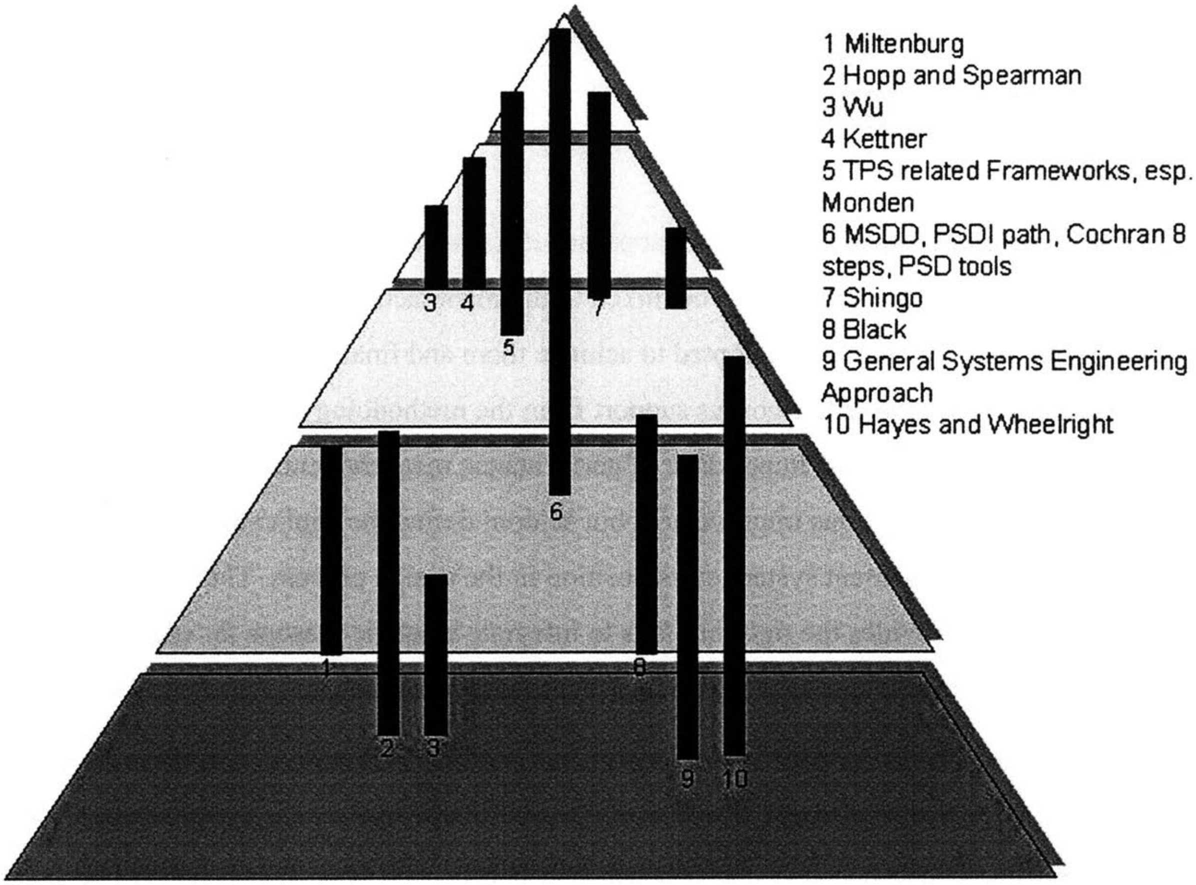


Figure 2-13: Mapping influence of various literatures on system design pyramid.

Chapter 3 Proposed Multi-Phase Manufacturing System Design Process

3.1 Introduction

The previous chapter discussed various approaches to manufacturing system design. An argument was made for the approach to be linked to the manufacturing strategy, with objectives separated from the ultimate means adopted to achieve them and finally to pursue the system design and implementation with rigorous support from the methodology adopted. Most system design methodologies stress the importance of performance measurement for feedback aimed at problem solving and continuous improvement but seldom define the applicable performance measurement and management system or its position in the design process. The system engineering process provides the rigor but fails to integrate strategic reasons for change with the performance measurement that drives the subsequent implementation and improvement efforts.

The hypotheses or reasons for poor system design and performance suggest that there are other factors in the design and implementation process that ultimately affects the system design and performance. The relevance of these hypotheses is discussed with an actual case illustration in the next couple of chapters. The hypotheses primarily focus attention beyond the role of system designers to the leadership, external business environment and the structure of the processes within the system and outside the realm of manufacturing. These processes, a function of the enterprise design and policies set in place by the organizational leadership, typically influence the organizational structure, performance measurement, incentives and accounting policies. Accounting policies measure business, functional and departmental performance almost always in financial terms. The financial figures at each of these levels translate to performance measures for individuals at each of these levels. The ownership of tasks translates into responsibility for figures that leads to a polarization of the organizational structure along departmental lines. The personnel have strong incentives to optimize their areas of responsibility even at the cost of the systemic performance as their metrics are based on the departmental or functional performance. The misalignment leads to resistance towards change if systemic change is in conflict with personal incentives and leads to creation of organizational barriers. Even if the personal incentives are aligned towards change, often-financial numbers obviate the need for change, even if the change is likely to produce operationally superior performance and related benefits in the future. The myopia of systemic inertia requires not only alignment of processes and enterprise interfaces but also training and physical simulation to demonstrate benefits. Thus while the strategy dictates the need for change and prepares the stage for the system engineering process, a crucial step not discussed extensively in literature is that of preparing the system for change. To further illustrate the role of leadership, extraneous situations and organizational processes in conjunction with the system design on operational performance, a general framework for the process of system change and implementation is proposed in Figure 3-1. The process highlights the three important levels through which the process of change advances. This chapter focuses on this crucial step as well as explains the role of three important levels in a proposed manufacturing system design process.

3.2 Strategic and Facilitation Level

At the strategic and facilitation level the manufacturing strategy is derived from the corporate strategy and vision and highlights the need and importance of systemic change. Traditionally the process of strategy development has been viewed as top-down, hierarchical with an end-ways-means approach [Hayes, 1985]. The process begins with business vision and corporate goals that trigger the planning process for determining ways to achieve these ends. Strategy itself is vaguely defined in literature and one attempt [Hayes and Wheelright, 1984] defines it in terms of its characteristics.

- *Time horizon:* Strategic activities have long time frames for implementation and impact.
- *Impact:* Strategic activities are aimed at having significant organizational and business impact.
- *Focus:* Effective strategic actions follow the 80-20; greater efforts on the more important issues for greater bang for the buck.
- *Consistency:* Strategies influence business decisions. It is vital that these decisions are supportive of each other and have a coherent pattern.
- *Pervasiveness:* The strategy must influence all functions and levels of an organization in a manner that is mutually reinforcing.

The top down approach to strategy development is an immediate outcome of the requirements of consistency and pervasiveness. To ensure that all divisions and functions align their objectives from the same source viz. the corporate strategy. The objectives of different divisions and functions would be different but would have the same thread of corporate goals running through them. Figure 3-2 [Hayes, 1984] portrays the hierarchy in the strategy development process proceeding from the corporate strategy to divisional/business strategy and finally to strategy at functional levels of Manufacturing, Marketing etc.

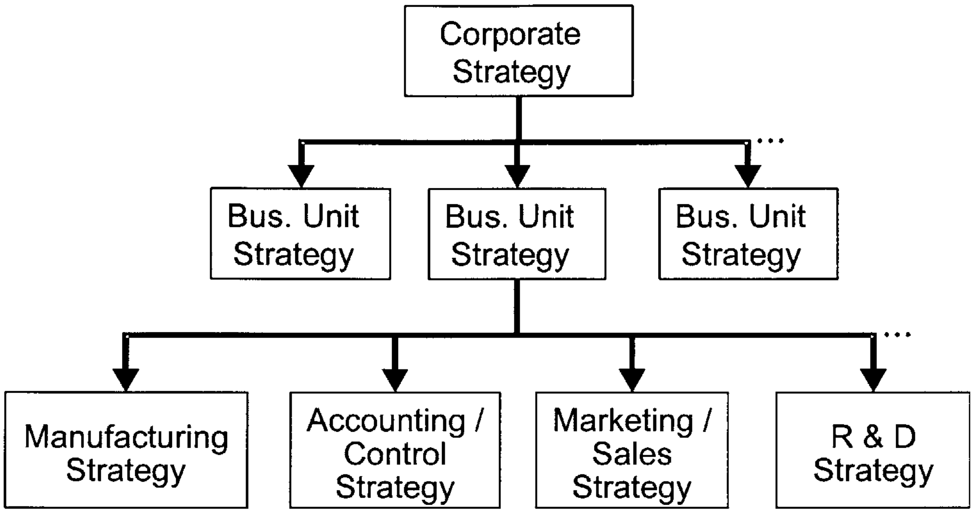


Figure 3-2: Levels of strategy (adapted from Hayes and Wheelwright, 1984)

The corporate strategy is primarily focused on defining the mission of the firm, the businesses it wishes to compete in and the long and short term returns it seeks to provide all its stakeholders including company employees and customers. The corporate strategy is reflected in the pattern of decisions the top management typically the CEO, COO, CFO, CTO and VP's of the firm make that determine the core competencies and competitive advantages the firm would focus its efforts on. For a non-diversified or single business enterprise, the corporate strategy is essentially the business strategy; however when diverse business units make up a corporation, individual business units may adapt the corporate strategy to their individual business environments to define their scope of business and develop more specific plans for competing effectively. The priorities for competition may vary among these business units and still be aligned with the corporate strategy. At a given time most business units focus on more of the following categories of competitive positioning; cost, quality delivery performance (speed or dependability), flexibility of volume, mix, customization and innovativeness of product or process.

An important step listed at the third level in the hierarchy of strategies is the formation of the functional strategies or specifically in the context of the process of manufacturing system design, the manufacturing strategy. The manufacturing function especially in large organizations where the sale of produced goods is the primary source of revenues becomes a potential area of competitive advantage and an important functional strategy. It must define what aspects of manufacturing the organizations must focus on and have a strategic fit with other functions that is both consistent and reinforcing. Different decision categories of manufacturing strategy and the key elements of competitiveness are discussed in greater detail in later chapters.

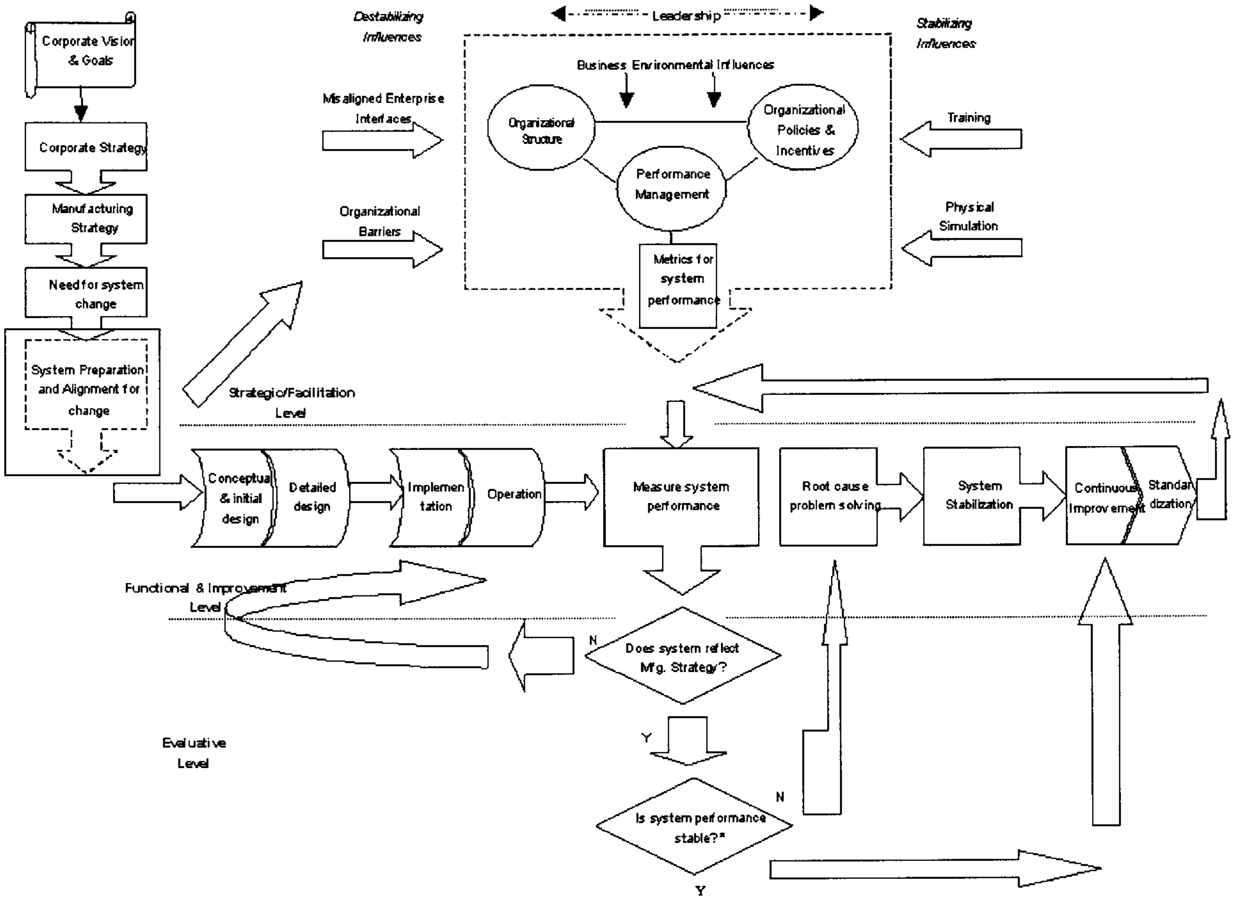


Figure 3-1: Manufacturing System Design and Improvement Process

Two key characteristics of strategy are the time period over which it is pursued and the impact it produces. Some companies use time as a source of competitive advantage by producing the planned impact over a short duration of time. Depending on the elements of the strategy the time horizons over which they can be implemented and have impact vary but the key is the need to pursue changes in a prioritized, pervasive and consistent manner so as to produce the desired impact on the company's competitive position and performance. As discussed in the first chapter, the performance of a system and the behavior of its elements especially people is a function of the structure of the system. The structure of a system is a result not only of its design but also the interactive influences of policies, external environment, personnel incentives and its fit with other constituent systems of the enterprise. Thus it is not sufficient to design a system in line with the strategy; for successful implementation there is a critical step in system preparation that involves among others the removal of organizational barriers, alignment of organizational interfaces and incentives towards such a change. The responsibility for preparing systems for change to reflect their changing business needs lies with the leadership who should contribute towards stabilizing the process of transition towards the corporate goals. The major areas of leadership influence are discussed here.

- *Aligning the manufacturing system design with the rest of the enterprise*: Manufacturing needs to produce what the customer wants, when it wants it and in the mix and quantity desired with various options for delivery, purchase plans, custom features and warranty. For instance marketing would like to promise a car with features tailored to the customer at the customer's choice of delivery lead time and together with the finance department may wish to offer attractive financing schemes. The accounting department would like to produce a certain margin on the car placing the challenge on manufacturing to streamline its operations, reduce costs, improve lead time and flexibility. Without mutual appreciation of each other's needs and capabilities it would be difficult for any organization to pursue the choices reflected in their strategy, profitably. The leadership having a more holistic view and over-arching influence on various pieces of the enterprise is best positioned to facilitate such an alignment.

- *Aligning organizational policies structure and incentives:* Individuals in an organization pursue activities and objectives that produce the best personal reward be it in terms of recognition, monetary benefits or increased influence. Organizational policies must prevent departmentalization in the process of delineating responsibility and ownership and instead should align individual incentives towards activities that support organizational goals. System performance measurement drives improvements on the chosen set of metrics. Assuming that we get what we measure it becomes crucial that the accounting policies are chosen such that improvements are consistent and meaningful to desired system performance. The system must be designed based on the objectives of the company and the performance measures used to evaluate whether the objectives or functional requirements are being achieved.

- *Training personnel:* Training of personnel has two dimensions. One dimension is to develop personnel resources and capabilities. The other is to convince the personnel of the need for change. Physically simulating the desired future state value stream and operations is a powerful manner of selling management vision as well as serve as a tool for understanding the operations in the new system. Leadership must leverage its resources and use training and physical simulation as tools for stabilizing the process for change by enthusing the people about the benefits [Shukla, Cochran 2001], [Cochran et al, 2001].
- *Removing impediments*: The impediments being talked about could range from union issues, cultural resistances, organizational barriers created by seemingly conflicting departmental interests, personal incentives or employee motivation issues affecting the change process.
- *Active participation in the design and improvement process*: Leadership must involve itself in the important stages of implementation and ensure that feedback from performance measurement is used constructively to define and refine the system design.

Figure 3-1, illustrates the need for the system preparation and alignment step as a part of the strategic level in systemic change and particularly highlights the overarching influence of leadership. The important observations from the above discussion on the strategic and facilitation level is that the primary responsibility for the steps in this phase rest with the leadership who must define the vision and corporate goals as well as strategies to achieve them across different levels. As observed in the previous chapter separating objectives from the means to achieve them is crucial at every level and hence it would be instructive for the leadership to use a decomposition of their strategy top down from corporate level to business division and finally at a functional level ensuring that functional strategies are consistent, have impact and relate to higher level objectives without conflict. The manufacturing system design decomposition (MSDD) has potential use in defining functional strategies from the corporate strategy, in a manner that is comprehensive and uses principles of axiomatic design. It must be ensured that the functional strategies are uncoupled (not in conflict) while at the same time are mutually consistent. For instance ensuring superior profits may be a corporate and its resolution at the manufacturing level would lead to reduction of costs. The functional strategy for marketing would involve creating demand for the product or innovative pricing so that both volumes and per unit price can be raised. The two strategies are uncoupled and not in conflict yet consistent with the high level objective of superior profitability. Finally it is important to observe that systemic change is a gradual process that requires at its foundation certain activities that help prepare the system and its constituents for change.

3.3 Design, Operation and Improvement Level

The stage for actual design and implementation work is set once there is buy-in from all sources and both the leadership and personnel have aligned their processes and incentives and understand the importance for a system design that supports the goals. The process of manufacturing system design has traditionally adopted systems engineering methods and approaches in the design and implementation phases to manage the complexity of manufacturing systems [Wu, 1992, Hitomi, 1996]. Systems Engineering is essentially a structured approach to think about and work with systems [Linck, 2001]. A life cycle orientation addresses all phases of the manufacturing system design from conceptualization, preliminary design, detailed design, operation and phase out. The definition of system requirements is the starting point and relating these to design decisions in implementation becomes the objective of the engineering process. During the system engineering process especially at the conceptual design phase, the Manufacturing System Design Decomposition [Cochran, Lima, Suh 1998] is a very useful tool in relating the requirements to design decisions. It also helps relate the different issues in manufacturing system design and ensures that the classical constrained based optimization approach to design is avoided by stressing on decoupling design decisions. Performance evaluation relative to the requirements follows the system engineering process and determines the line of future action. The performance evaluation indicates whether the system is stable or unstable. A stable system meets systemic requirements while an unstable system does not or does so unreliably. Only stable systems can be improved [Cochran -steps, 2001]; stability of a system is indicated by the achievement of all the Functional Requirements FR's derived from high level objectives in the manufacturing system design decomposition. A system is also stabilized through prioritized root cause problem solving in operation as well as modifications to the system design; it sets up an iterative loop for system design and operation until the system is stable in terms of its FR's. A stable system is not the ultimate goal for manufacturing systems and there is always room for continuous improvement. Continuous improvement has at its core the philosophy of doing things more effectively and sharing improved work practices throughout the system. Stable systems are best positioned for continuous improvement as they have already achieved the FR's of the system design; hence going forward there is need for evaluating how well these FR's are achieved and working on the work to improve it further. Improvements that are made and are effective must be documented for operators to perform a standard improved version of the work procedure until another improved version replaces it. Standardizing tasks ensures that the work is repeatable and uniform, thus production is standard and uniform across operators and shifts. It does not restrict a system's ability to improve as new improvements can be incorporated in future versions of the standardized work.

The important difference between the system engineering phases and the post operation stabilization and improvement phase to the right of the evaluation boxes in the figure is that the responsibility for the former is shared between the leadership, system designers and various engineers and to some extent the operators. However, the processes of system stabilization through problem solving and Kaizen through improvements at both process and operation level require inputs and high involvement from the doers of the system, namely the operators. They must contribute suggestions for how operations can be performed differently, modifications to work processes and station designs, modifications to equipment as well as suggestions for layout and value stream waste reduction. The manufacturing system design process thus also follows a top down hierarchy in terms of responsibility from the strategic level to the design and operational level. It is important to note that there is bottom up feedback through performance measurement that helps ensure there is interaction across the levels.

3.4 Evaluation Level

The evaluation level is discussed separate from the system engineering and improvement phases as it determines the direction for system design and improvement efforts. The evaluation tools must ideally indicate to managers, engineers and workers the areas for improvement, whether structural or operational. In case of the need for structural improvements efforts are focused on the re-engineering the manufacturing system through the design phases to the left of the evaluation boxes in the figure until after subsequent iterations the structure of the system relates to the manufacturing strategy or the system functional requirements set forth earlier. Evaluation on the decomposition (MSDD) based tools described in the previous chapter help indicate if the system performance is stable. Unstable system performance that is aligned with the manufacturing strategy can be improved through root cause problem solving and stable system performance can be continuously improved and standardized by evaluation of how well the system achieves these FR's. The decomposition-based tools allow the evaluator to determine from several options the one that best describes system performance on a scale of 0 to 6 typically. This has two principal advantages; one it helps determine how close the system is to achieving ideal performance as well as provides a description of what perfect achievement of that FR involves. Since the feedback from this level is key to future performance it is essential that the information collected through this level is accurate, relevant and available in an easily usable manner. Performance evaluation must collect relevant measures on the shop floor, as well as measures that describe the design of the system. They must also be in different forms for personnel across different levels. The chapter on performance evaluation shall address these issues in greater detail.

3.5 Conclusions

The chapter described in detail a proposed view of the manufacturing system design process that articulates three important levels through which the design process moves. The strategic and facilitation level whose primary responsibility rests with the leadership, defines what needs to be achieved and relates it to corporate goals through a manufacturing strategy. There is need for preparing a manufacturing system for change and aligning processes and policies that assist change to create the desired impact. It also provides an insight to important limitations of system designers in producing change and implementation, which are listed below.

- System designers may be constrained by misaligned performance accounting systems – performance accounting system may promote departmental layout to increase machine utilization and reduce unit labor cost per part as opposed to producing high quality parts as per customer demand at low costs.
- External environmental issues and considerations may produce aberrations in design – for example low wages in Mexico provide incentives to overstaff production system in order to increase volume.

- Poor organizational leadership can shift the focus from effective system design to optimizing on a few measures of operational performance that may lead to ill-designed systems and long-term poor health of the production system.

The proposed system design process combines the system engineering process in the design, implementation and improvement level. After implementation, the performance evaluation determines if the design meets objectives (Functional Requirements) of the manufacturing strategy. An additional iteration through the system engineering process may be needed to identify and correct design flaws. Evaluation using the manufacturing system design decomposition developed for the system determines if the system is stable. In order to stabilize the system it may be necessary to do some prioritized root cause problem solving so as to achieve the functional requirements across the decomposition. In a stable system it is possible to perform improvements on a continuous basis and standardize the best practices in the system. The system iterates between the evaluation and functional levels on a continuous basis during the operation.

Chapter 4 Case Study Illustration

This chapter discusses a case study that seeks to illustrate the application of systems engineering to the design of manufacturing systems. The idea is to show how rigor and comprehension in the design process is achieved through the system engineering process. The case study involves the re-design of a manufacturing system using the methodologies developed at PSD, MIT in conjunction with the literature on systems engineering. The project not only highlights the benefits from such an approach as well as indicates how the relevance of the system engineering approach is restricted to the design, operation and improvement levels of the proposed manufacturing system process and how that affects the translation of the benefits system-wide. This chapter prepares the stage for the proposal of a methodology that combines the system engineering thinking with a model for system conversion that addresses enterprise issues.

4.1 Introduction

In June of 1999, the Production System Design (PSD) Laboratory at MIT teamed up with engineers and production managers at Mexican facilities owned and operated by a giant automobile components supplier, to re-design their production system. The plants manufacture tube connectors used in automobile air-conditioning systems. The design sought embodied fundamental "lean" concepts, while respecting current constraints of the company. A key objective of the ideal design was to create a plant that allows itself to change easily as financial resources become available and the business grows. The project was an excellent opportunity to review and apply existing methodologies for manufacturing system design as well as test a hypothesis on the design of existing departmental layout mass systems. The hypothesis being that the design of such systems was not as much a function of the constraints imposed on the system but a function of the design process and mental models of manufacturing systems shared by engineers and managers alike.

4.2 Project Motivation and Goals

The tube connector manufacturing operations were split across plants and this apart from creating logistical, operational and quality problems placed pressure on the company's floor space resources. As part of its product line expansion plans the company needed the additional floor space for production of a new compressor. One of the solutions being considered was the construction of a new building with adequate capacity to house all tube connector manufacturing. This solution would additionally provide a unique opportunity to re-organize the manufacturing operations as well as explore the application of the state of the art in production system design thinking especially in connection with 'lean manufacturing techniques' for system design. It was in this connection that the PSD Laboratory at MIT was asked to assist the management as well as the engineers on site.

A quick examination of the manufacturing operations at these plants revealed several problems. The major issues that required attention were: limited floor space for new products and expansion, high throughput time, quality problems, and wasteful processing methods. These problems were deeply rooted in the design of their manufacturing system, which has a departmental, mass production approach to manufacturing. At the start, the project constraints were outlined as lack of resources for any major investments in product, process or equipment to achieve the project goals. More specifically, these goals were:

- Simplify product and information flow.
- Reduce throughput time by eliminating lot delay.
- Eliminate the waste of transport and storage.
- Prevent occurrence of defects by integrating quality control into the station design.
- Separate the workers from the machines to effectively utilize direct labor.
- Reduce the time and complexity of machine setup by designing the machines to system takt time (rather than high speed to reduce labor cost) and by eliminating adjustment need during setup.

In addition, the deliverables from the project were outlined as:

- Plan for a new facility design or re-design of the existing manufacturing system with the future state map and detailed designs at system, sub system and unit level that would help indicate future requirements of personnel, equipment and layout.
- Demonstration of the benefits from the future state value stream through a pilot project.
- Detailed project plan for moving from the current situation to the future state value stream.

4.3 Product Description and Overview

The product is the hose and tube assembly shown in Figure 4-1, which acts as a connector between components of an automotive air conditioning system. At either end of the product there are aluminum tubes, each with a different type of end joint. In final assembly, the tubes are joined to a flexible, rubber hose by a crimping process. Other assembly steps include attaching O-rings to the tubes, leak testing the assembly, and placing caps on the tube ends for protection during shipping.

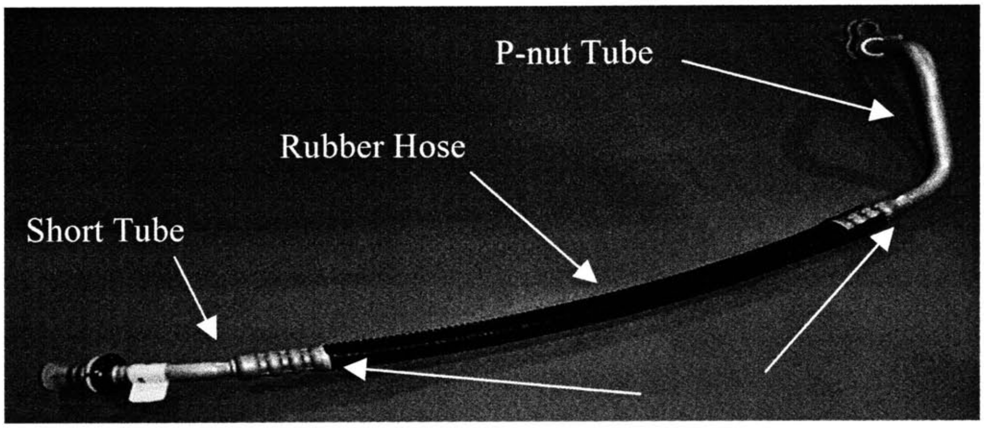


Figure 4-1: Connector between air conditioning components

4.4 Pre-Project State of the Manufacturing System

A wall separates the assembly and fabrication sections of the plant and on the fabrication side there are two distinct paths parts follow depending on their material type. Aluminum tubes are formed, washed, then go to rotary braze machines, and finally to assembly. Steel parts tend to have more complicated brazes and require parts to be press-fitted at Steel Sub-Assembly department prior to being brazed. Brazing of steel parts is then done on a conveyor oven rather than rotary machines. Additionally, steel parts also leave the plant for anti-corrosive plating by external vendors. Once the tubes reach the assembly side, their paths are identical as they get bent and then sent to the final assembly lines, to be assembled into hoses. Of all tubes being fabricated, 70% are aluminum and 30% are steel. Steel tubes are being phased out because they are heavier and require extra processing.

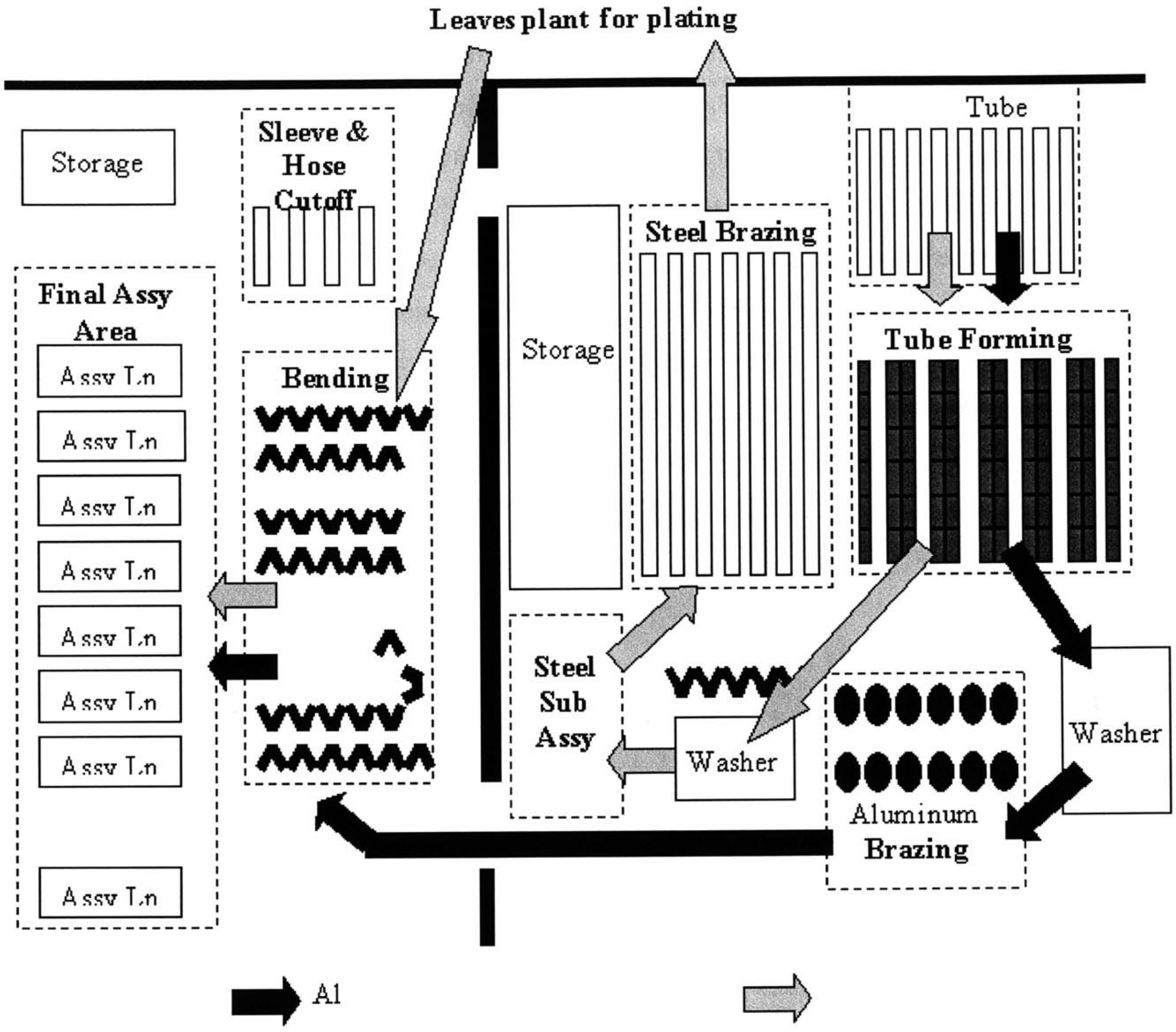


Figure 4-2: Layout of the Manufacturing System

4.4.1 Virtual Tour of the Plant

This section provides a virtual tour of the plant following a part from the raw material stock through fabrication and finally to assembly. At each stage of the process the processing involved and the problems that are a function of the system or equipment design are indicated.

4.4.1.1 Tube Cutoff

Aluminum stock is loaded on to cutoff machines and the machine indexes automatically to a preset length and cut and repeats the process for the number of tubes needed. Oil is applied to reduce the friction between the aluminum and the nylon roller and this creates the need for washing the aluminum tubes downstream. The index and cut operation leads to end stock losses and continuous operation leads to over production. The scheduling of production that could reduce the losses above is difficult as quality related losses downstream prevent accurate forecasts of tube requirements. Batch production with each batch consisting of over 200 parts creates problems of lot delay and hence increased throughput time. Lot delay also increases response time to problems that cause defects and often the entire batch gets affected.

4.4.1.2 Tube Forming

In this department, both ends of the tube undergo a series of forming processes to make different end geometries. Any end that will eventually be crimped to the hose gets a ferrule forming, while ends that do not connect to the hose may receive either an end cage or P-nut end form. Figure 4-3 shows examples of the different end types that are formed.

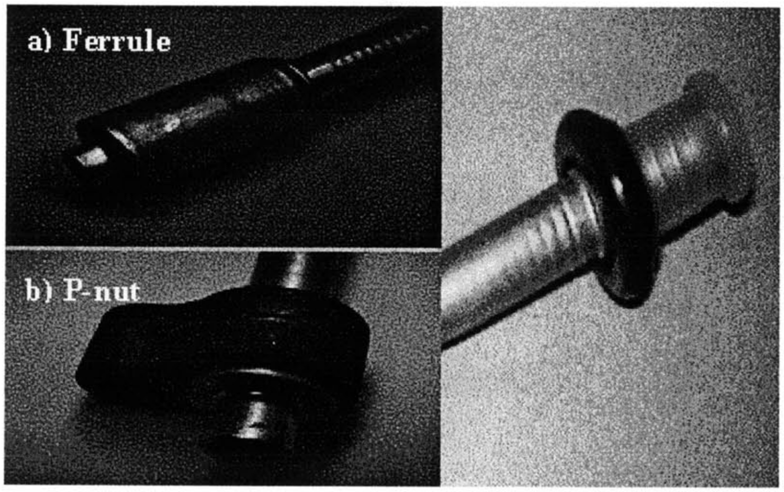


Figure 4-3: Formed end types

In ferrule machining the tubes are cold worked during a six second cycle time and the process requires application of oil for lubrication. The parts are dipped in oil and the technique causes oil to enter the tube interiors further complicating the task of washing. The ferrule forming operations require three machines or more machines, with one or more needed for diameter reduction, one needed for forming V-shaped grooves and the last one for forming the ferrule bead on the tube. The end cage formation operations are similar to the ferrule except that no diameter reduction is needed, hence the operation can be completed using two machines.

4.4.1.3 Washing

The need to wash is a direct result of having to remove the oil used in tube cutoff and end forming. If the parts are not properly cleaned, the subsequent process of brazing may produce braze joints that are weak and porous. Washing is thus an operation that is made necessary through the use of oil is the previous processes and is not intrinsically value adding.

Washing is done in 4 stages – pre-soak, detergent bath, rinse, and dry. In order to wash the tubes, bundles of about 200 are loaded into a large metal basket, and then within each of the first three stages the metal basket is introduced into the bath and rotated by an overhead joist. The washing system, shown in Figure 4-4 has two major problems. First, it is not a capable process since some parts remain oily after passing through the washer. Secondly, the washing process causes damage to a high number of the tubes due to deformation and scratching caused during the rotation of the basket in the washing stages.

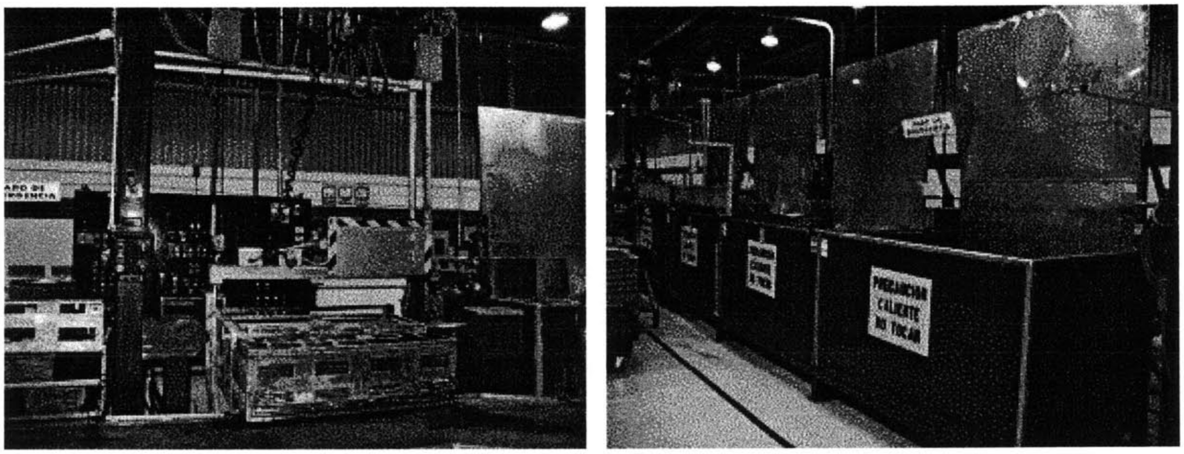


Figure 4-4: (left) Metal basket that holds parts (b) Washer stations.

Post-wash inspection station requires four operators to visually inspect all parts and given the large number of tubes the inspectors have to look through, they often choose to inspect about ten parts at a time. Thus defective tubes often get camouflaged and are overlooked. However, the more serious problem with washer-related defects is that they come after a significant amount of tube fabrication has already taken place.

4.4.1.4 Brazing

Brazing is necessary when the geometry of the parts do not allow joining by forming. For instance, forming can only be used at the tubes' ends, while some designs require the joining of tubes along their length. For aluminum tubes there are 4 typical braze types made which include saddle, stem adaptor, charge valve, and P-nut. The aluminum-brazing machine has two workers tied to it, one for loading the parts onto the fixture and the other for unloading the brazed parts. The braze machines run a single part type at a time and thus there are identical fixtures at each of the twelve stations of the machine causing the storage of these fixtures to take up precious floor space. However, the larger issue is that of changing over between models and the task of removing each fixture and replacing it with the new one takes about 20 minutes. The process of adjusting parameters to account for the new tube geometry and heating requirements of the braze type is not standard. Consequently, several parts are run before the first good part is obtained.

4.4.1.5 Assembly Area - Bending

The assembly area consists of two departments bending and final assembly. In the bending department, the machines bend the tubes through the use of impact dies. All machines have one operator tied to them whose task is to load two stationary dies with tubes and activate the machine causing the impact dies to bend both tubes simultaneously as shown in Figure 4-5.

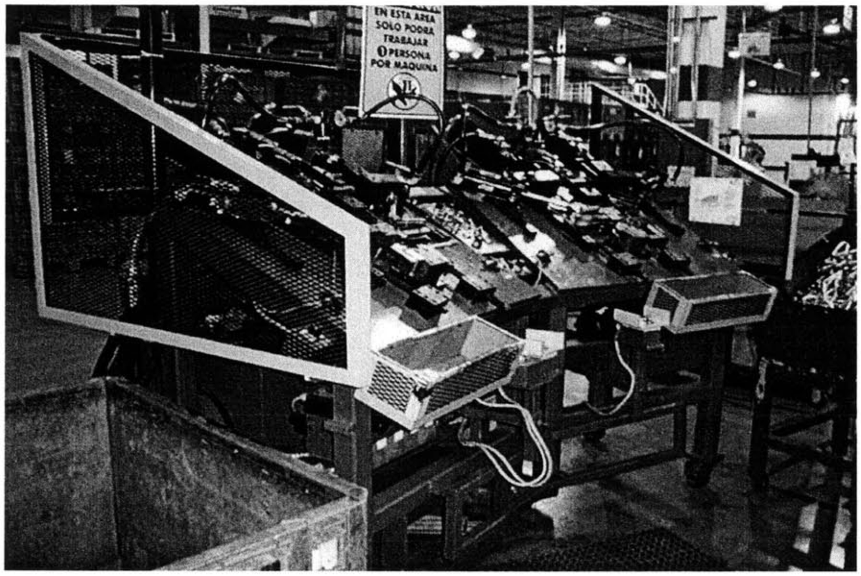


Figure 4-5: Dual-station bending machine

4.4.1.6 Assembly Area – Final Assembly Lines

After passing through all other departments, the tubes reach moving-belt assembly lines and are assembled to rubber hoses for construction of the end product. A typical assembly line is responsible for the production of about 3,000 to 4,200 parts a day, which is equal to a cycle time of 6.2 to 8.7 seconds. Given that final assembly has been designed to run at such a short cycle time, the work is greatly subdivided. As a result, the assembly lines measure close to 100' in length, and the number of workers per line ranges from 18 to about 30 depending on the complexity of the hose being assembled. The operations that take place on the line are inspection of the tubes, attaching O-rings, crimping of the tubes to the hoses, leak testing the assembly, and preparing the product for shipping by attaching protective caps to the tube ends. Several quality problems exist in final assembly. Some of the problems are due to incoming material from fabrication. Other problems are caused by the abusive handling of the material on the line itself in which the operator tosses the part back on the conveyor after each operation.

4.5 Scorecard of the Pre-Project Manufacturing System

Manufacturing operations can be classified into one of the following: processing, inspection, storage, and transport [Shingo, 1989]. Processing is often the only value adding operation where the latter is defined as changing the form or function of a part to a state that the final customer is willing to pay for. For example, customers will pay for connectors that do not leak. However, while inspecting the connectors for leaks in the assembly may ensure a quality product, the act of inspection adds no value. In any case, all manufacturing systems require some amount of inspection, storage, and transport, reduction of these non-value adding operations and improvement of value adding operations is always the goal. Thus, while each operation of the system could have been analyzed individually and stripped of its non-value adding components, many problems were the direct result of the departmental mass system design. Table 4-1 offers a summary of the manufacturing systems key features that served as objective parameters for evaluation, where objective implies being measurable as well as relevant to system performance. Measures such as throughput time and scrap help highlight how the mass departmental layout with large lot sizes, complicated material and information flow in the push system, unnecessary transport and storage at successive processing stages and high setup time machines contribute to high throughput time, poor quality (high scrap rates) and high levels of inventory.

<table>
<tr><th>Features</th><th colspan="2">Manufacturing System</th></tr>
<tr><td>Production</td><td colspan="2">~7,000,000 parts/year</td></tr>
<tr><td>Floor Space</td><td colspan="2">163,140 sq. ft</td></tr>
<tr><td>Direct Labor proportion</td><td colspan="2">0.83</td></tr>
<tr><td>Man Hours/part</td><td colspan="2">0.31</td></tr>
<tr><td>Fab Scrap Expenses/Part</td><td colspan="2">~8 cents/part</td></tr>
<tr><td>Fab WIP</td><td colspan="2">Variable~64,000</td></tr>
<tr><td>Fab Throughput Time</td><td colspan="2">Variable~1 day</td></tr>
<tr><td>Assembly Scrap Expenses/part</td><td colspan="2">~2 cents/part</td></tr>
<tr><td>Assembly WIP</td><td colspan="2">Variable~1800</td></tr>
<tr><td>Assembly Throughput Time</td><td colspan="2">Variable~1 day</td></tr>
<tr><td>Fabrication Production</td><td>a) Machine cycle time</td><td>b) Number of machines</td></tr>
</table>

tube cutoff machines	2-4 sec (length dependent)	10
formers (3 stroke)	6-8 sec	56
formers (6 stroke)	6-8 sec	23
groovers (ferrule)	6-8 sec	21
groovers (end cage)	6-8 sec	4
piercing machines	2 sec	13
washers	~ 30 min	5
Aluminum brazers	9-11 sec	16
Assembly Production	a) Cycle time	b) Number of machines
assembly lines	6.2 – 8.7 sec	12
Bending machines	4 sec	132
crimping machines	4 sec	46
Leak testing machines	operator dependent	28

Table 4-1: Scorecard for Pre-Project State of Manufacturing System

4.6 Manufacturing System Design Process and Phases

The methodology chosen for the system design change and implementation was based on the relative evaluation on the system design pyramid presented in the previous chapter. The MSDD helps make explicit the interdependencies among the various aspects of design and the relation of high-level project goals with the lower level design tools. The MSDD [Suh, Cochran, Lima, 1998] also helps in design evaluation by comparing the system design on various FR categories such as identification and resolution of problems, quality, delay reduction etc. to check if it meets the functional requirements at various levels. Used in conjunction with the 8 Steps to Lean [Cochran 1999] also known as the Production System Design and Deployment Framework (PSD-DF), it was intended to provide detailed direction for the new system design. The combination of the MSDD and Eight steps to Lean also addressed most levels of the pyramid and the issues with the system. The steps are not exhaustive but can be mapped with respect to the system engineering phases described earlier in order to produce a set of actionable items to guide the design and implementation process. The steps are listed below:

- Step 0. Determine who the customers are
- Step 1. Define linked cell system
- Step 2. Form cells based on takt time
- Step 3. Reduce setup times - Single minute changeovers

- Step 4. Improve quality and output predictability
- Step 5. Level manufacturing in assembly cells
- Step 6. Link cells with a pull system
- Step 7. Link suppliers with plant pull system
- Step 8. Integrate product development

The 8 steps do not necessarily follow the design hierarchy inherent in the phases. A mapping of the steps with the system design phases is presented in Figure 4-6 below.

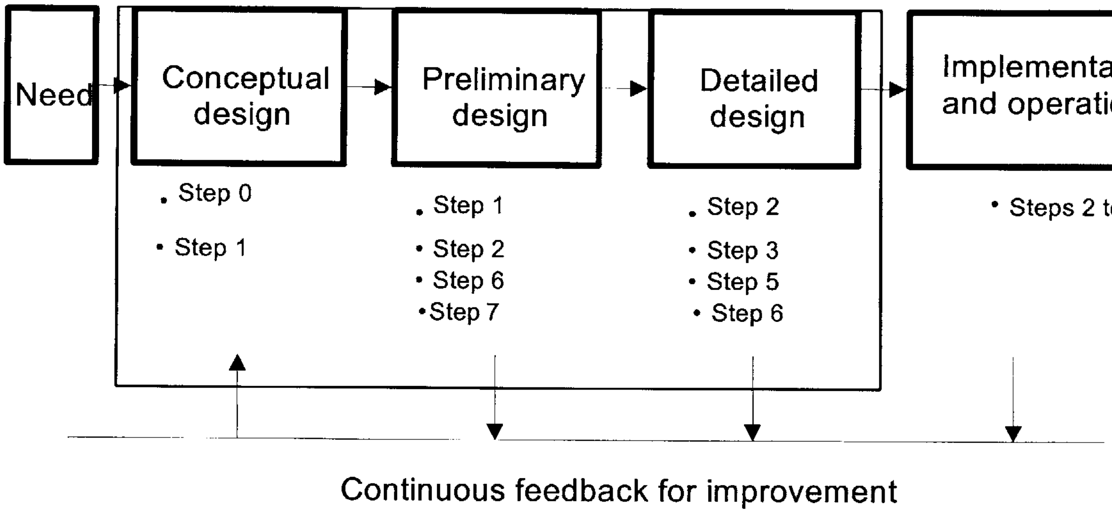


Figure 4-6: MSDD Steps mapped with the System Engineering Phases

4.7 System Engineering Approach to Manufacturing System Design

This section describes the application of the chosen methodology within the system-engineering framework. As the design progresses through the conceptual and preliminary design phases into the detailed design phase it becomes more and more granular. The system engineering approach has a three-tier view of the MSD process.

The design takes place at three levels starting with the system level, leading to the sub-system level, and finally the unit level. Figure 4-7 attempts to capture the three-tier view. As one moves down the levels the scope becomes more specific. At the system level, questions must be answered regarding criteria for forming product families, information flow between cells and the final customer, and the strategy for linking fabrication and assembly. Once a system-level picture is painted, the subsystem level focuses on the specifics of designing individual cells, which are the building blocks of a lean manufacturing system. At the subsystem level, the design choices pertain to takt time, layout, and the linkage of suppliers and material handling for the sub-systems. At the unit level, attention is focused on the cell details since each cell presents a unique set of constraints and needs to be designed differently. The unit level design also places attention on the station and equipment design.

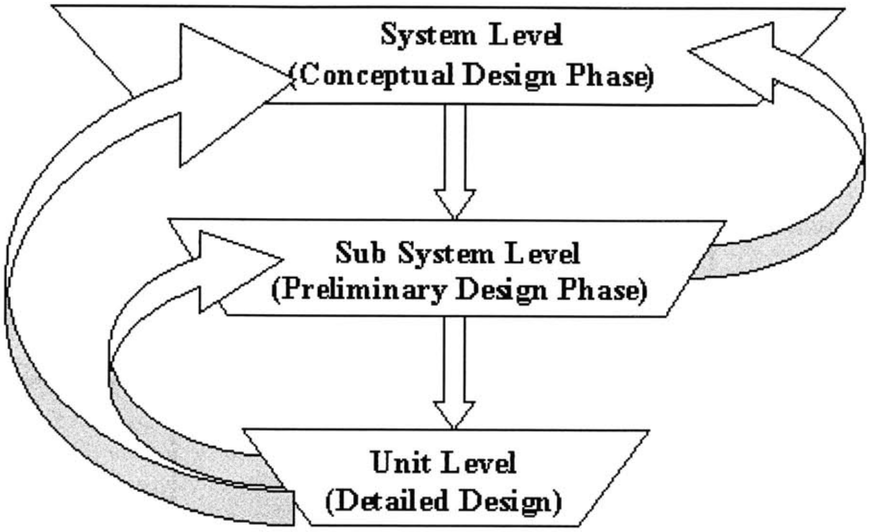


Figure 4-7: Design Levels of a Manufacturing System

Decisions made at the lower level should be in line with the goals of the level above it. Once a design decision is made at a lower level, the levels above have to be adjusted to account for the decision. Thus, the higher levels are continually fine tuned in response to the discoveries and decisions made at the lower levels, allowing rough designs to become more detailed. Each of the above design phases as applied to the manufacturing system design project are discussed in detail in the next few sections.

4.7.1 Conceptual Design Phase

A significant deviation from Cochran's list of steps came in Step 0, "Determine who the customers are." Identifying the customers gives a basis for product family formation. The rationale for forming families in this manner is that if all products going to a single customer constitute a family, then the system shown in Figure 4-8 can be achieved. In this system, the flow of parts and information is in its simplest form, and a system-level goal is achieved. However, in the case being studied more than one hose made up a single automobile's air conditioning unit. Thus, hoses going to a single customer are not necessarily similar in material, geometry, and size, and hence undergo different manufacturing processing routes. Forming product families based on customers would have led to an increased level of complexity at the subsystem level of design. Therefore, families were instead formed on the basis of processing using the following criteria in the same order of priority as shown in Figure 4-9.

- Material make up (all steel, all aluminum or hybrid)
- Number of crimps (0, 2, 4, 6 or 8), related to number of connector tubes making the end product
- Braze type (none, saddle, charge valve, P-nut, stem adaptor, or other.)
- Hose diameter (5/16", 1/2", 5/8" or 3/4")

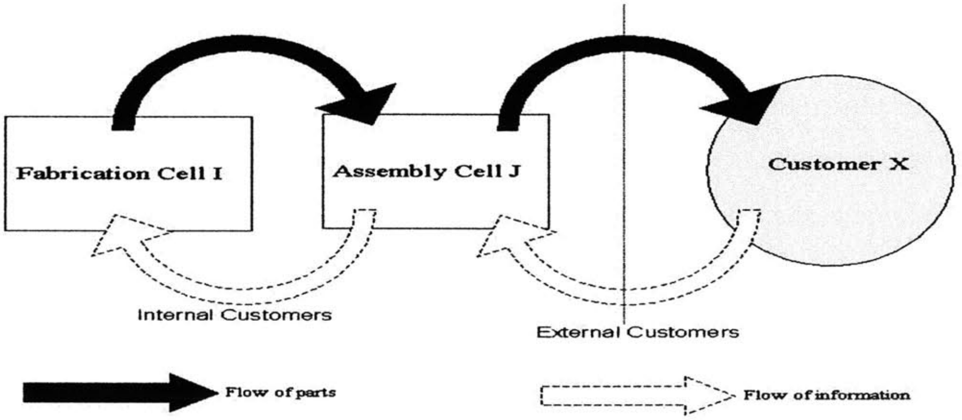


Figure 4-8: Simplified Flow- Customer based families

The criteria for product family formation influences complexity across all levels of the manufacturing system design -- system, subsystem (cell), and machine. At the system level, the greatest impact of product family formation is on physical layout, which determines the material and information flow. At the cell level, product families dictate the complexity of the fixture design, the amount of changeover required, and the "intuitiveness" of the cell -- how easy it is for the cell operators to learn their job and make suggestions for improvement. The manner in which product families are formed also dictates the number and complexity of individual machines within a cell.

In comparing the two approaches to product family formation, processing and customer based, in cases that multiple customer demand similar product types but different products, forming cells strictly on the basis of the final customer leads to the unnecessary duplication of similar cells. Moreover, individual cells have to run hose models with very different processing routes and specifications.

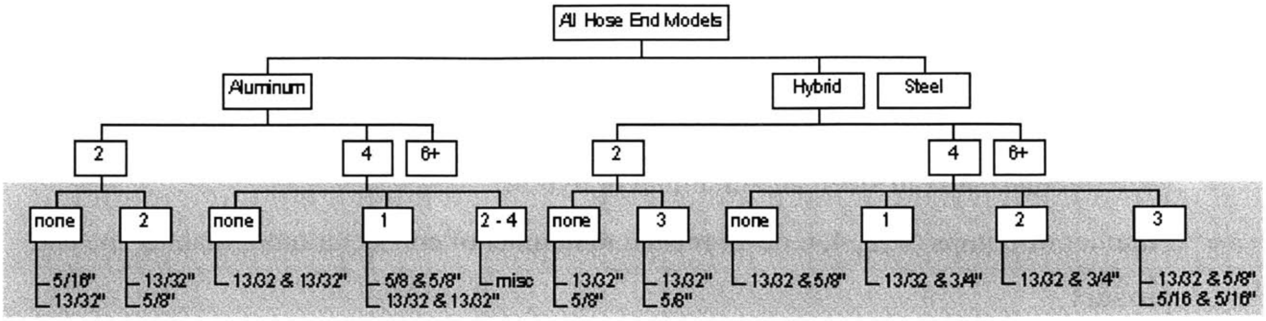


Figure 4-9: Product Family Tree with second, third and fourth levels representing number of crimps, brazes and hose diameter respectively.

For steps 1 and 6 we needed to define a linked cellular system and devise a system for linking the cells with a pull system. A linked cellular manufacturing system was chosen as the conceptual model for the system design as the manufacturing at these plants was an example of repetitive discrete part manufacturing. The linked cellular subsystem design model has been shown in literature to meet the subsystem requirements of reduction of throughput time, reduction of transport and storage delay, and increased worker utilization through single-piece flow and multi-functional workers [see also Shukla, Estrada, Cochran, 2000]. For a linked cellular manufacturing sub-system three points are important:

- Cells formed in assembly and fabrication that run products from the same family.
- Linking the material and information flow.
- Pacing and leveling production in the subsystem based on customer demand.

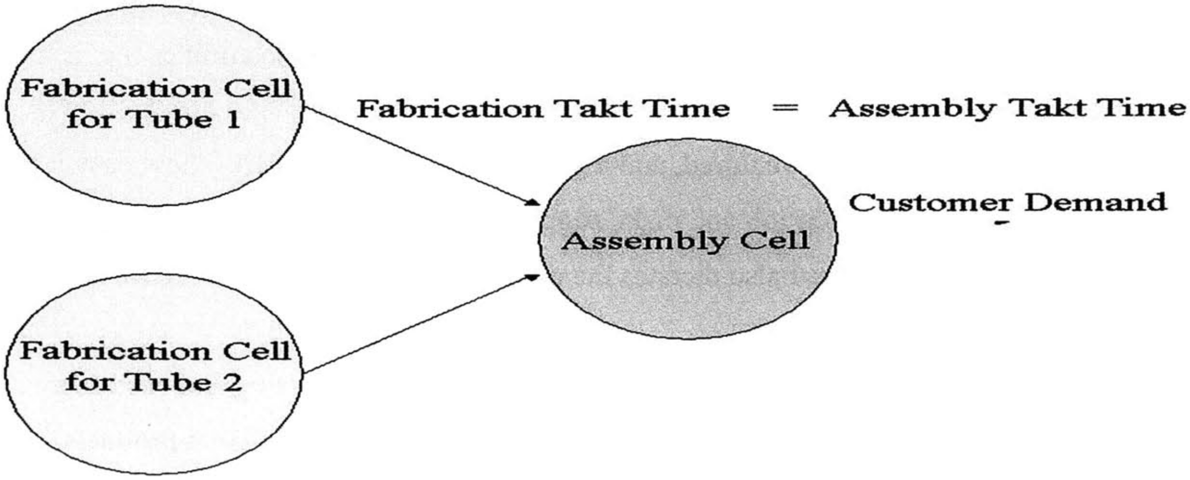


Figure 4-10: Linking Fabrication cells to Assembly

The strategy for linkage of fabrication and assembly was to have the number of fabrication cells feeding the assembly equal to the number of connector tubes being assembled in the end product. The general model for linking a 2-connector assembly with fabrication cell is presented in Figure 4-10.

4.7.2 Preliminary Design Phase

This phase was essentially an extension of the principles set forth in the previous phase. In order to implement the conceptual model it was crucial that cells were defined and based on the customer demand time also known as takt time, the available production time by the demanded quantity in that period. Also the pull system linking the cells and a process for integrating suppliers both internal (material handlers) and external (raw material) was needed to implement Steps 1,2, 6 and 7. Additionally, it was critical that the definition of the cellular subsystem articulated:

- Elimination of the non-value adding operations of leak testing in assembly and post-wash inspection in fabrication
- Redesign the equipment so it is cell compatible
- Personnel re-organization on lines of formed product families

The issue of the non-value adding operations is addressed in the structure of the linked cell sub-system that was proposed. The ideal system design integrated the bending process with the assembly and washing was integrated in the fabrication cells with the future plan including critical examination of the need for washing and its possible elimination altogether. For the cells in Figure 4-11 to be implemented it was apparent that some of the machines would need to be replaced (washing, bending) while all would need some modification for cell compatibility. The linkage of the cells in design was further achieved through the provision for Standard WIP (SWIP) or decoupler between assembly and fabrication and the final assembly Heijunka helps level and pace the cells based on customer demand. This structure helps provide the framework for integrating supply and distribution at a later stage. The implementation scheme of some of these cells on lines of formed families and the proposed equipment designs for replacement and modification of equipment would be the subject of the detailed design phase.

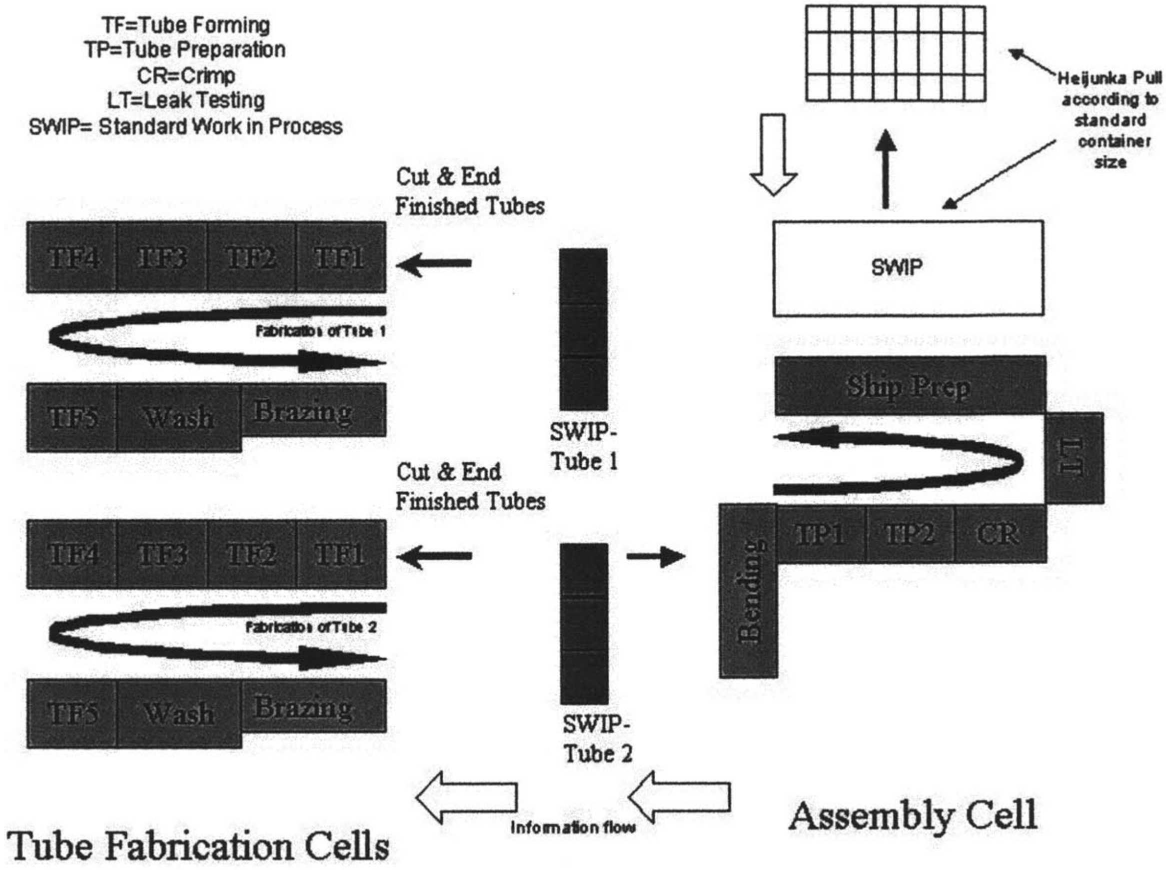


Figure 4-11: Proposed Ideal Design for Linked (cellular) Sub-System for the plants; Fabrication cells are designed for the ideal case with washing and brazing integrated.

4.7.3 Detailed Design

The detailed design builds on the ideal design proposed in the preliminary design phase. The detailed design process was two-fold. One involved the design of the assembly cells based on the ideal design proposed in the previous phase and modified according to the system constraints. The second dimension in the detailed design phase was to modify or design new equipment suitable for operation in the fabrication cells or in the case of assembly cells for integration of bending equipment with the cells. This phase therefore involved the detailed design of cells based on takt time, means to reduce setup times on equipment and equipment redesign and ultimately link the cells with a pull system (Steps 2,3,5 and 6).

4.7.3.1 Final Assembly

The final assembly in the previous system consisted of bending and the final assembly lines. These assembly lines were conveyor-belt driven and the design process followed four main steps. First the line cycle time was determined using the demand information, then industrial engineering provided standard times for each operation which together with the line cycle time, helped determine the number of direct workers. Finally the length of the lime was determined based on line cycle time and operation times. The layout of the assembly line is shown in Figure 4-12.

The Industrial Engineering Department provided standard times for each operation; however over time, as the workers moved over the learning curve they worked faster. The obvious problem was that almost all workers by design had a significant portion of idle time per cycle. Figure 4-13 provides a plot of the work standard times against typical line cycle time and shows that the workers are idle for nearly half a part's throughput time. Initially this line was designed for an output of 470 parts an hour translating to a line cycle time of 6.2 seconds/part (assuming 0.85 uptime factor). However, when volume increased the only option available was to operate the line on overtime with all workers present. The loss of worker utilization was a result of the short cycle time of the line that made line balancing very difficult. Moreover, several problems that caused line stoppages for varying amounts of time were observed to be a direct consequence of the moving assembly line design [Estrada, Shukla et al, 2000].

- Conveyors create the need for final inspection; since a part can pass through a station unprocessed.
- Linear conveyors prevent inspectors from fixing the problem themselves; part has to be pulled off line, placed in rework areas and receive attention after indefinite periods of time, output quality is therefore variable and unpredictable leading to addition scheduling costs, floor space and expediting costs.
- Lines are never truly balanced; workers operating at different cycle times cause increased WIP and throughput time, leading to unpredictability.
- Intentional line stoppages have gained prominence as a lean concept. However, when the workers are focused on their operation and do not respond as a team to the problem then its causes and resolution are not known and the problem could repeat itself. Physical isolation in long assembly lines tends to stifle teamwork.

Basic variables such as belt speed and operator times are standard and not subject to analysis thus limiting scope for continuous improvement.

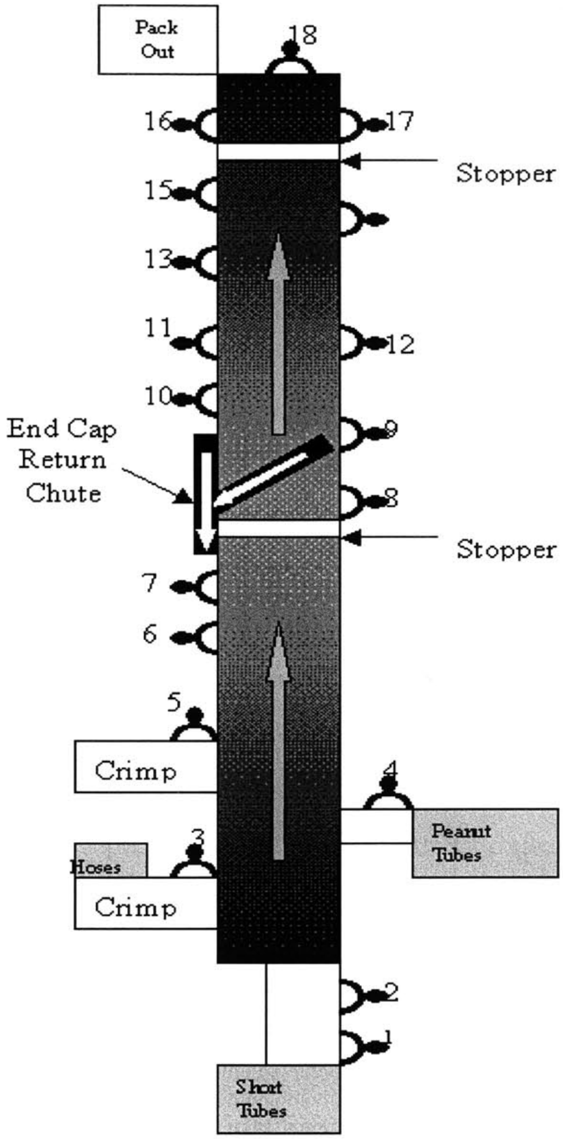


Figure 4-12: Layout of the Assembly Line

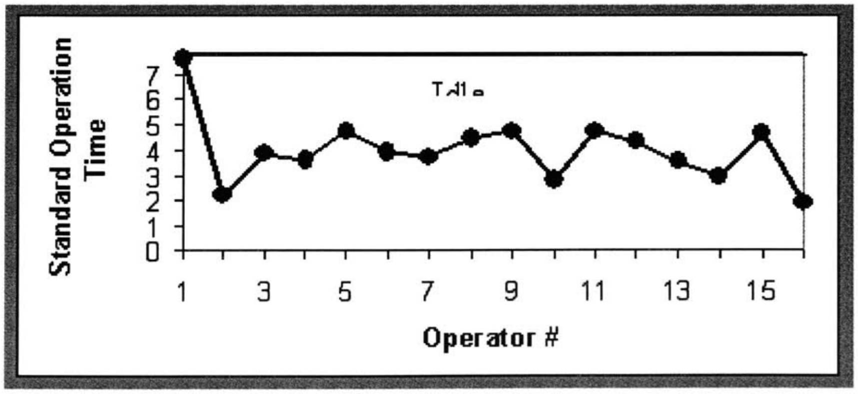


Figure 4-13: Proportion of Idle Time in Operation Times

The project constraint of minimal investment translated into constraints on the number of leak testing equipment and crimping machines that could be used in the new cell design. Ideally, the cells in this system for highest volume flexibility would have been arranged in a parallel row layout allowing workers to be shared between cells. However, the constraint of leak testing equipment implied that each piece of the latter had to be shared between two cells. Moreover since all equipment for the cells had to come off from the lines being converted, a single crimping machine would have to make both the crimps in the assembly. Thus equipment off each line would help produce two assembly cells placed in a U-shape to share the leak testing equipment in the layout shown in Figure 4-14.

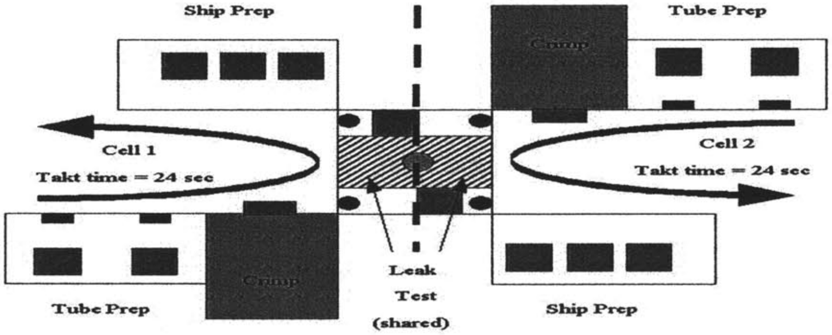


Figure 4-14: Layout of two cells formed from equipment offthe line

The individual operations on the assembly lines and their equivalents in cellular operation, the choice of work loops in the cells, the number of workers needed and other implementation challenges would be discussed in the sub-section on the implementation and operation phase in the context of an actual pilot implementation. The remaining portion of the detailed design phase covers the modifications that were conceptualized for incorporation of bending into final assembly. The discussion is at a conceptual level and hence arguably more relevant at earlier stages. However, incorporation of bending was proposed in the earlier stages and it was the inability to invest in modifying bending equipment that influenced the pilot implementation. The design modifications are therefore included in the detail design phase.

4.7.3.1.1 Bending Machine Design

The bending machines were incompatible for use in final assembly cells due to physical size constraints as well as poor design of these machines for cellular operation. The number of bends per tube in a connector assembly ranged from 0 to 12. However, two tubes with an equal number of bends did not necessarily have similar geometry since the position and/or angle of the bends along the tube length could vary. A specific die was needed for each bend required with changeover times exceeding 20 minutes. A family of products being run in a cell would thus need a bending station (2 per machine) for each connector tube assembled in the cell. Thus with the current design of machines it was not difficult to imagine situations where more than half a dozen of these machines would be needed, greatly increasing physical cell size. It was therefore suggested that the current bending machines be completely replaced if they bending is to be incorporated into assembly cells.

With CNC (Computer Numerically Controlled) benders a single machine can bend any tube regardless of the number of bends or geometry required and the need for dies is eliminated. However, it is necessary that the machines be capable of bending tubes with formed ends. In order to make the CNC bender capable of handling formed tubes, it is necessary to change the mechanism used to rotate and index the tubes. On the CNC benders currently used within the prototype shop of the system, the tube is fed into a single jaw that rotates and indexes it, as well as holds it in place during bending. Since the jaw requires that the tube have a uniform outer diameter over its entire length, a tube with formed ends cannot be fed into the jaw. The current design is depicted in Figure 4-15.

In the new two-jaw design, one jaw would be able move along the length of the tube dictating the location of the bend, while a stationary jaw would be used to rotate the part. Thus, the material would not feed into the stationary jaw as in the current design; instead, the stationary jaw located to the side of the tube, would be positioned at a convenient point along the length of the tube. In this arrangement, a tube with formed ends can be handled. The concept for the new design is shown in Figure 4-16. The current design exposes a fundamental flaw in most design processes that the body of literature on axiomatic design [Suh, 1990] uncovers. Most designs have parameters that solve more than one need. The classic example is the problem of designing faucets to deliver water at a particular temperature and rate. Most faucets have two independent supplies of hot and cold water, thus each stream (design parameter) can influence both requirements. This leads to an iterative trial and error process of adjustment and almost never is the end result an accurate combination of desired temperature and flow. The solution would be to have two controls one which sets the temperature and the other the flow, independent of each other. The application of the above principle of separating the design decisions from the requirements is reflected in the proposed design and Figure 4-17 that compares the two approaches.

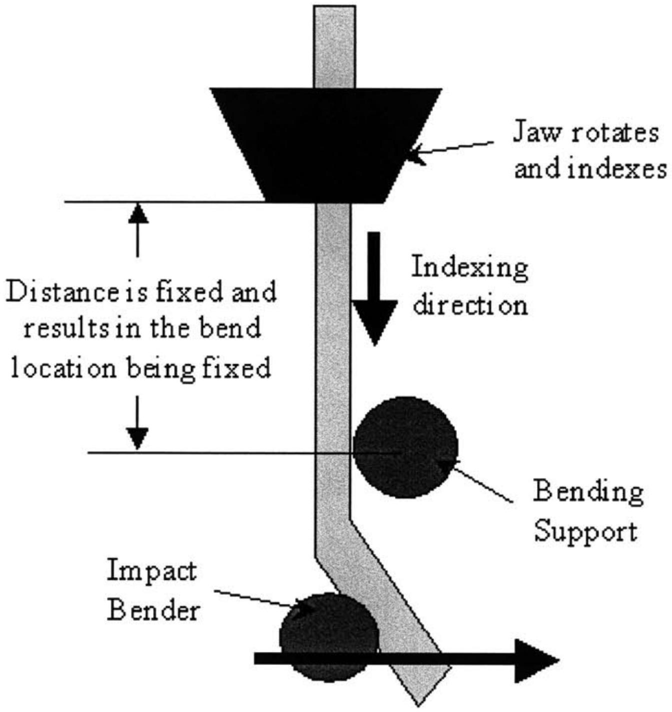


Figure 4-15: Current design couples the indexing and rotating functions into a single jaw, and therefore cannot accommodate formed tubes.

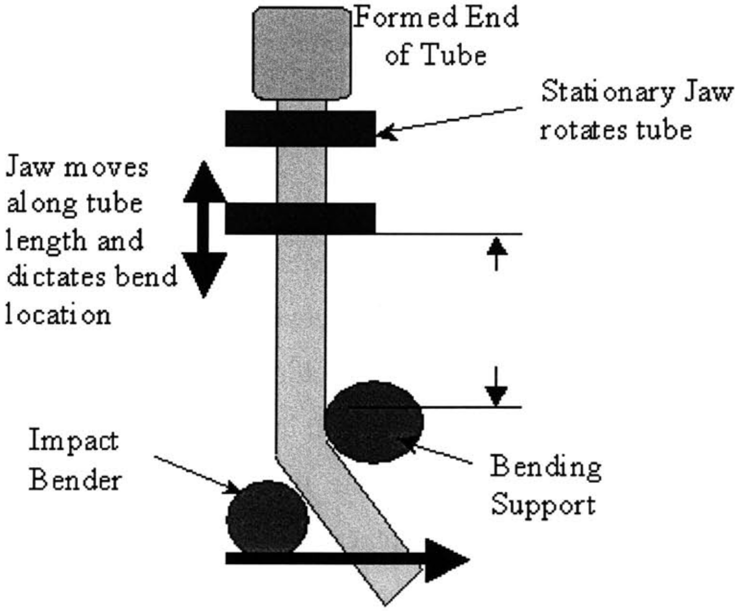
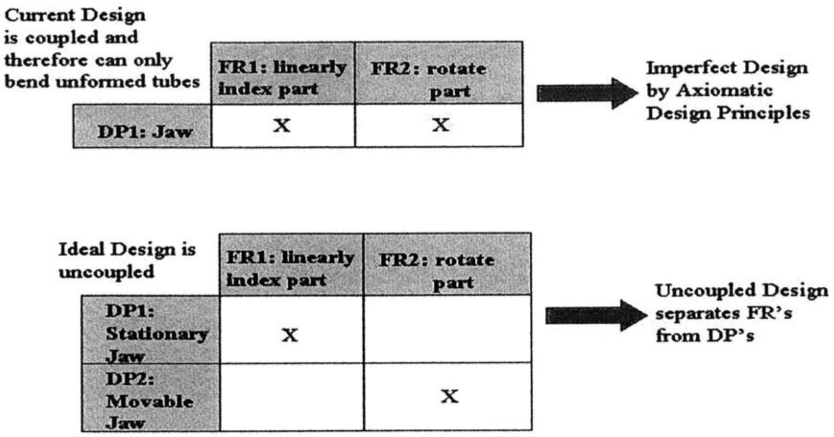


Figure 4-16: Proposed design for uncoupling rotation and indexing of the tube. Part is not linearly indexed, instead a jaw moves along the length to dictate bend location. Allows formed tubes to be bent.



Current Design is coupled and therefore can only bend unformed tubes

	FR1: linearly index part	FR2: rotate part
DP1: Jaw	X	X

Imperfect Design by Axiomatic Design Principles

Ideal Design is uncoupled

	FR1: linearly index part	FR2: rotate part
DP1: Stationary Jaw	X	
DP2: Movable Jaw		X

Uncoupled Design separates FR's from DP's

Figure 4-17: Comparison of the proposed design with previous design approach

4.7.3.2 Fabrication

The benefits of linking fabrication to the cellular assembly are in terms of enabling better control over the production system and producing at the average pace of customer demand. The generic model for a sub-system in the proposed production system as presented in Figure 4-7 suggests creation of a fabrication cell per tube regardless of the number of tubes in the connector assembly. This design scheme ensures that the fabrication of the tube is based on the same takt time as the assembly thus making it possible to pace all cells at the same rate. More importantly it also ensures that the fabrication cells do not have to operate at very low takt times as that causes problems in balancing work loops. The design scheme also assumes that the equipment used for forming, washing and brazing would be cell compatible. However, several problems with the design of current equipment prohibit their operation based on the principles of cell design. These principles include SWIP between cells and single piece flow within the cell and the separation of the worker from the machine. These goals ensure low throughput time and high quality as well as simplify the product and information flow.

To make fabrication in cells possible, the equipment must be capable of meeting cell design requirements. In addition there are other requirements from worker safety, ergonomics, quality and material handling points of view that the equipment design must satisfy. The approach to equipment design for new brazing machines has been based on the PSD framework for the design of an actual manufacturing system. Selecting key FR-DP pairs and grouping them into the various categories resulted in a document that provided guidelines for equipment design. Figure

4-18 [Arinez, 1998] shows the shaded FRs-DPs that were selected from the PSD decomposition hierarchy according to the five categories listed in the figure. Selected FR-DP pairs relevant to each category and the evaluation of existing equipment design relative to those FR-DP pairs would be discussed under individual equipment analysis in subsequent sections.

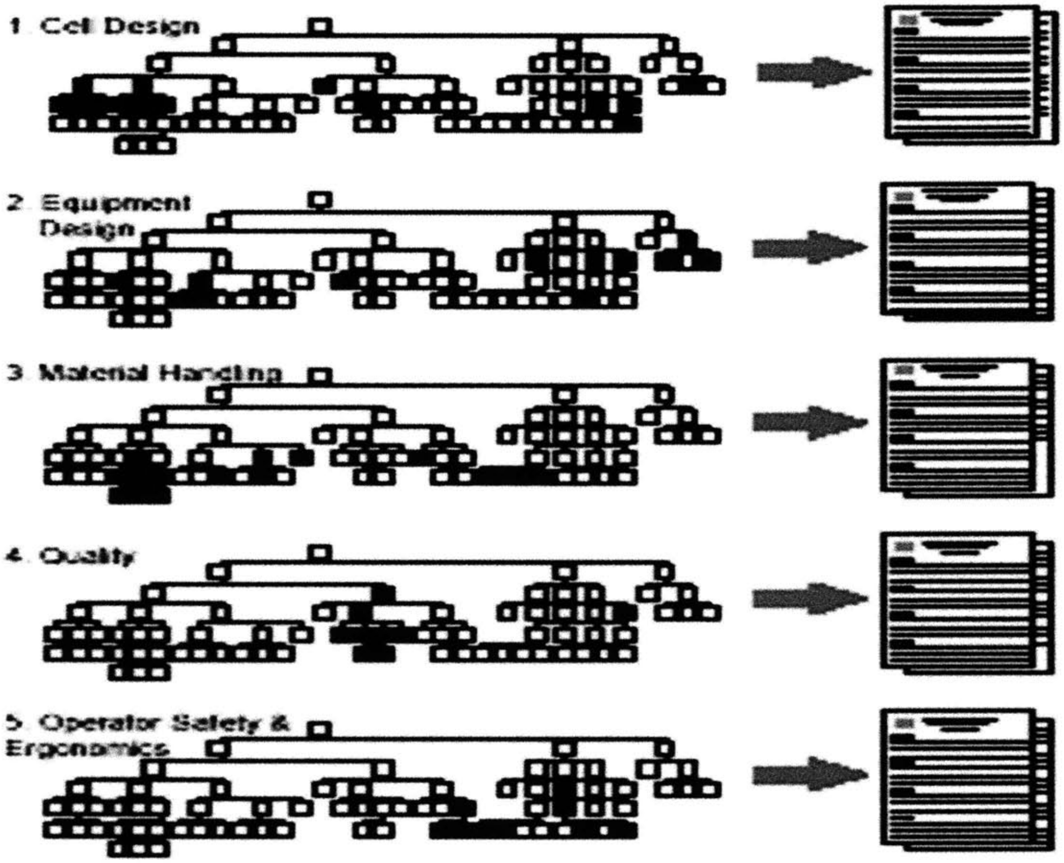


Figure 4-18: Generation of guidelines for equipment design based on the Production System Design Framework.

For reasons mentioned briefly below, cellular operation with current equipment was not feasible.

1. *Forming Machines:* These machines operate on cycle times as low as 6-8 seconds and require an operator to be *fixed* at the station to feed the parts.
2. *Washing Machines:* Too large machines that required large batches of about 1000-2000 and with cycle times as large as a couple of hours precluded the possibility of being included in cells.

3. *Brazing Machines:* Operators fixed to the station, unreliable production, and multi-piece continuous motion machines made separation of workers from machine different. Long change over times would make the leveling and mixing of production difficult.

The next few subsections discuss in detail the challenges imposed to formation of fabrication cells by each set of equipment and the detailed plans proposed for addressing these challenges. In the case of washers and brazing machines proposed plans included detailed conceptual designs of replacement machines.

4.7.3.2.1 Forming Machines

The major issues with the current forming machines are their cycle times, operator ergonomics, physical design and maintenance procedures, use of oil and its application method. Specifically, the machines have cycle times on the order of 6 to 8 seconds, and in the departmental layout it is most logical to have one operator per machine. The machines are also designed with a single seated operator in mind. The loading position thus is lower and does not permit mobility in workers.

In the current design, a control panel and tank are located on either side of the machine extending the overall width by about two feet. It is important to note that the control panel is not used for activating the machine during production, but rather is used during routine maintenance checkups and changeovers. Currently, the protective cage has doors on either side that are opened for daily cleaning which involves picking up the oil that falls off the tubes and chips created during the forming process. This increases the effective width of the machine thus increasing the walking distance if the machine is placed in cells. The use of oil in forming machines serves two important purposes. One, given the high machine speed (low cycle times) it helps act as a coolant for the high speed dies as natural convection cooling is not sufficient. Two, it helps lubricate the die as it moves over the tube. The oil is currently applied by dipping the tube in oil. This causes the oil to flow along the inner and outer walls of the tube while its application is necessary only at the end, where the tube gets formed.

The following modifications to the machine design are suggested in order to make the forming machines compatible for cellular operation. Some of these modifications can be easily made on existing machines as suggested in Figure 4-19 that shows the former and proposed designs of existing machines.

1. Slowing the machine dies so that machines have cycle times of 25-30 seconds, allows machines to be designed with lesser dies consuming lesser energy as well as allowing workers to separate from the machine in cellular operation.
2. Slower cycle times would translate into significantly less oil being needed and the current oils should be replaced with water-soluble ones.
3. A minimum amount of oil needed to ensure an acceptable formed end and prolong die life should be applied only at the required point. This could ensure that the subsequent task of washing may reduce to simply rinsing the ends of each tube and wiping them dry.
4. To make the machine accessible for cleaning from the front, a funnel-like device could be used to carry the waste and channel it toward a reservoir in the front of the machine. In this way the reservoir can be quickly removed and replaced by a clean one, with cleaning taking place off-line by maintenance personnel.
5. The control panel (used only for maintenance purposes) should be placed above the machine and the tank below.
6. The machine should be raised to a convenient height so that a walking worker can easily load a tube.
7. For cell compatibility it would also be ideal for the forming machine to be placed on casters to allow various cell configurations to be continually tested with minimal effort. It also allows a machine requiring service to be easily taken out of the cell, and replaced by another machine with a minimum disruption to production.

These suggested modifications address specific functional requirements related to equipment design from the MSDD and translate into guidelines for equipment design. In order to illustrate how the design modifications serve as DP's for equipment design FR's, Table 4-2 evaluates the existing and proposed designs against the relevant FR-DP pairs.

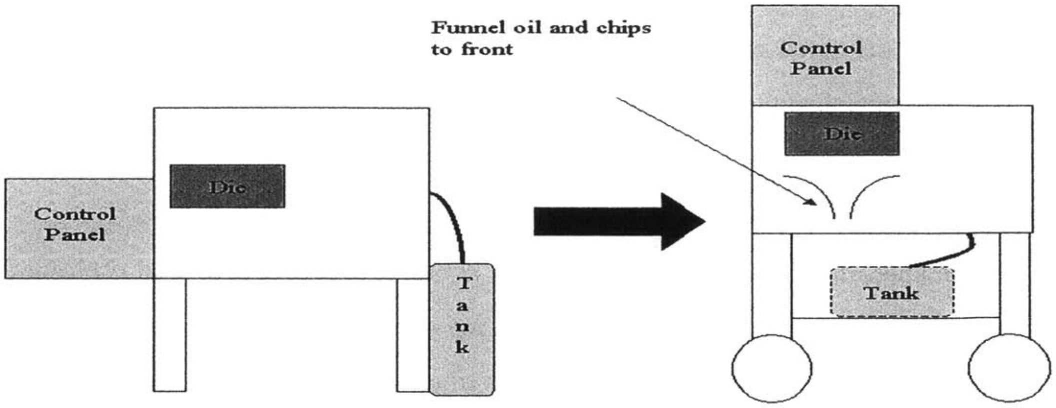


Figure 4-19: Suggested changes to the current forming machine design for the purpose of cell compatibility

Criteria	*Functional Requirement/ Design Parameter*	*Existing Equipment Design*	*Proposed Design*
1. Cell Design	a) Reduce walking distance/ Machine width < 4ft, in a U or parallel row configuration.	6 ft	<4 ft. The control panel should be placed above the machine and the tank below.
2. Equipment & Station Design	a) Do not disrupt production for simple maintenance activities/ Controls and systems accessible from the rear of station	Maintenance activities disrupt production.	8. Machines placed on castors allow easy removal from cell for service, and can be replaced by another machine with a minimum disruption to production.
	b) Reduce tasks that tie the operator to the machine/ Machines designed to run autonomously	Fast cycle times, seated and continuous operation tie operator to station	Operator only loads the part and slowing the machine dies so that machines operate efficiently in slower cell cycle times (~ 25-30 seconds) allows workers to leave the station.
	c) Reduce long term investment on machines and equipments/ Acquisition of simple and flexible machines	Fast cycle time machines are expensive to replace.	Machines with slower cycle times are less expensive, more energy efficient and have higher die longevity.
3. Material Handling	a) Finish processing and part unloading before the operator arrives at the machine/ Automatic unloading of parts	Fast machine cycle times require operator to load and hold the part.	Auto unloading of parts coupled with slow cycle times would allow worker to load the part, proceed on her work loop and return to find an auto unloaded part.
4. Operator Safety and Ergonomics	a) Load parts cost effectively and quickly into machines/ Ergonomic interface between the worker, machine and the fixture	Machine designed for seated operator continuously holding the part.	Machine is raised to a convenient height so that a walking worker can easily load a tube and leave the part in the machining slot that auto-unloads.

Table 4-2: FR-DP based evaluation of the existing and proposed equipment designs

4.7.3.2.2 Brazing Machines

The above discussion leads to the most important concern in the formation of the fabrication cells, the process of brazing. Brazing is necessary when the geometry of the parts do not allow joining by forming. The 4 typical braze types on tubes in the system were saddle, stem adaptor, charge valve, and P-nut. A saddle braze joins the end of one tube along the length of another tube, forming a T-shape. In case of stem adaptors an adaptor is inserted along a tube's length and the last two braze types, the charge valve and P-nut, are joined to the end of the tube. In the current system, brazing is the source of a number of defects produced in the final assembly. Figure 4-20 shows the difference in the braze types. Additionally, there is no control over the process as the parts regularly have defects and the machine operation is continuous with a fixed output rate. Often the parts do not move along a defined path through the brazing process.

4.7.3.2.2.1 Current Design

The current machines are designed as continuous rotary table machines with 12 stations. The reason for the rotary station design is to achieve high speed of machine operation. Each station has a fixture mounted on it, capable of holding a part. The table rotates through one station every 9-11 seconds depending on the braze type being run, producing a brazed part every 9-11 seconds. The throughput time of the brazing machine is around 2 minutes. At the first station, the parts are manually loaded and flux is applied while at each of the next three stations there is a set

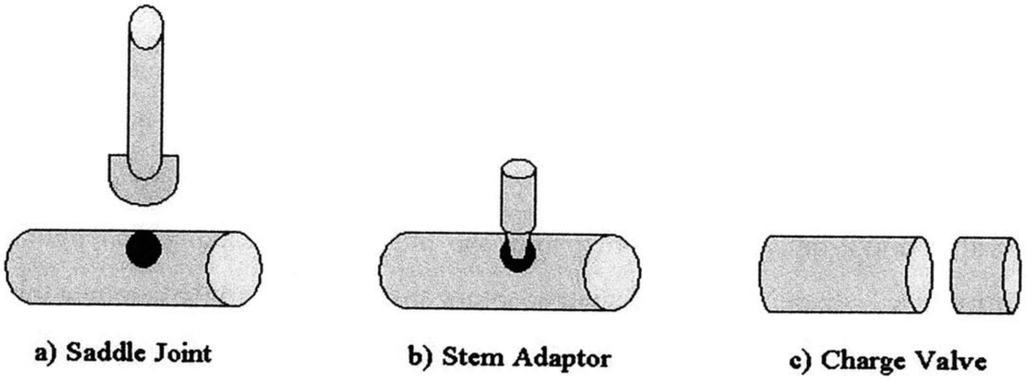

a) Saddle Joint
b) Stem Adaptor
c) Charge Valve

Figure 4-20: Different braze types

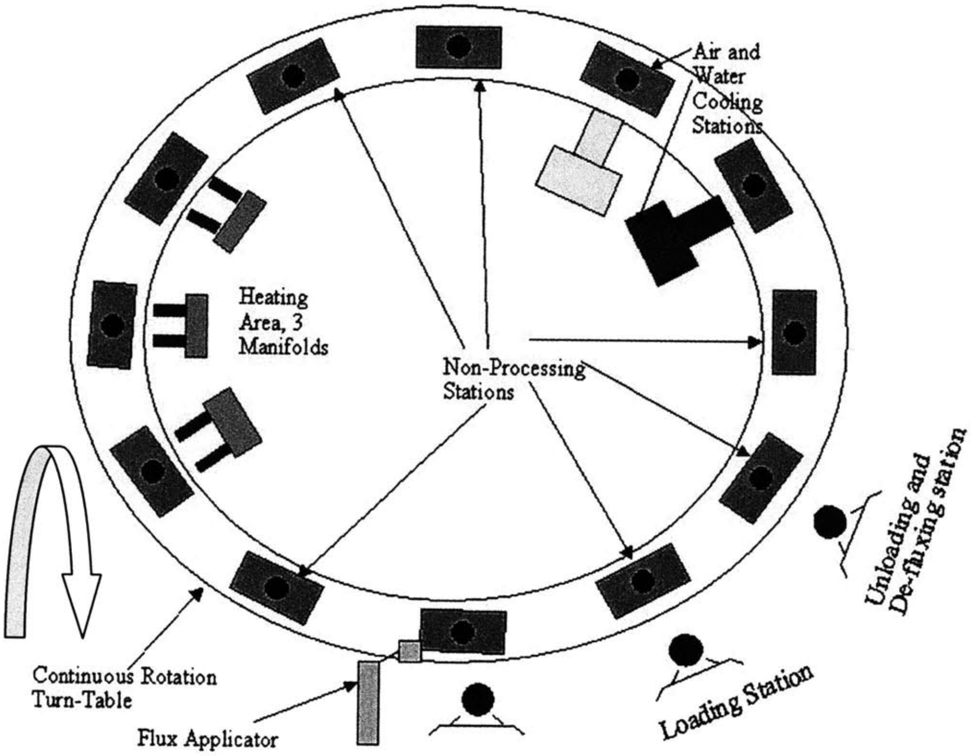


Figure 4-21: Schematic Overview of Existing Brazing Equipment

of burners to heat the part. Of the three stations used to heat the part, the first preheats the base metal and the filler, the second focuses heat on raising the filler to the melt temperature while the third causes the melting of the filler and subsequent adherence. After a couple of non-processing stations, there is a station each for water and air-cooling and at the last station parts are unloaded followed by flash removal. Figure 4-21 shows a schematic of the high speed, large sized brazing machine with the rotary table and the fixtures for the parts mounted on the stations.

4.7.3.2.2.2 Problems with current brazing machines

There are a number of problems associated with the design of the machine that make it incapable of cellular operation. The continuous rotation of the table causes batching of parts at the loading and unloading stations of the machine, making single piece flow impossible at the process level. The machine is not autonomous and cannot stop or detect the presence of a part. The operator has no control over the work. The machine is dependent on the worker's ability to load the part every 9-11 seconds. To summarize, the problems with the current design:

- Current brazing is a non-standard, incapable process since a large number of defects can be traced back to brazing. This machine incapability is one of the prime reasons for having a non value-adding inspection process called 'leak test' in final assembly.
- The machine requires three workers and since parts come out every 9-11 seconds, these workers are essentially tied to their respective stations with no control on the operation.
- At the non-processing stations on the machine, there is wasted time and motion of parts. As a result, the part throughput time across the machine (excluding manual operations) exceeds 2 minutes.
- Since the machine has 12 fixtures for the 12 stations, changeover from one type of braze to another involves 12 fixture changes in addition to changes in the flame parameters. Changeover time thus currently exceeds 15 minutes on most machines and requires complex manual adjustment of nozzle positions, time for which a part is at each station, flame temperature and gas flow.
- The adjustments for changeover are non-standard and variability in worker judgment often causes re-work due to insufficient melting of the filler or damage to the base metal by way of hot spots or diffusion of filler into the base metal.
- Due to an unreliable method of fluxing, there is often insufficient filler melt causing a lot of defects or rework.
- Most re-work takes place locally after flash removal and inspection. The local rework does not allow the identification of the root problem as the parts are fed back to the machine. The problem often lies with the non-standardized process control parameters.

- The large number of fixtures needed for every changeover is not only expensive but also occupies a lot of space. There is wasted operator time and motion in transport of these fixtures for every changeover.

4.7.3.2.2.3 Ideal Brazing machine design for cells

A case was made for longer cycle times in the discussion of conveyor belt or high speed asynchronous lines on the basis of increased difficulty in balancing the worker operating loops. As cycle time in cells decreases, it becomes more difficult to balance the cell, resulting in layouts where an operator is isolated to one machine. On the other hand, as the cycle time increases, there are more operations that need to be performed, and consequently, more mistake-proofing devices need be incorporated since the cushion of other operators in the following work loops acting as inspectors for previous operations is lost. Based on the experience of the author and Prof. Cochran (Thesis Supervisor) in various automotive components plants, a sweet spot has been identified between approximately 30 seconds and 2 minutes. The cells in the system being studied were designed for a minimum takt time of 30 seconds.

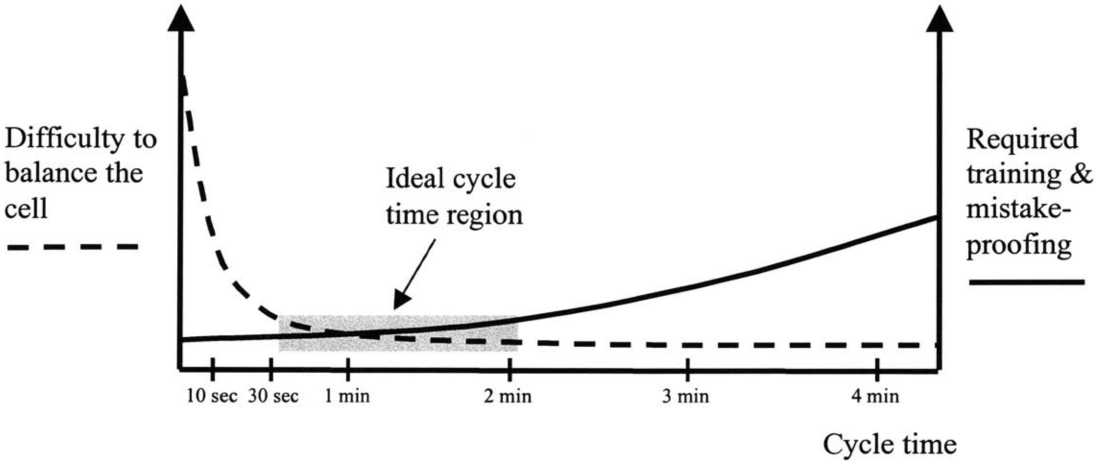


Figure 4-22: Trade-offs and Ideal Cycle Time for Capacity Selection in Cells [Cochran]

The machine designed for the above applications (excluding manifold brazing) would have two stages, one for heating and the other for cooling. The choice of the number of stages in the machine design is a function of the minimum design takt time. In addition, there would be a station for loading and applying flux on the part. Each of the two stages would takes less than 30 seconds (consistent with heating and cooling times on standard machines) and would have a single part in each stage. As soon as the stage finishes processing the part, its operation would be stopped. So once the heating cycle is completed for melting the filler, the burners would turn off or withdraw using a servo- mechanism. Similarly, air and water sprouts would turn off, once the part has cooled. The parts would remain at their respective stages until the operator loads another part to the machine and hits the walk-away switch. At this point, each of the parts would advance by one stage, so that the loaded part moves to the heating station, the heated part moves to be cooled and the cooled part unloads itself, ready for the operator. The operator's work-loop consists of loading the part and using an automatic wire flux applicator that places a predetermined amount of flux on the part. The important features of the design are discussed in the next few paragraphs.

Worker controlled rotary indexed machine

A rotary machine design has been chosen for the new design as well. The reason being that for a given number of stations, the rotary design helps place the stations so that the machine width is a minimum. The important difference between this design and the current machines is that the designed machines will separate the worker from the machine. The parts on the machine will not advance to the next station/stage unless the operator hits the walk-away switch. The machine then processes the part without needing the worker's physical presence. This dependence is essential since it allows the worker to control the operation of the machine. In cells when machines are designed to separate the worker from the machine, a change in the takt time is taken care of by varying the number of workers. In automatic machines, parts advance automatically to the next stage after a pre-set time, and the machine is incapable of adjusting to changes in Takt time and hence cell cycle times. The operator would have to ensure that he is at the machine to load a part every time the machine advances to the next stage. Hence, the advantage of reducing a worker from the cell on account of a higher takt time is lost, since the operators are tied to the machine. Often the worker would just have to wait for the machine to process parts after loading them and the output rate would be inflexible. The machines are designed for high speed to reduce the operator's waiting time. This inflexibility has the added cost of over and underproduction on changes in demand.

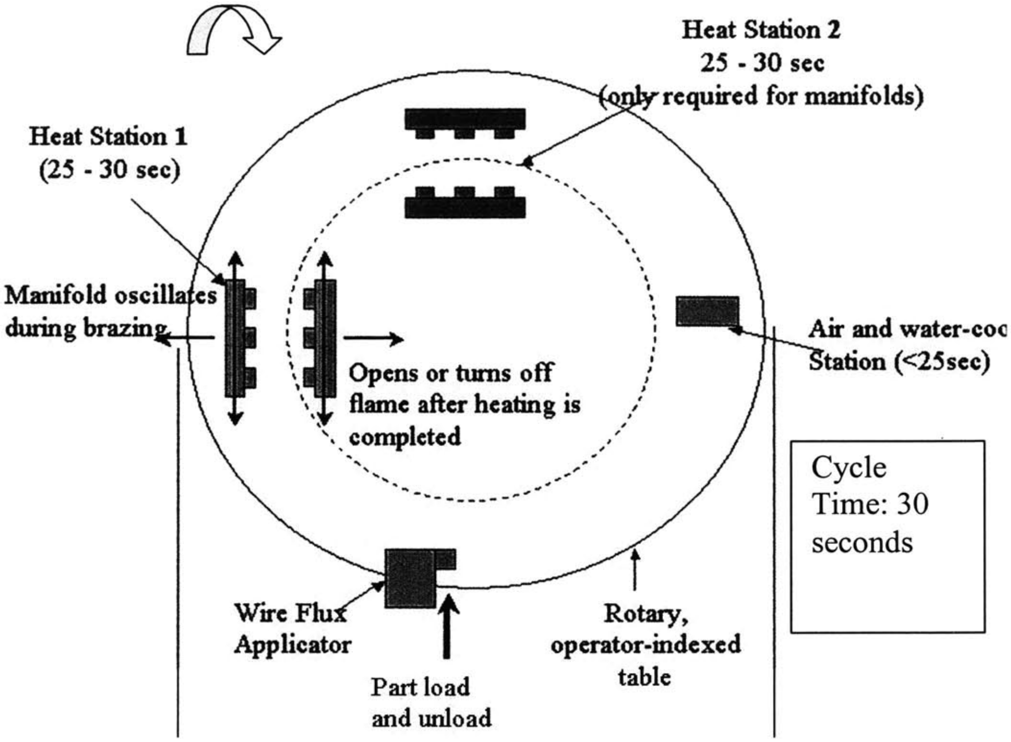


Figure 4-23: Proposed conceptual design for a cellular brazing machine

Programmable Logic Controller for changeovers

In assembly parts of the same family have been grouped together on the basis of similar number of brazes as far as possible. However, in cases where the number of brazes are not the same, the number of brazing machines would equal the maximum number of brazes on any connector to be produced in that cell. Since a braze machine has been dedicated for every brazed joint on a connector, the need for changing over from one braze type to another has been substantially reduced. This strategy is a significant way to solve the changeover problem, by reducing the need for it through the design of the cell itself. The changeover problem is encountered in cases that the braze type needed on different connectors to be run on the same machine is different. In most brazing machines the changeover is brought about by a complex worker adjustment of flame nozzles and gas flow, and a few trial runs. This adjustment takes time and leaves a lot on the judgment of the operator, as the settings are non-standard. Some other machines also require a change of the heating manifold, by unscrewing the manifold from the gas hose and then screwing on the new one. Easy snap-on-connection of the hose to the manifold are currently not safety approved.

In the design suggested, a programmable logic controller would be adopted. Such a controller has a memory and records the specific adjustments such as duration for heating and cooling, flame temperature and the configuration of burners to be switched on. These parameters can be pre-set for all braze and part types to be run on the machine as a list of numbers. In case of a changeover, all the operator needs to do is select the number corresponding to the braze type to be run in that cycle and the machine automatically sets those parameters for brazing. This feature helps minimize the need for any manifold changeover and by a logical grouping of products in the final assembly the need for any manifold changeover is altogether eliminated. The changeover problem, one of the largest concerns of the current machines, is thus solved.

Size of machine and Ergonomics

The machine width is 4-feet based on a two-stage brazing machine design. The machine width is important in cells as it influences the walking distance and hence the time taken by the operators. The logic controller interface with the operator would be on the left of the machine at a convenient height and position for the operator to enter the part type selection and hit the walk-away switch. Rather than manually apply flux O rings or a braze paste, a flux applicator would automatically descend to the height of the joint as set in the logic controller and apply the relevant quantity of flux after the worker hits the walk away switch. The fixtures for loading the part would be snap on and mounted on the machine at a convenient height of 3 and one half feet for the worker.

4.7.3.2.2.4 Comparison of Machine Designs

The proposed ideal design for the brazing machine would enable the machine to be placed in cells. The benefits of the new machine design would be experienced at the system level directly, since it would enable the production system to move as a whole from a batch production system to a lean linked cellular system with the model previously described. A comparison between the two machine designs is presented in Table 4-3 below. It indicates how every aspect of the machine design is influenced by the choice of the system design.

Finally the proposed design is also compared with existing off-the shelf equipment and designs in order to illustrate the need for high concurrency in design as well as linking system requirements to equipment design. When production system designers work closely with equipment designers (high concurrency), then requirements from the system perspective get communicated to the equipment designers effectively helping in the system integration. Table 4-

4 shows the selected FR-DP pairs relevant to each category and the evaluation of existing off the shelf equipment design relative to the system level design requirements for the brazing machines. The table emphasizes the importance of the true system requirements as reflected by the FR-DP pairs.

	Comparison Features	Existing Machines	Proposed Design
1	Total Number of Stations	12	3 (non manifold) or 4 (manifold)
	Heat Stations-	3	1 (non-manifold) or 2 (manifold)
	Cooling Stations-	2	1
	Loading and Unloading	Separate	Identical
	Flux Application	Separate from Loading	Same Station
	Non-Processing Stations	6	0
2	Method of Flux Application	Manual	Automatic Wire-feed
3	Turn-Table Diameter	6 ft	~3 ft
4	Front Size of Machine	~7 ft	~4ft
5	Standard Machine WIP	12	3 (non manifold) or 4 (manifold)
6	Machine Throughput time	~2 min	~1 to 1.5 min
7	Method of Operation Control	Continuous Rotary	Operator Controlled, Indexed Rotation
8	Rate of Processing Parts	Fixed, every 10 secs	Flexible, 25 secs minimum
9	Changeover Time	~10-15 min	~1 min
10	Changeover Process	Manual	PLC controlled
11	Number of Workers	3	1

Table 4-3: Comparison of existing design with proposed design

Criteria	*Functional Requirement/ Design Parameter*	*Off th e Shelf-Equipment*	*Ideal Design*
1. Cell Design	a) Produce in small run sizes/ Set up performed in less than 10 mins.	2-3 min	Ideally <1 min
	b) Reduce walking distance/ Machine width < 4ft, in a U shape or parallel rows	3 ft	<4 ft
	c) Enable volume flexibility/ No workers are physically isolated	Achieved	
	d) Eliminate lot delay/ Single piece production within a cell	Achieved	
2. Equipment & Station Design	a) Eliminate common cause disruptions/ Machines designed to avoid production disruptions due to routine tasks	Machine normally does not have disruptions in routine operation.	Flux feeding and gas supply should be continuous and automatic and heating manifolds should be capable of continuous operation.
	b) Do not disrupt production for simple maintenance activities/ Controls and systems accessible from the rear of station	Maintenance activities disrupt production.	Only parts/controls of the machine the operator interfaces with every loop, should be in front of the machine
	c) Reduce tasks that tie the operator to the machine/ Machines designed to run autonomously	Operator uses an automatic wire feeder to apply flux	Operator only loads the part and fluxing is automatic
	d) Reduce setup costs/ Set up performed with reduced resources	In changeovers requiring manifold replacement, the operator must screw and unscrew gas connections.	Ideally, the changeovers between braze types should not require manifold changes, maximum number of braze types to be run on the same manifold.
	e) Reduce long term investment on machines and equipments/ Acquisition of simple and flexible machines	Machines flexible enough to braze most types with manifold changes.	Machines flexible to run as many braze types as possible on single manifold with braze parameters PLC controlled.
	f) Add production capacity in smaller increments at lowest cost/ Machine design focussed on meeting min. takt time with lowest cost and complexity	Single station machine produces parts may or may not meet min. takt time (30secs) depending on braze complexity.	Single or multi-station (operator indexed) machine that produces 1 braze joint irrespective of the type, every 30 seconds.
3. Material Handling	a) Finish processing and part unloading before the operator arrives at the machine/ Automatic unloading of parts	Not a feature	Required
	b) Separate worker from the part/ Standard WIP of one part at each machine	Allows single piece flow.	Single piece flow a MUST.
4. Quality	a) Ensure capable processes/ Capable machines, equipment, tools and fixtures	Cpk=2	Cpk<=2
	b) Standardize work procedures and methods/ Consistent work procedures performed by operators and equipment	Machine operation is standard and repeatable. The operator has to apply a predetermined quantity of flux using an auto dispenser.	Machine operation should be programmable logic controlled for consistency. Ideally, the operator should only load the part, select its number and hit the switch.
5. Operator Safety and Ergonomics	a) Load parts cost effectively and quickly into machines/ Ergonomic interface between the worker, machine and fixture	Easy snap on fixtures for loading parts	Ample room for the operator to load the part- fixture shuttles out of the machine. Fixture design makes loading orientation/location obvious.

Table 4-4: FR-DP Relative evaluation of off-shelf equipment with proposed design

4.7.3.2.3 *Washing*

In the current washing process, parts are loaded into basket containers in large batches. The wash cycle consists of the baskets rotating in the wash chambers. The parts are loaded with slight amount of 'play' to allow wash fluid through them and are then rinsed in separate baths.

The entire basket is then removed with the hoist and placed in a large oven for drying. The cycle time of these machines is of the order of an hour. The oil to be removed (SAE 407, typically) comes from the forming processes used in the preparation of connectors. As discussed earlier, the current washing process damages and/or leaves parts oily. Figure 4-24 is a schematic of the current washing machines.

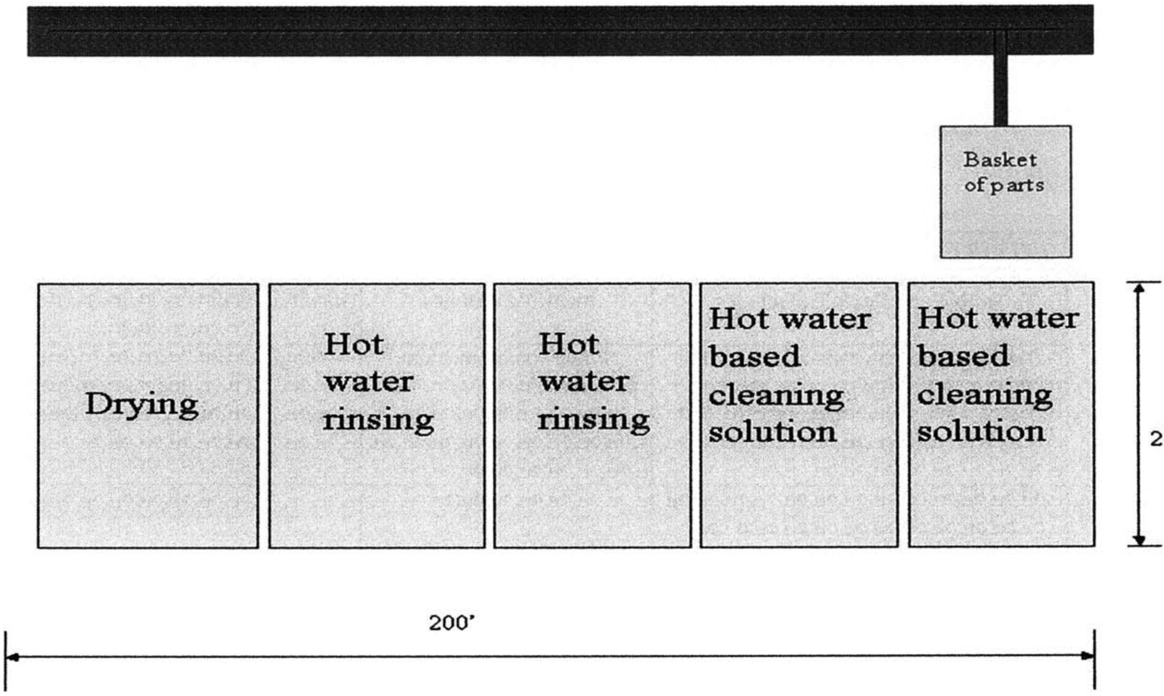


Figure 4-24: Schematic of current washing machines

Several problems with the current washing process are a function of the machine's design and the system's departmental layout. These are listed below:

- Rotation of the basket and loading practices cause the parts to collide with each other causing possibility of damage
  - Results in need of 100% inspection, requires two workers
  - Washing takes place after preparation of connector tubes, a damaged part thus has already undergone a lot of waste processing in fabrication

•Inspection is visual, in a batch and often damaged parts escape inspection. Part cleanliness is not measured or compared with a standard, unclean parts can miss inspection.

•Unclean parts are a source of scrap and rework in the subsequent process of brazing that requires part cleanliness.

•Parts are often unclean internally and the dripping oily fluid from parts may soil others in the batch

•Batch processing causes lot delay and high throughput times.

Washing itself could be eliminated if the tubes were not contaminated with oil during the cutoff and forming processes. If oil must be used and washed, then there are two options worth exploration. First, the possibility of using either water-soluble or vanishing oils that do not require detergent washing could be examined. The company needs to define the level of cleanliness required such that brazing quality will not be affected as these standards would be relevant to the design of the next generation of washer. Alternately application of oil in controlled amounts at specific points would help reduce the need for washing.

As a consequence of the departmental system parts to the washer are supplied in large bundles, leading to the design of washers with large baths and rotating baskets carrying large batches of tubes. Moreover, the amount of oil on the tubes requires the washing process to include a pre-soak station to assist in removing the bulk of the oil.

To correct many of these drawbacks, the washer to be used within the new manufacturing system should be designed to have the following characteristics:

- The washer should be able to wash smaller batches of tubes; preferably single tubes at a time. This would reduce the size and complexity of washer; clean tubes more thoroughly and also enable single piece flow at the system level.
- The washer should be designed to wash only the ends of the tube where the oil is applied. However, the oil application process must change accordingly before.
- The machine should preferably be less than 4' in width, to reduce walking time of the operator if the washers are to be incorporated within fabrication cells.
- Pre-soaking would be rendered unnecessary if oil does not spread across the tube with improved application methods and use of non-organic oils. The washers should only be comprised of wash, rinse, and dry stations.
- The washers should have a cycle time that meets the takt time.

One conceptual design of the new washer machine is to load the part vertically so that the length of the tube does not affect machine size. Also, the machine could have an overhead spray gun that attaches to the tube end, and can be used to flush the tube's interior and wash the ends' exterior. A diagram of the conceptual machine is shown in Figure 4-25.

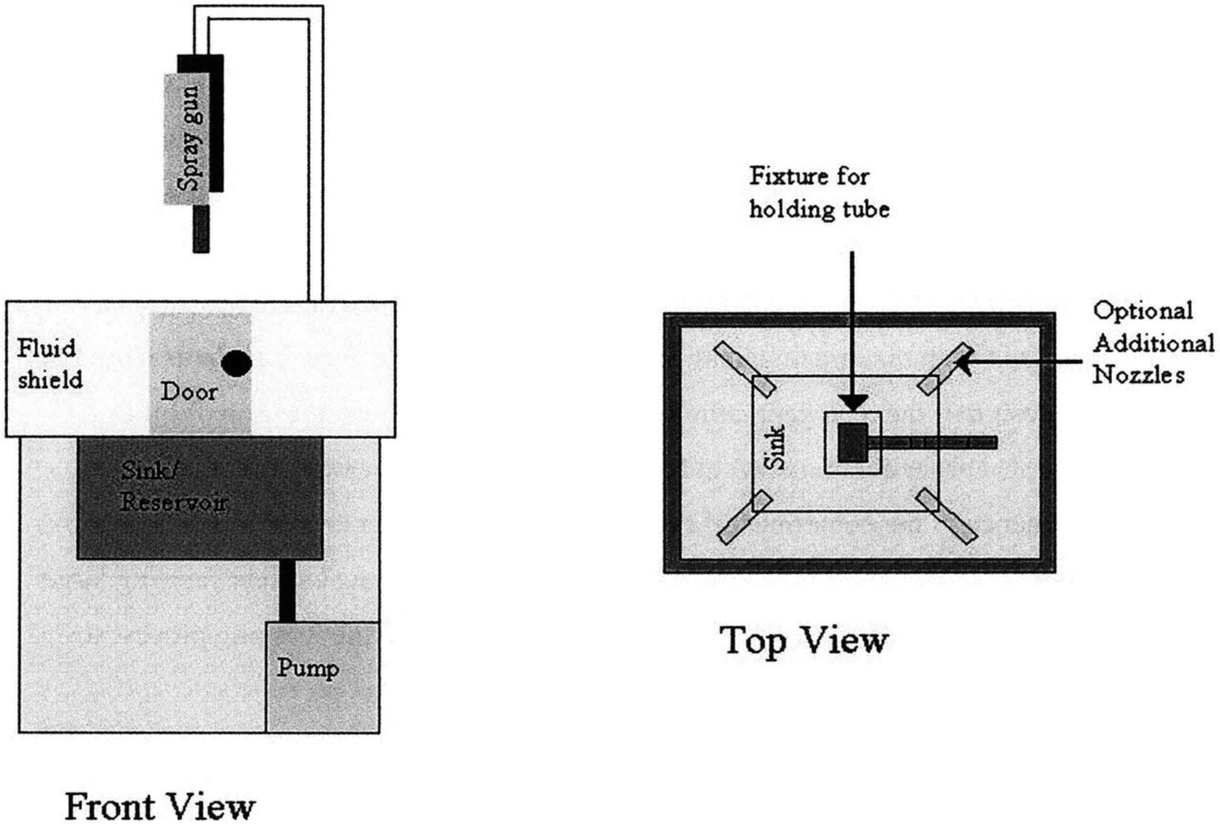


Figure 4-25: Schematic of one of the proposed designs for next generation washers for the manufacturing system

The above process of washing assumes parts would be dried before the operator moves them to the next stage of brazing in the fabrication process. The operator would place a wet part on the peg and move a dried one to the next stage of brazing. This arrangement is one of the ways of achieving single piece flow through a small SWIP at one of the machines. Alternately, a dryer could be included to the fabrication cells or the parts could be placed in pegs after the washer. The schematic proposed above assumes that internal cleaning of tubes would not be a necessity once the use of vanishing oils or a change in the oil application and tube handling methods is made possible. However, even with the current handling of oils there are several technologies and designs based on these that can ensure that washers do a reliable job of cleaning parts without damaging them. One such cleaning technology in popular use is the ultra-sonic cleaning method. The method uses the process of cavitation for cleaning. A sinusoidal pressure wave is formed through ultra-Sonics that causes the build up and burst (implosions) of bubbles of cleaning solution. The bubbles remove dirt, grease and oil from the par. Higher the frequency, finer the bubbles more precise and uniform is the cleaning. The principal advantage of this cleaning method is that it ensures uniform and complete cleaning both on surface and inside and even blind holes. It is also a very capable process; and can meet rigorous cleaning standards and specifications.

Figure 4-26 is a schematic of an ultra-sonic washer designed by the authors for operation in cells for high cleaning standards. The washer is built along an operator-indexed conveyor driven platform less than 6 ft wide that houses the ultra-sonic cleaning and rinsing tanks as well as a dryer section. The operator simply loads the part in a holder at the front of the machine and hits a wal-way switch that activates the machine. The part moves into the cleaning tank while the part previously in the cleaning tank moves into the rinsing station. Cleaning and rinsing are ultra-sonic processes and the rinsed part in the next cycle when the operator hits the switch again, advances to the drier section. The drying is through a hot dry air blower and the dried part indexes to the unload station to be removed by the operator as he proceeds to the brazing machine. The above design helps achieve all the FR's of equipment design for cellular operation as shall be illustrated in Table 4-5 that evaluates the current and proposed designs on the system FR's from these machines.

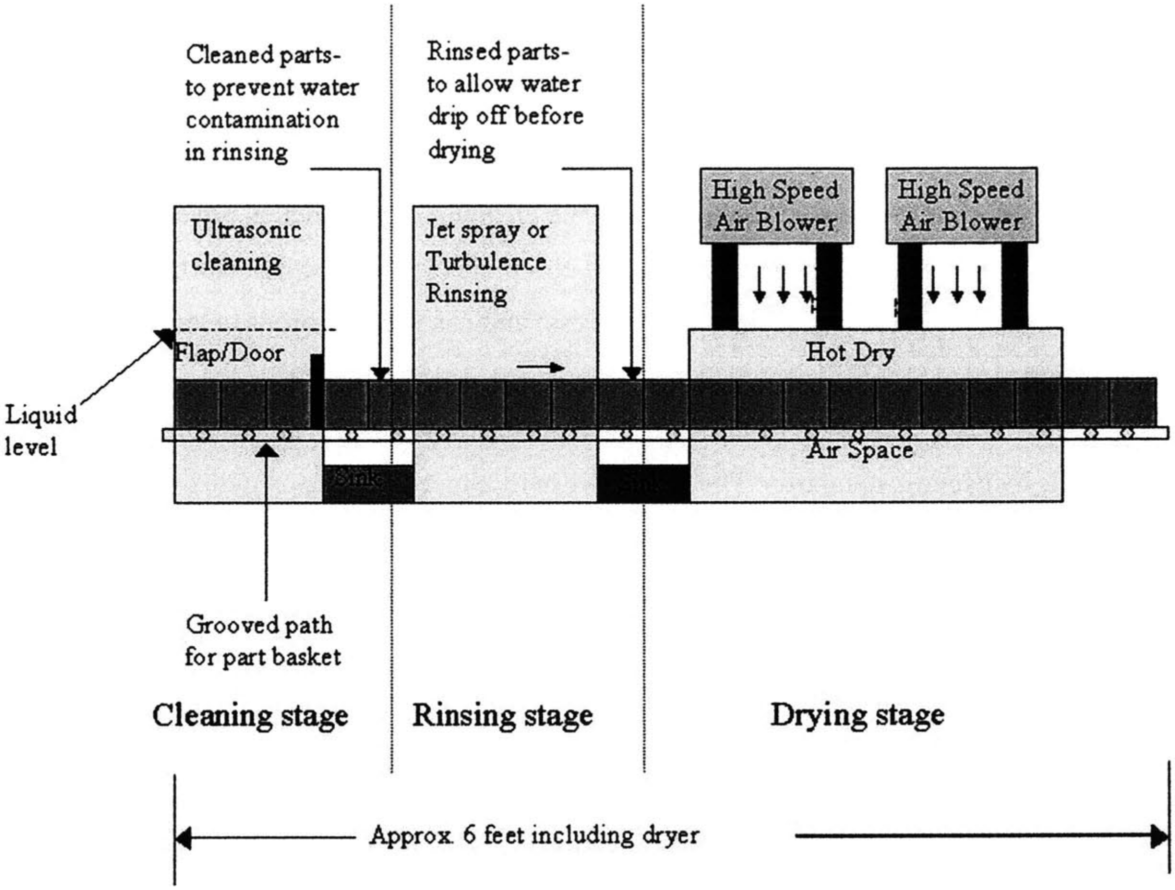


Figure 4-26: Proposed Schematic of Ultra-sonic Washers for the Manufacturing System

Criteria	*Functional Requirement/ Design Parameter*	*Current Equipment*	*Proposed Design of Ultrasonic Washers*
1. Cell Design	a) Produce in small run sizes/ Set up performed in less than 10 mins.	1 hour	<1 min
	b) Reduce walking distance/ Machine width < 4ft	200 ft	<4 ft
	c) Enable volume flexibility/ No workers are physically isolated	Island Machine in Departmental Layout promotes worker isolation.	Workers operate in a cell where adjustment of operator work loops provides volume flexibility.
	d) Eliminate lot delay/ Single piece production within a cell	Current batches of parts vary between 1000-4000	Single Piece flow achieved through SWIP at each wash station
2. Equipment & Station Design	a) Eliminate common cause disruptions/ Machines designed to avoid production disruptions due to routine tasks	Machine does not have disruptions during routine production; however control of wash temperature and wash cycle is difficult to adjust to match the level of part dirtiness.	Common disruptions in machine operation are prevented through total preventive maintenance and equipment design that ensures reliability.
	b) Do not disrupt production for simple maintenance activities/ Controls and systems accessible from the rear of station	Machines require low maintenance, however the entire washer is not functional during maintenance	Only parts/controls of the machine the operator interfaces with every loop should be in front of the machine. The machine should allow maintenance

			activities to be carried during machine operation.
	c) Reduce tasks that tie the operator to the machine/ Machines designed to run autonomously	Operator moves baskets of parts from one stage to the other.	Operator only loads the part.
	d) Reduce long term investment on machines and equipments/ Acquisition of simple and flexible machines	Machines are huge island machines that require huge capital investment and increase the cost of defects through poor and unreliable operation.	Machines flexible to wash and dry all shapes of tubes; simple machines are easy to purchase and maintain.
	f) Add production capacity in smaller increments at lowest cost/ Machine design focussed on meeting min. takt time with lowest cost and complexity	No concept of customer demand time; large batches cleaned in several hours.	Single or multi-station (operator indexed) machine that produces 1 washed part irrespective of the type, every 30 seconds.
3. Material Handling	a) Finish processing and part unloading before the operator arrives at the machine/ Automatic unloading of parts	Not a feature	Can be easily incorporated through part dropoff at last station.
	b) Separate worker from the part/ Standard WIP of one part at each machine	Requirements of large batches in excess of 2000 parts makes single piece flow impossible at the system level.	Single piece flow possible; in case of multiple stations the machine has a SWIP, but single piece flow is possible at the system level.
4. Quality	a) Ensure capable processes/ Capable machines, equipment, tools and fixtures	Cpk>>2; The process is highly ireegular and incapable, it does not often clean parts and also damages them.	Cpk<=2
5. Operator Safety and Ergonomics	a) Load parts cost effectively and quickly into machines/ Ergonomic interface between the worker, machine and the fixture	The worker has to operate air hoists for large baskets pf parts, this makes it ergonomically cumbersome as well as a potential safety hazard.	Operator simple has to load a part each cycle and hit a walk away switch. Fixture design should make loading orientation and location obvious.

Table 4-5: FR-DP based evaluation of current and proposed designs.

4.7.4 Implementation and Operation Phases - Pilot

There was a high level of enthusiasm to convert the entire manufacturing system based on the detailed design process. However, financial constraint made the re-design and purchase of equipment especially in fabrication impossible. Moreover, if all departments were to form cells independent of one another, the result would be a scatter of cells throughout the manufacturing system, all based on different logic without the value stream or customer in mind. The logical approach was to pilot the conversion of final assembly lines to cells as part of the linked cell model described in the conceptual and preliminary design phases. Piloting a miniature version of the new system design was the first step in the implementation and operation phase that followed the system engineering based design process. A pilot in any production system change project serves the following important functions:

- Demonstrates feasibility of the design philosophy.

- Gives an estimate of the scope of benefits the system would experience with the transformation.
- Exposes the typical challenges the system would face on a large scale of transformation.
- Serves as a learning tool to illustrate principles and features of design to personnel not actively involved in the design.
- Exposes some of the root causes of problems being experienced in the system.
- Challenges every element of system design with regard to its contribution to the system performance.
- Create an easily scalable model of the system.

Formation of product families in the conceptual phase provided a framework for choosing the pilot. From Figure 4-9 the Al-2crimp models seem the most simple, representative and generic product type. They also constituted a third of all products in the system. Of the Al-2 crimp models, an entire assembly line was dedicated entirely to the manufacture of the largest volume product system wide that belonged to this category. The authors decided that given the considerable attention surrounding the product and the simplicity of its attributes, the implementation would be well supported by the leadership.

4.7.4.1 Determining Takt Time

Adopting the generic model developed for the 2-crimp Al cells under the system constraints, the next step was to determine the takt time for the cells. Based on 16 hours of available working time from 2 shifts, daily demand of 4200 and an assumed uptime factor of 0.85, the takt time was 12 seconds for a single cell working two shifts. Cells running on low takt times of 12 seconds experience similar problems of balancing as the assembly lines and it is difficult to separate the operators from the station and the production is inflexible. Thus it was chosen to implement two cells running on a takt time of 24 seconds.

The system constraint of a single leak tester for both cells added the complexity of interdependency and coordination across cells while the two crimp machines taken off the line meant that each cell had one crimp machine that would produce both the crimps in the final product. This meant redesigning fixtures for the crimp machine that could produce both crimps with minimal changeover.

4.7.4.2 Standardize Process and Operator Routine

Multi-functional and moving workers in cells provides greater flexibility in formation of work loops as the order of operations need not necessarily follow the product's assembly sequence. Along with higher takt time this added flexibility provides several options for defining standard work loops that are always subject to improvement. The only constraint in designing work loops is that the sum of each worker's operations, plus walk time must be less than the takt time. The number of workers needed to run the cell was decided by dividing the sum of operating times that were determined initially from assembly line standards (67.9 seconds) by the takt time. This first pass calculation suggested that three workers would be needed with about 23 seconds f work in each loop. After several theoretical iterations it was decided that in terms of balancing the workload and minimizing the amount of non-active walking time it would be best to have the first worker prepare both tubes and make the first crimp, the second worker make the second crimp and leak test, and finally the third worker remove the end caps and prepare the part for shipping.

4.7.4.3 Important challenges in Testing Phase

- Operators experience a learning curve working in cells and hence initially it was difficult to meet takt time with 3 workers. Instead of mastering a single task now they became efficient over time at completing their work loops and learning all the operations.
- Teamwork and communication were emphasized as being critical to meeting the production requirements. The change in approach from individual responsibility for a single operation on the line to collective responsibility for improving work loops was an interesting challenge for the workers and they responded through effective communication aimed at improving their work loops, stations and identifying non-essential processing steps.
- While coordinating the sharing of leak tester threatened work disruption in the cells, over a period of time the sharing was synchronized and the physical proximity of the cells in the layout of Figure 18 helped exchange best practices across cells.
- The temptation of the workers from over producing after completing the work loops ahead of time was regulated through material handling. A single material handler replenished both cells by offering 50 parts every 20 minutes for production. It provided feedback to the workers about their pace of production.

- Absenteeism became apparent as underproduction in a particular time interval thus providing feedback for improving worker habits.

4.7.5 Comparison of Results

The comparison between mass assembly lines and cells on some of the quantifiable terms is shown in Table 4-6. Most striking are 78% reductions in floor space and 45% reduction in man-hours required for production.

Measurable	Assembly Line	2 Cells
Floor Space	1500 sq. ft.	320 sq. ft.
Direct Workers	18	12 (2 cells, 2 shifts)
Cycle Time	6.2 sec	24 sec
Man-hours required	~170	96
Avg defects/month	226	2.5
% Absenteeism	4	0
Throughput time	Variable (~20 min)	72 secs
WIP	Variable (~150)	6 (3/cell)
Incoming Material	High and variable	50 pcs/20 min
Conveyor	90 ft	None

Table 4-6: Comparison of mass assembly line with cells

- Increased ability to balance work content.
- Improvement in worker's attitudes, increased teamwork and enthusiasm as well as interest in improving work methods; drop in absenteeism.
- Volume flexibility by addition or removal of workers.
- Predictable output that exposes problems caused by upstream processes or operation in cells.

4.8 Plan for system wide roll out

The remarkable success of the pilot on quantifiable and non-quantifiable dimensions triggered a system wide excitement for producing cells. However, random formation of cells would complicate product and information flow that would ultimately result in low quality and increased throughput time. A plan for system wide rollout was therefore devised based on the product families. The interim plan for system conversion focused on all the assembly operations before forming and linking fabrication cells since

- Modifications to assembly equipment for cell compatibility met system constraint of minimal investment funds while fabrication did not meet the same constraint.
- Assembly cells formed could easily be linked to the fabrication area in the short run and eventually to corresponding fabrication cells.
- System designers to finalize new fabrication equipment designs or retrofit existing ones and use the time engineers and implementing team would spend on conversion of assembly.
- Leadership and finance functions in these companies would be further convinced of the benefits from conversion; realized benefits would help justify expenditure on new equipment.

The idea of formation of product families on the lines of the manufacturing processes it undergoes helped reduce the equipment requirements per cell. For instance, to minimize the number of crimping machines used per assembly cell within each material type, the end models were sorted by the number of crimps required viz. 0, 2, 4, or 6+. Classifying by this characteristic meant there would be no situations in which a cell would have crimp machines not used for the particular products of a family. Again, while maximizing machine utilization is not a goal of cell design, efficiently distributing existing machines among the cells helps reduce the investment required to implement the new production system design.

Considering these two attributes, the end models could be sorted into ten large families, as can be seen in Figure 4-27. Each family is referred to by these initial characteristics, one being the "Aluminum, 2 crimp" family, another the "Aluminum, 4 crimp" family, and so on. Taken as a whole, the ten families are referred to as the Large Families, since subset families were later formed within each family. The results of the Large Family groupings are summarized in the first column of Table 4-7.

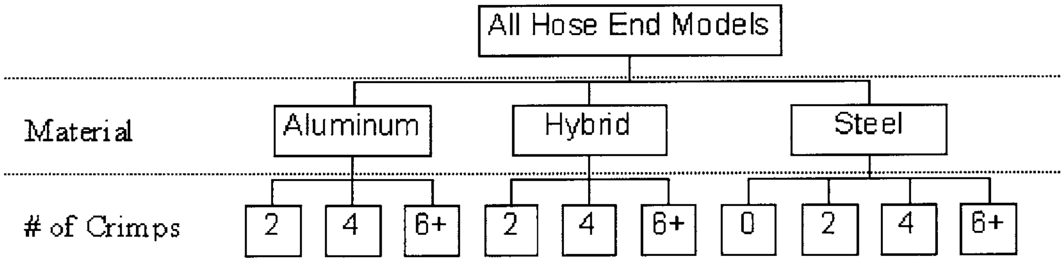


Figure 4-27: Large Families formed on the basis of material type and crimping

Looking at the Large Families, it is possible to form a rough sketch of the assembly cell requirements. One of the most striking features of the Large Family summary is the high volume associated with the "Aluminum, 2 crimp" family, which represents one third of all hoses produced, despite having only half as many end models as the "Hybrid, 4 crimp" family. It is also interesting to note that six families, the all steel product families plus the hybrid and aluminum 6 crimp families, account for only 12% of the total volume of hoses. This low volume suggests that forming cells to run these particular products is of low priority, and that the real focus should be on forming cells for the aluminum and hybrid, 2 and 4 crimp models.

By taking the aggregate demand for products in each family, the number of cells required per family was estimated by assuming that all cells will run two shifts.

	# of models in family	# of cells for family	# of shifts cells will run	avg Takt time for cells (sec)	% of total cells	# of crimp machines
Family 1 - Al or St, 0 crimp	5	1	2	36	4.2	0
Family 2 - Al, 2 crimp	14	9	2	32	33.3	9
Family 3 - Hybrid, 2 crimp	9	3	2	39	12.5	3
Family 5 - Al, 4 crimp	11	3	2	39	12.5	6
Family 6 - Hybrid, 4 crimp	30	7	2	30	25.0	14
Family 9 - Hybrid, 6+ crimp	4	2	2	35	4.1	7
Family 8 - Al, 6 crimp	5	1	1	49	2.0	3
Family 4 - St, 2 crimp	3					
Family 7 - St, 4 crimp	2					
Family 10 - St, 6 crimp	2	1	1	45	2.1	
						42

12% of volume

Table 4-7: Summary of Large Families

4.8.1.1 Interim Plan for System Conversion

Given that the existing crimp machines are suitable for use in cells without any need for redesign, and that there are a sufficient number on hand, an interim plan calling for the complete conversion of final assembly to cells was proposed. With the subset families in place, the design of specific assembly cells could begin, and the next level of planning involved prioritizing the cells to be implemented. Due to low volume, the steel end models and those with 6 or more crimps were given low priority. Thus, the choices to be made were mainly between aluminum and hybrid, two and four crimp models.

A decision to first form cells for the "Aluminum, 2 crimp" family was made for three reasons. First, aluminum products were chosen over hybrid ones to postpone the need to find a common crimping spec between steel and aluminum tubes. Second, the demo cells belonged to this family, and thus could serve as a reference while the plants worked on the first cell designs for the new system. Lastly, and stemming from more long term thinking, seven of the nine assembly cells required for this family do not need to be fed by fabrication cells with brazing machines. Thus, if fabrication cells are implemented in the same order as the assembly cells, then the first ones will be simple since no brazing is necessary. Planning for the first fabrication cells to be those that do not include brazing machines also means that more time can be spent designing the new machine.

The next family to be converted to cells would be the "Steel, 0 crimp" family. Since the cell requires no crimp machines, it should be fairly easy to implement. The third family to be converted is the "Aluminum, 4 crimp" family. The reason for choosing it over the "Hybrid, 2 crimp" family is again to allow more time to find the common crimping spec between steel and aluminum. Unless this crimping spec is changed, the "Hybrid, 2 crimp" cells will require two crimp machines, one for each material type. The cells for the "Aluminum, 4 crimp" family will also be largely based on the demo cells, but will make use of two crimping machines—with each machine making two crimps. In this family, it is necessary to prepare three tubes for the assembly of the model, and the tube prep section of the cell may differ from that of the demonstration cells. The various steps of the plan are listed here.

1. Design and implementation of cells for the "Aluminum, 2 crimp" family
2. Design and implementation of cells for the "Steel, 0 crimp" family
3. Design and implementation of cells for the "Aluminum, 4 crimp" family
4. Redesign of St manifold, making most "Hybrid, 4 crimp" models into "Aluminum, 4 crimp"
5. Design and implementation of cells for the newly formed "Aluminum, 4 crimp" family
6. Design and implementation of cells for the "Hybrid, 2 crimp" family
7. Design and implementation of cells for any remaining "Hybrid, 4 crimp" family
8. Design and implementation of cells for the "Hybrid, 6+ crimp" family
9. Design and implementation of cell for the "Aluminum, 6+ crimp" and Steel families

The expected savings of implementing the interim design are highlighted in Table 4-8. The largest source of savings comes through the reduction in the direct labor, which is calculated to be roughly three times less in the new manufacturing system. Other significant savings come from the reduction in scrap anticipated in the interim system. The scrap figure presented is based on the scrap of the pilot cells collected in the four-month period after their installation, and is believed to be reliable.

Features	Current	Assembly Conversion
Floor Space	1	0.68
Direct lab. Ratio	1	0.65
Indirect lab. Ratio	1	1
Man-hours Ratio	1	0.61
Scrap Expense Ratio	1	0.33
Assembly WIP	Variable~1800	81
Assembly Throughput time	Variable~1 day	11-12 min

Table 4-8: Expected Savings from Implementing Interim (No Investment) Design

4.8.1.2 Plan to achieve Ideal Future State Vision

While the interim design involved a great deal of work, it was the first phase of the larger scale plan to convert the entire manufacturing system. In the next phase, also referred to as the ideal plan, the formation of cells in the fabrication is followed by their linkage to assembly cells. The expected savings at this point in the conversion process are summarized in Table 4-17.

Upon completion of the ideal phase, it is estimated that the assembly area of the plant would be sufficient to house the entire linked-cell manufacturing system, as shown in Figure 4-32. The estimates used to calculate the floor space requirements are based on the dimensions of the pilot cell, while estimates of the aluminum fabrication cells are based on the dimensions of the current forming machines and assumptions about the new brazing and washing machines.

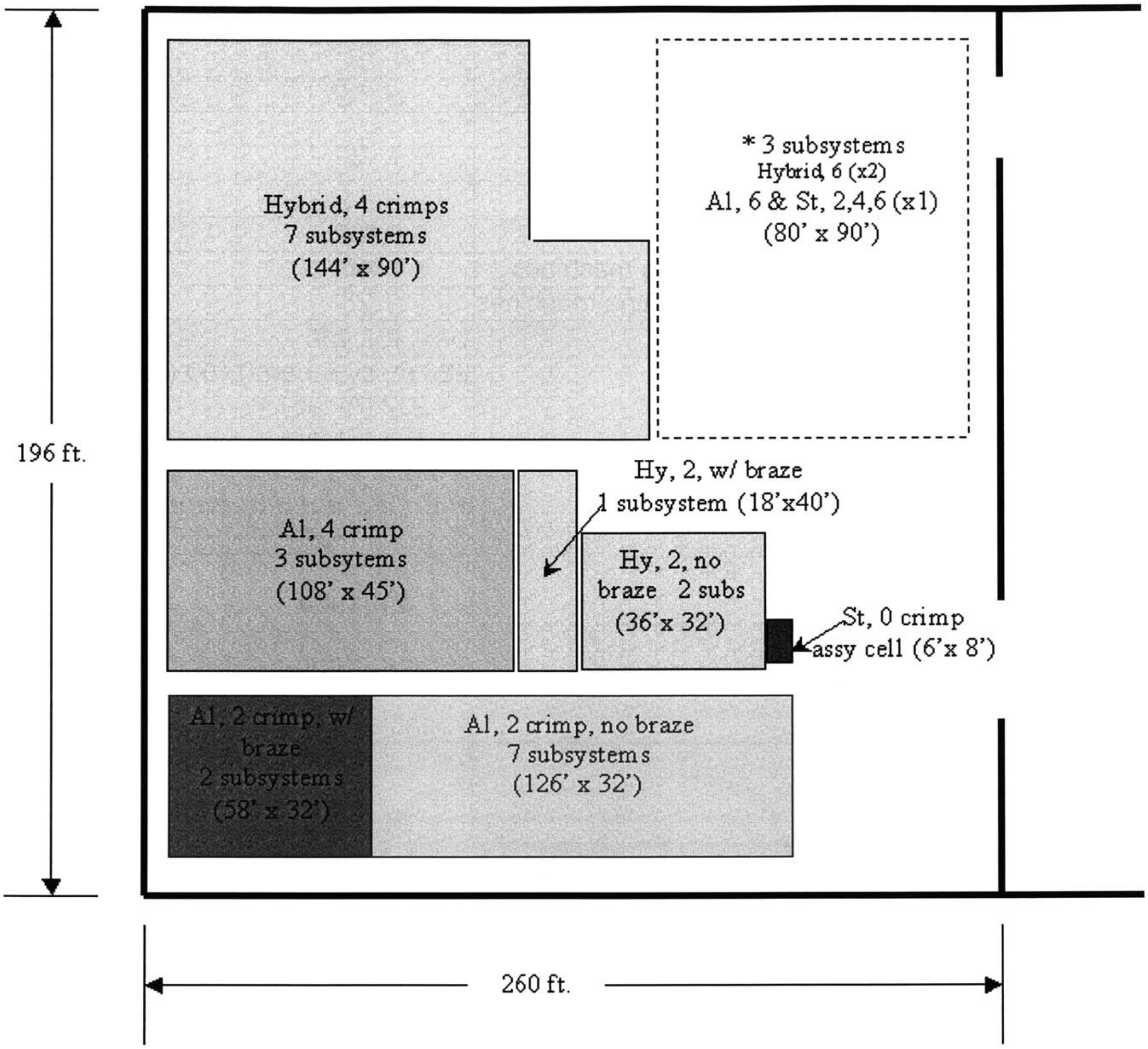


Figure 4-28: Layout in the Ideal System utilizes only assembly space of previous system.

Features		Current	Ideal
Production		~7,000,000 pcs/year	~7,000,000 pcs/year
Fab Production			
	# of Aluminum fab cells	0	41
	# of tube cutoff machines	10	8
	# of formers (3 stroke)	56	99
	# of formers (6 stroke)	23	43
	# of groovers (ferrule)	21	48
	# of groovers (end cage)	4	22

	# of piercing machines	13	13
	# of washers	5	41
	# of Aluminum brazers	16	29
Assy Production			
	# of cells	4	26
	# of assembly lines	11	0
	# of benders	132	70
	# of crimping machines	46	82
	# of leak testing machines	28	26
Floor Space (sq. ft)		163,140	51352
Total Direct Workers (all shifts)		623 (assy & bend) + 232 (Al fab) + 198 (St fab)	160 (assy & bend) + 141 (Al fab) + 198 (St fab)
Total Indirect Workers (all shifts)		76 (assy & bend) + 45 (Al fab) + 54 (St fab)	140 (Al assy, bend, & fab) + 54 (St fab)
Total required man-hours per year		2191980	838320
Yearly Fab Scrap Expenses		$540,000	$80,500
Fab WIP		Variable (~64,000)	285 (~7 per cell)
Fab Throughput Time		Variable (~1 day)	4 min
Yearly Assy Scrap Expenses		$135,000	$7,000
Assembly WIP		Variable (~1800)	78 (3/cell)
Assy Throughput Time		Variable (~1 day)	2 min

Table 4-9: Comparison of the Current and Ideal Systems

(Aluminum fabrication cells formed and linked to assembly cells formed in interim plan)

4.9 Post Pilot System Change and Implementation

Summary of the changes proposed for the system with respect to the FR-DP pairs of the MSDD especially ones that relate to the physical design are presented in Table 4-10.

FR-DP	Question from Questionnaire	Old *	New *	Explanation of changes
Q121	We have standard training procedures for each operation.	2	5	The implemented cells documented standard training procedures
Q121	Operators know upstream and downstream processes.	3	4	Very good training of system coherences for all participants of the system with the physical model was emphasized
Q121	Operators are usually trained on the job.	4	4	No change.
Q121	We continuously improve training procedures.	3	3	No change.
Q122	Operators are involved in creating the work methods.	2	5	Assembly operators participated in the layout of the assembly area Work loops and elimination of wasteful processing steps.
Q122	Work methods have been defined for each operation and contain information about required quality standards.	4	5	The work methods have now been formally posted on the implementation cells and provide information on quality standards.
Q122	A written copy of operator's standardized work is available at each station.	2	4	All instructions are displayed in the assembly cell. System wide this Still needs to be achieved
Q122	Variation in quality is reduced either by adjusting the work method or through operator training.	2	3	Increased operator involvement will likely lead to adjusting the work standards as well to reduce quality variation.
Q122	We enforce that every operator performs the tasks according to the work method.	3	4	Supervisors ensure that operators work reflects documented standard However system wide this is yet to be achieved.
R111	Machine downtimes are immediately noticed (e.g. through information technology or process design)	3	5	Downtimes in the original system were noticed downstream by missing parts. In the linked cell subsystem model these would be noticed Instantly.
R111	We use devices such as Andon boards or radio communications to signal the occurrence of disruptions.	3	5	Disruptions were indicated by stopping the line in the previous system In the new system these would be indicated by a flashing light.
R111	Operators can easily see whether they are ahead or behind schedule.	1	5	Yes for assembly. Schedule shows time increments of 20 minutes, i.e. operators can see every 20 minutes if they are ahead or behind schedule.
R111	Variation in work completion time is easily identified.	1	4	Made possible by recording work completion times
R112	We can always determine which upstream machine is responsible for a defect.	2	4	In the new system the upstream machine responsible for defect would be recognized due to operation in cells
R112	Process lay out allows immediate detection of disruptions (e.g. downstream operations are quickly starved).	2	5	Linked cellular layout makes defect detection easist
R112	Machine downtimes can be unnoticed by downstream processes because processes are separated from each other either physically or through large buffers.	4	1	Much better communication between fab and assembly in the new system due to linked cellular operation.
R113	We have standard procedures for determining the root cause of disruptions.	2	4	Formal capturing of problems in assembly. No established standard program yet.
R113	Our system exposes disruptions and makes them easy to recognize.	2	4	The whole system supports the exposition of disruptions much better than before (e.g. by having schedules on the floor, defined inventory levels).
R113	Breakdowns in equipment are easy to diagnose.	3	5	Simple, reliable equipment design in new system
P11	Our operators have access to all information regarding their tasks.	3	5	Yes in assembly. Board in the middle of the assembly area shows all work sequences etc. Production schedules are clearly displayed.
P11	The operator always understand what to produce, when to produce, and how to produce.	1	5	Better communication of schedules and system coherences desired.
P11	Operators have easy access to process information.	4	4	No change
P11	We often have production disruptions due to missing information.	3	1	Missing information often causes over or underproduction that leads to disruptions. In the new system the production information would be communicated clearly through use of kanbans
P131	We time each operating step in detail and include the information in the work instructions.	4	4	Operator is free to recommend changes that improve work times
P131	Variation in work completion time is being solved either by adjusting the work method or through operator training.	1	4	Variation in work completion time is corrected through operator training from supervisor.
P131	If one team operator is unable to finish a cycle on time, another operator is able to help him finishing the cycle (the work loops are flexible and operators can help each other).	3	5	Feature of the assembly cells, hall-mark of linked cell manufacturing
P131	Work completion time of the same task often varies between operators.	4	3	Operator training and discipline in new system.
P131	There is high variation of work completion time between cycles of the same operator.	5	4	No significant change proposed
P141	We have standard levels of inventory between sub-systems for each part.	1	4	The levels are defined but need to be maintained in assembly. System wide linked cell manufacturing would make this FR a reality.
P141	Operations are frequently starved due to unavailability of incoming parts.	5	1	In the new system the fabrication cells would feed the assembly cells and thus in the ideal case the production matches the assembly consumption.

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

FR-DP	Question from Questionnaire	Old *	New *	Explanation of changes
P142	Our part suppliers deliver on a just-in-time basis.	2	4	Supplied materials should be delivered on a just in time basis, if border restrictions are an issue, small shipments on a shift basis.
P142	The frequency of material delivery is based on consumption as opposed to preset delivery times.	5	4	The raw material supply is based on consumption of parts in fabrication that is linked to customer demand by assembly
P142	Part deliveries are independent of downstream consumption.	4	4	Part delivery should be related to consumption of parts downstream in Fabrication and assembly.
T21	We determine takt time at an early stage of a manufacturing system design project.	1	5	Schedule must reflect the customer demand time as a start point in System design.
T21	We have clear customer - supplier relations throughout the value stream and production pace is based on takt time.	2	5	The linked cell subsystem model clearly defines the supplier customer relationship.
T222	We design each operator's work loop to run as close to takt time as possible.	1	4	The work loops must match and run close to the customer demand time.
T222	When manual cycle times are longer than takt time, we try to divide the operation into two or more operations to achieve takt time with each operation (rather than having two operators performing the same operation in parallel)	3	5	In the new systems cells tasks are designed that provide sufficient opportunities for dividing manual tasks into two or more operations.
T23	We are well balanced across the process flow.	1	4	Do not let fabrication produce ahead of assembly, linked cell model ensures balanced production across the flow.
T23	We use a Heijunka box or some other means to communicate the pace of customer demand into the value stream.	1	5	The schedule would be presented in a Heijunka box. Assembly operators can then see pace of production.
T3	We usually meet the production schedule every day.	3	5	The schedule should be accurately known and the assembly production paced with the Heijunka to produce the daily output, consistently and reliably.
T3	We frequently produce more (or less) than scheduled.	5	3	The assembly schedule should be met all the time. The cells provide for volume flexibility.
T3	We frequently produce more (or less) of a particular part type per day than the downstream customer consumes per day.	5	4	Scheduling must consider the real customer demand time when pacing the linked cell subsystem with the Heijunka.
T31	We schedule only one operation in the value stream. Upstream operations are scheduled based on the consumption of the scheduled operation.	1	4	Only assembly should be scheduled.
T31	We use a pull system for production control.	1	4	Linked cell sub system model supports pull production.
T31	Our operators have easy access to the production schedule.	3	5	The operators should have the schedule at the assembly cell.
T32	We are working aggressively to reduce setup times.	2	4	No change with current equipment design. New design provides rapid changeover
T32	We have converted most of the setup time to external time while the machine is running.	2	4	No change with current design.
T32	We have low setup times for equipment in the evaluated value stream.	1	4	No change
T32	We tend to have large run sizes in our master schedule.	5	2	The assembly production should be leveled based on customer demand within the product family.
D21	When the shop floor layout is designed, equipment and material are placed so as to minimize walking distances.	3	4	The linked cell layout minimizes walking distance
D21	We usually arrange equipment first and then consider the work loop of the operator.	4	2	Cells must be designed keeping operator workloops in mind.
D21	We design equipment to minimize walking of the operator.	3	5	The designed equipment minimizes the walking distance.
D21	Most of our operators are bound to one station and do not have to walk at all.	5	1	Linked cell model promotes and requires separation of man-machine.
D22	We have defined locations for all tools.	3	4	Some improvements based on operator input. But different operators put tools to different spots indicating the tool position is not optimal yet and not strictly defined.
D22	Tools to perform a task are frequently missing.	2	1	No change, since tools in assembly are seldomly missing in the existing system.
D22	We enforce keeping workstations in clean and orderly condition.	3	4	No change
D23	We continuously improve workplace ergonomics by rearranging equipment, tools, material presentation etc.	1	4	Operators should give more input and suggestions should be implemented.
D23	We use time studies to update standard work sheets.	1	4	Time studies from cellular operation used to update work sheets.
D23	Ergonomic interfaces among worker, machine, and fixture are an important consideration during initial layout design.	3	5	Operators must be encouraged to provide inputs for new design
D3	Balancing work loops of operators is an important system design objective.	2	4	Linked cell model encourages efforts on balancing operator workloops
D3	It is often the case that within a team of operators some are idle for part of the cycle, while others are busy for the entire cycle.	5	4	Work loops to be designed close to the cell takt time.

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

Table 4-10: Evaluation for questions of FR-DP pairs that were design objectives.

Despite a plan for system conversion based on a coherent strategy of pursuing assembly cells along the lines of the generic model and in the order defined by the product families, subsequent to the pilot phase numerous developments suggested a strong disconnect between plan and action.

4.9.1 What happened

Three cells were implemented and a fourth designed. Of the four cells, two produced single models, while the other two were used for re-inspection of models run on the assembly lines (customer requirements for some models mandated 200% inspection). In the two cells being used for production both products are aluminum, two crimp models similar to the pilot model. However, the cells looked and ran very differently because takt times were 25% lower. Each of the cells had a takt time of about 18 seconds due to the fact that all of production is designed to run in one shift. The result of running at such low takt times was an increase in the number of workers required. The cells had 9 direct workers each (as against 6 in the original design), increasing the floor space utilized by 50%. The key observations on the implementation process in the next couple of quarters after the pilot project implemented by the authors is summarized as under:

- **Strategic Issues**

Evidently the original plan for conversion was not followed while the replacement plan was not defined and hence limited in scope and lacking system level thinking. The product families have been ignored, and the goal has instead become one of converting each assembly line to cells, regardless of which products are currently being run on the line.

- **Communication Issues**

In creating the new plan, the project leaders in different plants worked independent of each other. Moreover, their focus on the conversion process was split along departmental lines as in the previous system. Hence, the person in charge of fabrication knew very little about his counterpart's plan to convert the assembly area, and vice versa. The result would be the assembly area as a cluster of cells formed on a certain set of logic, different from that of future fabrication cells. Thus, linking the two areas would become very difficult, and the simplicity of the original plan is lost.

- **System incentive Issues**

Performance evaluation and responsibility continued to be along departmental lines providing strong incentives for project leaders to pursue divergent goals and activities to ensure individual targets were met over system goals. For example, new fabrication equipment that were not along the guidelines defined by the design process were ordered even at a time when the leadership had mentioned budget constraints on the transformation process. Moreover, the inspection cells were pursued ahead of more important production cells. In fabrication there was a plan for massive movement of equipment for reasons of proximity to assembly. Without cells being linked the logic for the move was difficult to comprehend and reflected system tendency to kill a few easy bears than follow the original plan. Accustomed to resolving all production disruptions with a fire fighting approach, often the accounting policy of heavy equipment utilization even at the expense of overstaffing repeated itself with the logic being Mexican labor that was cheaper compared to US standards. A life cycle cost analysis of equipment utilization and substitution of equipment investment with labor, pointed a fundamental flaw in the accounting thought process. While machines get depreciated over a period of time, labor costs continue forever. Thus regardless of the business climatic conditions, maximizing machine utilization is not the right strategy. Finding it difficult to retain workers in the second shift, the system had a strong incentive to complete all production in first shift by increasing workers on first shift even at the cost of increasing total man-hours required for production. For instance, in the case of the inspection cells there were no crimping machines and thus no perceived machine capacity constraints, yet there was an insistence on only running in the first shift.

- **Subsystem design malpractices**

As understood by the above discussion, running cells at low takt times was a reflection of wanting to run single shifts. In addition there were other elements of poor design and implementation such as cells running clockwise and performing some of the non-essential processing steps made necessary by the assembly line design. The cell workers were seated and tied to a station, with the leaders citing cultural preferences of workers for the arrangement. The problem of poor balancing expressed itself with instances of operators having twice the work content of their co-workers. The cells continued to make use of a final inspector just like on the assembly line and the designed 'cells' were essentially a U-shaped miniaturization of the line. In all areas of the production system, the method being used for conversion appeared to be one of trial and error, with significant effort being devoted towards 'topping' the pilot efforts with no attention towards sharing practices or continuous improvement.

4.10 Case Study Discussion

The success of the pilot and subsequent failure of post pilot implementation discussed above helps illustrate the hypotheses postulated earlier.

***Hypothesis 1** Production systems have poor operational performance due to poor design or implementation.* The pilot project (Table 2) succeeded as the design combined the decomposition framework that helped defines objectives and means with a rigorous systems engineering approach. However, the subsequent altering of the plan for system conversion led to complexities in information and product flow at the system level as well as poor operational performance at the cell level. After the pilot project, cells were poorly designed and were mere modifications to the line to physically resemble pilot cells. These cells therefore did not replicate the benefits from the pilot cells in Table 2.

***Hypothesis 2** Poor MSD is a result of mental models for manufacturing performance improvement based on minimizing unit operation costs.* Accounting processes are typically geared towards minimizing the unit labor cost of a part or maximizing machine utilization. Both these practices lead to mass production systems with departmental layouts and are a continuation of the days when labor was the major component of part costs. Departments often measure their performance separately from system goals and compensate individual's on their performance rather than that of the system. There was no feedback loop from performance measures to highlight large WIP or throughput time when cells were operated as U-shaped lines. Moreover, benchmarking with past performance of the system led to complacency toward efforts for improvement. This apparent lack of critical feedback aimed at pointing sub-system design flaws thus further perpetuated poor system design, mental models and practices.

***Hypothesis 3** Financial Performance measures do not always reflect the true operational performance of a Manufacturing System or the effectiveness of its design [Cochran, Johnson 2001].* The fact that the plants belonged to a leading automotive components supplier based in the US with global operations, enabled the accounting department in these plants to compare their operational and distribution costs with those of American plants. Given the proximity to the US and the substantially lower Mexican wages, traditional accounting practices reflecting lower unit labor costs as the chief production cost indicated superior performance at these plants despite their flawed designs and operationally inferior performance. Thus lower personnel costs buffered the impact and camouflaged the problems of poor system design and processes. It encouraged the use of traditional accounting practices since they projected factory performance as superior.

Hypothesis 4 *Poor organizational leadership sets poor organizational processes. The resulting processes are misaligned with organizational objectives.* The leadership was more interested in impressive bottom-line figures reflecting their performance in a good light. Despite the possibility of potential benefits far exceeding the current returns from reduced labor costs, the leadership was not proactive in identifying change as the important step towards superior system performance in the future. Moreover, in order to avoid potential conflict between departments, the leadership should have committed to the implementation plan. The failure in changing traditional measurement practices and accepting departmentalization indicates poor leadership. Focusing on better financial performance relative to other plants in the company and overlooking poor operational performance relative to world class manufacturing systems was a principal cause of failure, thus illustrating the set of hypotheses.

Chapter 5 Proposed Manufacturing System Design Methodology

Systems are comprised of physical, informational and logical relationships. These relationships determine the structure or design of the system. The previous chapters have shown how the design and the process of its implementation influences system behavior and performance. The key to Manufacturing System Design therefore is to be able to define and align these relationships with respect to achieving the goals of the system.

The Manufacturing System Design Decomposition (MSDD) defines these relationships. However, the MSDD is inadequate to guide the process of alignment of the relationships between the manufacturing organization and the enterprise as demonstrated by the case study. Misaligned individual and departmental objectives and incentives, poor leadership and a performance management system that relied solely on financial figures to judge operational performance all illustrate the disconnect that often occurs between the enterprise system processes and the manufacturing system design process.

5.1 Introduction

The Manufacturing System consists of the operations required to convert a part from its initial state to its final state. These operations are of four main types: processing, transportation, storage and inspection. The conversion system is often called a Value Stream and a value stream map identifies how the parts flow between operations and how information is used to initiate production. The Enterprise system consists of all of the functions that should support the value addition that occurs in manufacturing. Therefore, waste at the Enterprise level is any activity that does not support the aims and goals of manufacturing vis-à-vis the enterprise. Waste in manufacturing is any activity that does not add value to the product that the customer is willing to pay for. The goals of the enterprise affect the manufacturing system. Likewise the goals of the manufacturing system affect the enterprise system design. These two systems must be complementary. The relationships between the systems must be well defined and must work congruently. Designing and implementing a stable manufacturing system will enable the resources in the business to concentrate on waste and variation reduction as the means to reducing cost.

5.2 Physical Simulation Focused Manufacturing System Design-Implementation Process

This chapter presents a methodology to re-design an existing manufacturing system based on implementation experience and illustrates the role of system preparation using physical simulation in the manufacturing system re-design process. Cochran [2001] suggests the following sequence for the change process to re-design a manufacturing system. The 12 major steps that make up the process are listed below.

- Establish the value stream map of the current state manufacturing system. Depict the material and information flows in the system.
- Develop a current state physical simulation based upon the existing manufacturing system's design and operating practices.
- Establish the future state value stream map.
- Design the future state physical simulation in alignment with the future state VSM that schematically illustrates the design to achieve system stability.
- Physical simulation demonstration of the current state versus the future state.
- System design education.
- Evaluate current state and future state system designs with the MSDD.
- Integrate IT infrastructure to support system objectives.
- Refine future state physical simulation with all team members.
- Develop standardized work.
- Finalize performance measures (PMs).
- Plant-wide education of the new system design using the physical simulation.

The above steps are also summarized in Figure 5-1, which is a flowchart of the change process to design and implement a manufacturing system.

Figure 3-1 proposed a model for the manufacturing system re-design process. The above steps influence all the three levels in the design process, strategic and facilitation, design and operation and evaluation. The mapping of these steps with a schematic of the manufacturing system design process is illustrated in Figure 5-2.

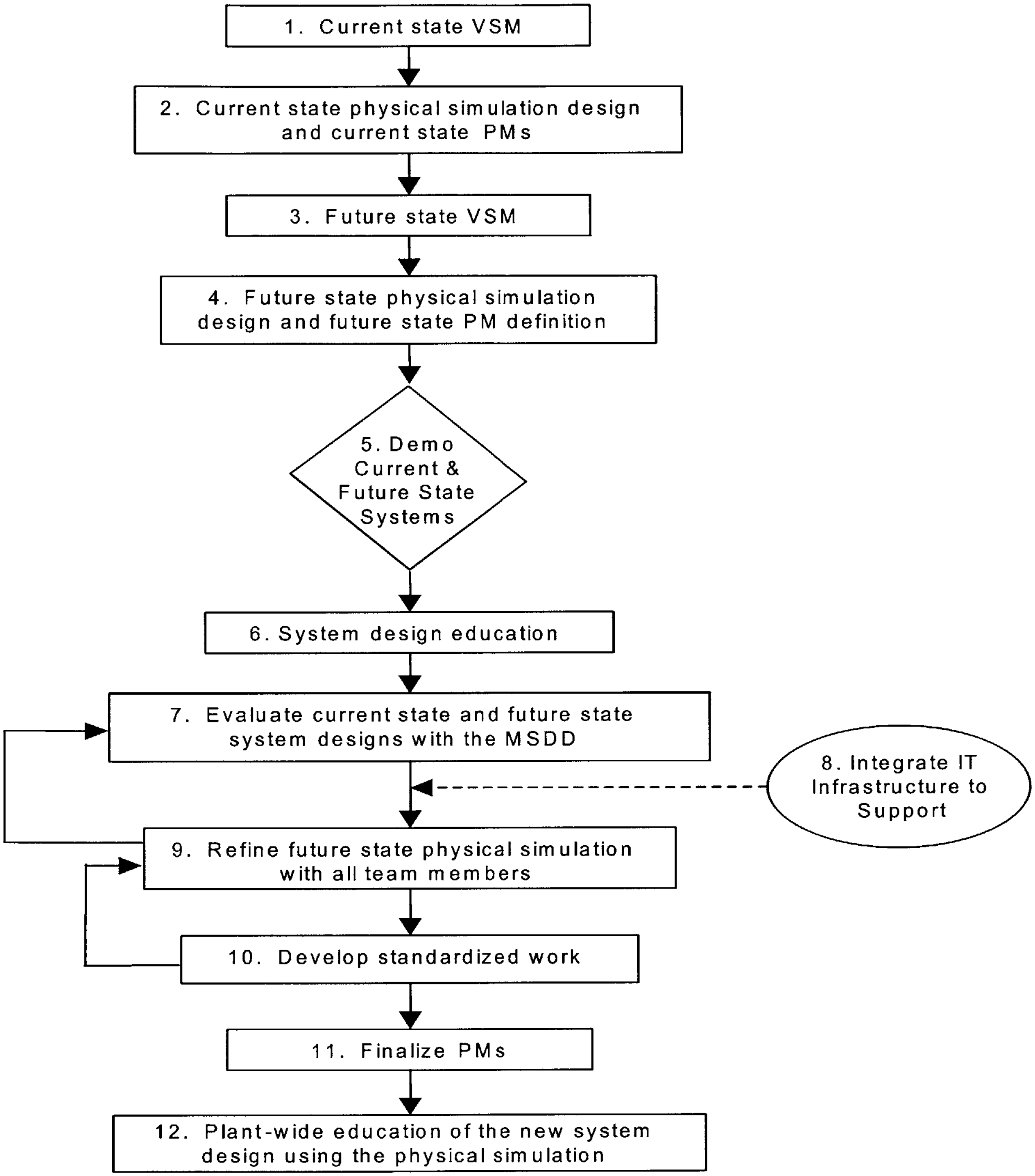


Figure 5-1: Flowchart of Change Process to Design and Implement a New Manufacturing System [Cochran et al, 2001]

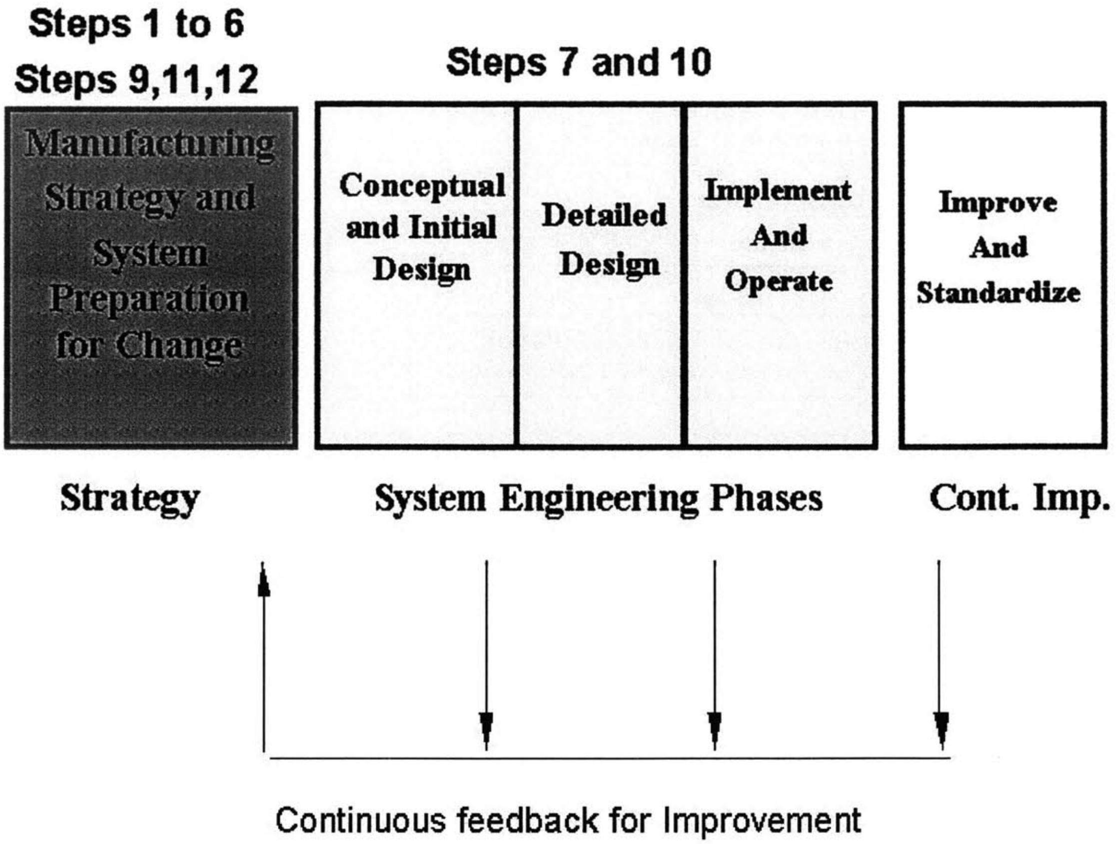


Figure 5-2: Mapping Cochran [2001] steps with proposed model for existing manufacturing system design process

Figure 5-2 provides insights to the strengths and areas for improvement in the proposed steps for change in the design of manufacturing systems. Most of the proposed steps are relevant to the strategic and facilitation level and system preparation phase (Strategy) of the design process (Figure 3-1). The proposed steps address the exact areas that the methodology adopted for the case study discussion failed to incorporate as the methodology adopted emphasized the system engineering and continuous improvement phases. The steps emphasize the role of physical simulation and education to facilitate the design process. The steps address the aspect of system evaluation, generation of the MSDD and development of standardized work in the System Engineering phase. However the steps do not define what the future state of the manufacturing system should look like. Defining the future state of the manufacturing system helps in guiding the process towards achievement of the state. The above steps also do not address customer satisfaction issues directly. In general, the above-proposed steps do not address areas relevant in the detailed design phase of the system engineering process, as they do not provide any guidance for subsystem and unit level of design. Finally the 12 steps proposed do not address the need for continuous improvement directly that was the focal point of the 8 Steps to Lean adopted for the Case implementation. There is therefore a need to integrate the two methodologies.

5.3 Integrated Methodology for Manufacturing System Re-design

The design and implementation process proposed here provides a guideline for designing and implementing a new system or revising an existing system.

5.3.1 Proposed Steps for Manufacturing System Re-design

The proposed steps for manufacturing system re-design are distributed across the three phases discussed earlier. The steps are discussed in greater detail in section 5.3.2. These steps are mapped with respect to the manufacturing system design process in Figure 5-3.

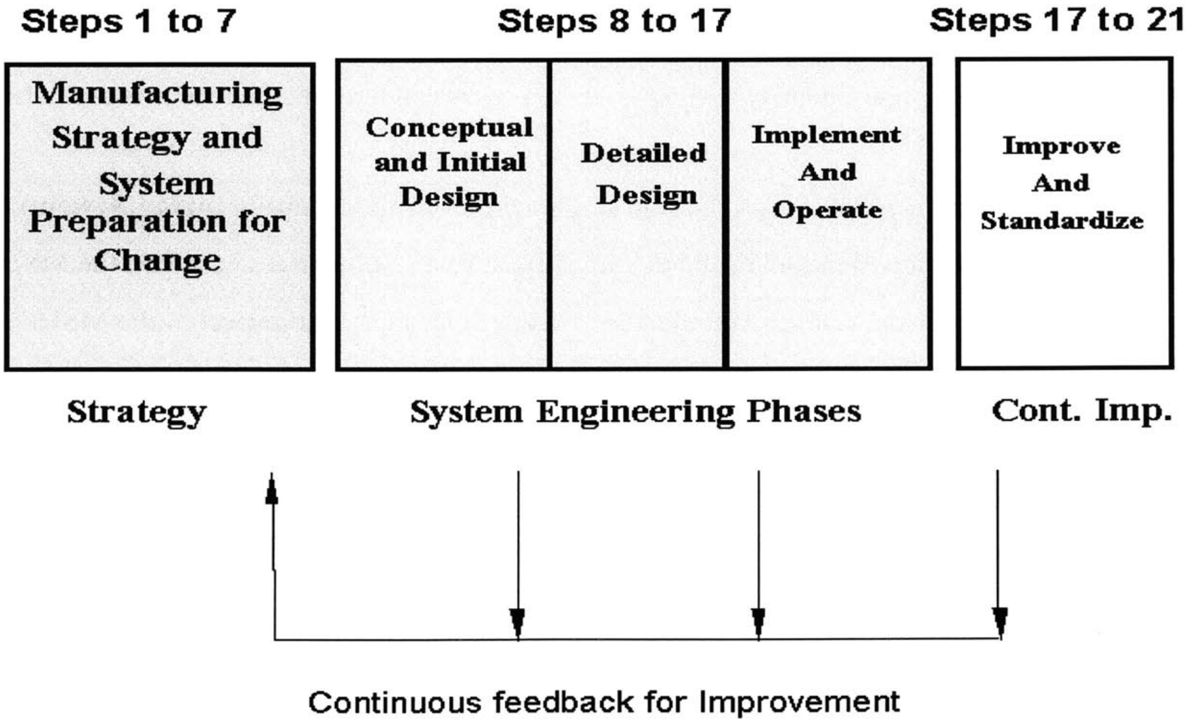


Figure 5-3: Mapping proposed steps with model for manufacturing system design process

5.3.1.1 Strategic and Facilitation Level (Organizational and Enterprise issues)

- Define the macro-level linked cell value stream design in the rough schematic of a linked-cell 'bubble diagram'. [Cochran, 2001]

- Identify external customer and create a customer-focused capacity and investment planning process to support above value stream.
- Integrate product development and IT processes and align the departments of business planning, material supply, IE and purchasing with Engineering towards supporting the capacity and investment planning process.
- Physical Simulation to be used as an organizational learning tool to 'win hearts and minds of people' and demonstrate the impact of the future state linked cell value stream and a stable system. Physical Simulation demonstration of the current state versus the future state.
- Establish the Performance Measures for the current system; define the performance measures for the future state.
- Derive key metrics for operating management's performance and compensation based on their success in establishing and implementing a stable manufacturing system design and improving it.
- Establish cross-functional teams to facilitate productive interface between manufacturing and the rest of the enterprise; identify and remove organizational barriers that can prevent putting the system in place.

5.3.1.2 Systems Engineering Steps (Design & Operation of the Manufacturing System)

- Create a common mental model of the manufacturing system objectives based on the MSDD.
- Evaluate the current state of the Manufacturing System Design with respect to the MSDD.
- Finalize and define the set of performance measures (PMs).
- Develop and examine the current state value stream map (VSM) to determine the weaknesses in current design especially with respect to material and information flow.
- Develop the future state map linking supplier customer relationships throughout the Value Stream.
- Develop a physical simulation model [Cochran, 2001] of the future state value stream. Refine future state physical simulation with all team members.
    - Teach people the merits of designing a stable manufacturing system (evidenced by achieving the FR's of stability). Train them to design the standardized work.
- Define the external customer in a way that allows flexibility in balancing work loops.
    - Maintain a one-to-one relationship between a supplying and customer process.
- Form volume flexible cells based on takt time.

  - Maintain adequate provision for variation.
- Design cells for zero changeover time.
- Design and operate the system with leveling and pacing.

5.3.1.3 Continuous Improvement and Standardization

- Evaluate the system with respect to the functional requirements of the MSDD in order to determine the weaknesses in the design and areas for root cause problem solving.
- Systematically reduce SWIP between cells to reduce variation, improve reliability and mistake-proof processes.
- Reduce the run size.
- Constantly improve the work.

These steps cover all levels of the system design pyramid presented earlier and also extend to all sections of the system design process in Figure 3-1 as shown in Figure 5-3 which maps these steps with the manufacturing system design process.

5.3.2 Strategic and Facilitation Level

The important steps in this level are discussed in greater detail in this section. The strategic and facilitation level focuses on the following aspects of enterprise and manufacturing system design:

- Alignment and integration of various enterprise disciplines with manufacturing.
- Using physical simulation and other educational tools to demonstrate the design and operation of stable manufacturing systems.
- Defining performance measures for the system that are aligned with the objectives of the new manufacturing system design as stated by the decomposition process.
- Aligning personnel incentives towards change.
- Establishing cross-functional teams to remove organizational barriers to change.

Define the macro-level linked cell value stream design in the schematic of a 'bubble diagram'.

The macro-level linked cell value stream provides a rough picture of the state of the manufacturing system envisioned. The manufacturing system in such a bubble diagram is typically part of the product supply chain and helps the enterprise evaluate where value addition from the manufacturing system contributes to the enterprise objectives. It also helps the system to establish and tie cost metrics for investment and capacity planning purposes based on system design.

Identify external customer and create a customer-focused capacity and investment planning process to support above value stream.

The investment planning process enables capacity to be put in place according to the MSDD. The investment planning process ensures that the linked cell value stream designed above is implemented and the cost for its implementation is justifiable. The investment planning process must not aim to optimize or minimize the unit cost of operation in the system as most traditional accounting practices promote. The cost justification must be based on the constraint of the linked cell design achieving the FR's and DP's of the manufacturing system design decomposition.

Integrate product development and IT processes towards change and align the departments of business planning, material supply, IE and purchasing with Engineering towards supporting the capacity and investment planning process.

Product development must be aligned towards the change process so that the product development planning process supports the linked cell value stream map. The processes used to manufacture a product are dependent on the design of the product hence it is absolutely essential that system designers are involved in the design of new products. Poor product designs can lead to systems that are full of waste and hard to improve. The people who understand how things are made, especially the shop floor workers, should be involved in the product design from the beginning of the concept stage. Their input and knowledge will be an invaluable asset to the product designers as they explore design options.

IT must support the objectives of the MSD. IT must be used as a tool in effective planning, the information source must be used to facilitate the operation of the linked cell value stream and not control it. Typical MRP based systems fail to appreciate that the role of IT must be a support and not an all round planning and control role. The problem with using IT to control the system is that there is less flexibility and the system cannot adapt easily to changes in customer requirements. There should be no ambiguity in the link between sender and receiver. The time constant of control or feedback being large creates further problems in meeting customer demand accurately. Moreover, MRP based systems do not convey accurate information to the shop floor regarding customer demands; the shop floor being the place where it is needed most. Business planning, material supply and IE must essentially play a support role to system engineers and designers. Heavy reliance on Industrial engineering leads to attempts at reducing operation times. However, this also leads to a mass departmental layout. based on lowering unit cost of operation by reducing direct labor content.

Physical Simulation to be used as an organizational learning tool to 'win hearts and minds of people' and demonstrate the impact of the future state linked cell value stream and a stable system. Physical Simulation based demonstration of the current state versus the future state system; define the performance measures for the future state. [Cochran et al., 2001]

The term *physical* simulation as used herein describes the creation of a scale model of a manufacturing system's material and information flow, operational practices and standardized work activities to operate a manufacturing system [Cochran et al., 2001]. Physical simulation illustrates the opportunity cost of people's time spent on getting parts out of the door within a poorly designed system, versus people's time spent on improvement of the work itself within a stable system. It may be used as a visualization and design tool to unambiguously define a system's design and operation. Physical simulation may be used to promote true learning. The key to promoting true learning is to first challenge the team members to understand the objectives of a manufacturing system's design and then to be able to associate the physical implementation of the system design to the achievement of the manufacturing system's objectives. Once the physical simulation model of a manufacturing system's value stream is built, it may then be used for education, training and improvement activities.

The physical simulation can be done easily by creating a Lego-model simulation of the current state. It can also be used to prototype future state. It is a great way to 'Win over people's hearts and minds' [Cochran, Johnson, 2001] by showing the organizational learning impact of working within a stable manufacturing system, versus not doing so. The physical simulation must include a simulation of the work, of the part placement decisions, of the automation and safety decisions. A current state physical simulation must be developed based upon the existing manufacturing system's design and operating practices. The physical simulation should be a simplified, scale model of an existing value stream within a plant. The current state physical simulation model provides the basis for people to learn, observe and to initiate change. The future state physical simulation must be designed to reflect the future state VSM that schematically illustrates the design to achieve system stability. Physical simulation helps create a common mental model of the future state of the system and defines the work and is hence a more powerful tool than Value Stream mapping.

Establish the Performance Measures for the current system; define the performance measures for the future state.

This step should capture how the existing system is measured and model the behaviour of the people within the system resulting from the existing performance measures. Concurrently, new performance measures should be established for the new manufacturing system. The performance measures should reward the achievement and improvement in the achievement of the system stability objectives of producing the right quantity, right mix with perfect quality to the customer.

Derive key metrics for operating management's performance and compensation based on their success in establishing a stable manufacturing system design and improving it.

The operating management's performance must not solely be measured in terms of financial results or parameters. When management compensation is based on financial figures it provides management with the incentive to focus on ways and means to optimize the unit cost of operation and lower the costs allocated to their department based on direct labor content. There are also personal incentives that promote activities aimed at increasing personal compensation even at the cost of poor systemic operational performance. The management must be compensated on establishing a stable manufacturing system design. A stable manufacturing system is defined as producing the right quantity, right mix, with perfect quality based on actual customer consumption every shift, in spite of variation at the individual operation level [Cochran, 2001]. Once a stable manufacturing system has been designed and implemented the root causes of costs can be identified and reduced thus having a beneficial financial impact on the enterprise. The implementation of a stable manufacturing system and its continuous improvement can provide significant results to the bottom line and must form the basis for management compensation.

The management or the leadership also has the responsibility to remove the organizational barriers that inhibit or destabilize the process of establishing a stable manufacturing system

[Cochran notes, 2001]. Some of these destabilizing influences such as poorly designed organizational processes and misaligned enterprise interfaces have been mentioned in Chapter 3.

- Planning process for obtaining new business must not focus on minimizing unit cost of operation independently.
- Material supply and containerization for new lines must not be based on traditional costing approach that favors large, disposable containers, delivered infrequently to minimize the cost of supplied material but rather should support the material supply requirements from the design of the system. For example, in the case study discussed this meant designing new containers that carried parts to the cells in small standard sizes that were related to the quantity produced in a given interval at the pace of customer demand.
- The problem resolution process mentioned previously requires the immediate identification and response to problem conditions. This approach necessitates the elimination of after-the-fact meetings that discuss conformance relative to shop floor measures. The communication of information must be unambiguous and unimpeded.
- A process must be established to define standardized work with the work force and management must invest in the workers ability to improve it as a regular process.
- Management must be creative and articulate in addressing union's incentives and motivating them to help improvement efforts.
- Management must identify and abolish arcane regulations and control standards such as the palm button that inhibits cellular operation and can be replaced using a flip switch or light curtain that does not affect system performance.

Establish cross-functional teams to facilitate productive interface between manufacturing and rest of the enterprise; identify and remove organizational barriers that can prevent putting the system in place.

The team must include the Materials Manager, Controller, Mfg. Engineering, Purchasing, Equipment Suppliers, Product Design, Product Stream Managers and the Operators to create the understandng, desire and belief that the goal is to implement a Stable Manufacturing System of Value Stream.

5.3.3 Design, Operation and Evaluation Level (System Engineering Phases)

The design operation and evaluation level focuses on the actual re-design of the manufacturing system. The design needs to be evaluated at different stages against the FR's stated in the MSDD and the design process thus becomes iterative.

Create a common mental model of the manufacturing system objectives based on the strategy.

There must be an innate and gut-level recognition on the part of everyone in the Enterprise that their job supports the following goals of stable manufacturing system every day of producing the right mix, right quantity and shipping perfect quality products to the customer. The supporting Enterprise processes and systems must achieve these FRs, in spite of internal and external variation with a safe, bright, clean, quiet, ergonomically sound working environment for workers who are doing standardized work. The manufacturing system design must be able to rapidly recognize and correct problem conditions in a standardized way. Once the manufacturing system is stable, true waste may then be reduced. When true waste is reduced, true cost is reduced.

Evaluate current position with respect to the MSDD.

Completion of the design decomposition process identifies the FRs (Functional Requirements) and DPs (Design Parameters) of a system design. This foundation in thought forms the basis for being able to adequately measure whether a system design has been implemented properly. A questionnaire has been developed to evaluate the current state manufacturing system designs [Cochran, Linck , NAMRC, 2001], [Linck, Ph.D Thesis]. The questionnaire evaluates how well the FR-DP pairs identified by the MSDD are actually achieved by the system design. Every member of the system design team may complete the questionnaire.

Finalize performance measures (PMs)

The above step ensures that the PMs that are used to evaluate the new system's performance are aligned with the objectives of the new system design. It can be disastrous to operate a new system design and yet measure its behaviour based on an inappropriate set of performance measures. In fact, many systems evolve into physical designs based upon the way they are measured [Cochran, Johnson, 2001].

Develop and examine the current state value stream map (VSM) to determine the weaknesses in the current design especially with material and information flow.

VSM identifies the material and information flow necessary to achieve the objectives and means stated by the MSDD.

Develop the future state map linking supplier customer relationships throughout the VS.

Establish the future state value stream map. The material and information flow for the future state value stream should be designed so that the objectives of a *stable* manufacturing system are achieved. [Won, Cochran 2001]. The system must be designed so that waste can be eliminated. To design a system to enable the elimination of waste means that waste must be made visible. The idea is analogous to the body knowing when it is bleeding and sending signals to the brain that the problem condition must be changed immediately.

Develop a physical simulation model [Cochran, 2001] of the future value stream. Teach people the merits of stable, pull replenishment system and train them to design the standardized work. Refine future state physical simulation with all team members.

Design the future state physical simulation in alignment with the future state VSM that schematically illustrates the design to achieve system stability. The demonstration contrasts the operation of the current state system with the future state with a focus on contrasting the role of people in a stable and an unstable manufacturing system. In an unstable system, the people's best efforts barely keep the system alive. The focus is on trying to ship parts, sometimes any part. In contrast, the new system design enables a focused problem identification and improvement process. The people work on improving the work itself and not on merely shipping parts out the door [Johnson, 2000]. The simulation illustrates the opportunity cost of people not working on improvement. The simulation requires multiple iterations of refinement to ensure success. All team members are asked to run the physical simulation (concurrently with the IT support). Each team member tries to make the simulation fail and asks "what if" questions. The purpose of the step is to make the work methods in the simulation as realistic as possible and to improve the system design's robustness in addressing problem conditions. Educational workshops cement the learning. During these workshops the participants learn how to design a manufacturing system to achieve the system stability objectives. The participants also learn how to design systems to achieve the objectives (FRs) and means (DPs) as decomposed by the Manufacturing System Design Decomposition (MSDD).

Standardized work defines the work methods necessary to operate the manufacturing system. Standardized work affects the work of both salaried and hourly team members. In fact, standardized work defines how management will react to specific problem conditions. Developing standardized work is crucial to the successful launch of the new manufacturing system. The people who operate the new system must know *what* to do and *why* they are doing it. The standardized work helps to answer these questions for the operating personnel. The physical simulation enables the participants to test the standardized work methods. The standardized work methods must be written down. Significant changes to the written standardized work instructions will be made as a result of testing the standardized work methods with the physical simulation.

Define the external customer in a way that allows flexibility in balancing work loops and maintains a one-to-one relationship between a supplying and customer process.

This step has no direct relationship to actual implementation, but is included to help the reader keep in mind the importance of designing a Manufacturing System based on actual customer needs. These customers are not just the end customers, but internal customers as well. A well-designed manufacturing system provides higher quality, through better quality feedback and allows for better response to customer needs through increased volume and mix flexibility. The number of workers in a manufacturing unit or cell provides the volume flexibility. Varying the number of workers also makes sure that the workers are fully utilized and are not idle. Consequently, cells must be designed such that a range of workers can work together. Machines should be a minimum distance apart and aisles should be no wider than 4 feet. This minimizes the walking distance and thus minimizes the waste of motion. For obvious reasons, there must not be any obstruction in the walking path. Ideally, no worker should be isolated and each worker should be able to see all of the operations in the cell. The one to one relationship between the supplying process and the customer in a linked cell manufacturing system is shown in Figure 5-3. The linked cellular subsystem design model has been shown in literature to meet the subsystem requirements of reduction of throughput time, reduction of transport and storage delay, and increased worker utilization through single-piece flow and multi-functional workers [see also Shukla, Estrada, Cochran, 2000].

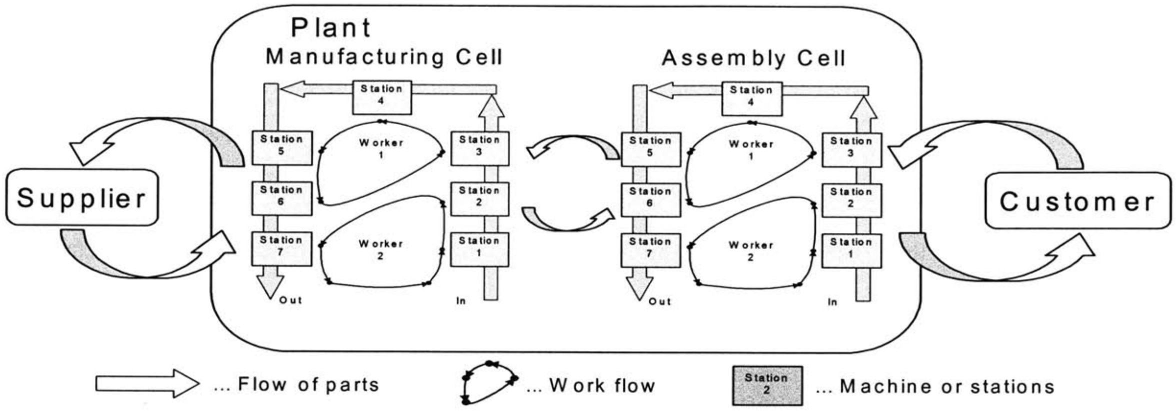


Figure 5-4: Linked Cell manufacturing system design that establishes a one to one relationship with suppliers and customers and flexibility in balancing work loops

Form volume flexible cells based on takt Time with adequate provision for variation.

The first step in forming a cell is to calculate the takt time range within which the cell will be operating. By knowing the minimum and maximum daily demand, the takt time range can be calculated. The average takt time is found with the following formula.

$$Takt\ Time = \frac{Available\ Daily\ Time}{Avg.\ Daily\ Demand}$$

As shown in Figure 5-4, customer demand usually follows a normal distribution. The calculation of takt time above, uses only the average demand hence cells must be designed to handle a range of takt time, as shown by the uniform distribution on the right half of the figure. The ability to handle a range of customer demand is what gives the cell volume flexibility. The cell can now be designed such that 1 worker can meet the maximum takt time (minimum customer demand), and the maximum number of workers can meet the minimum takt time. If the demand is too large then multiple cells may be needed to meet the customer demand.

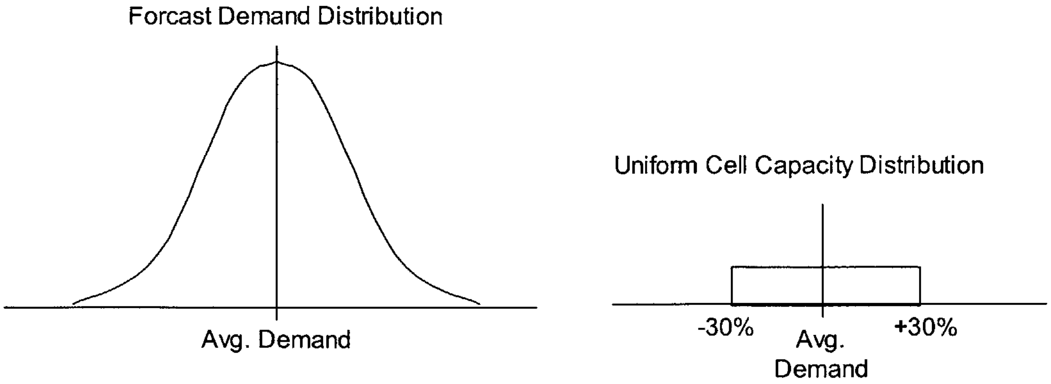


Figure 5-5: Showing the demand distribution over time and the translated uniform distribution for cell capacity.

Ideally, each machine in a cell must have a cycle time that is less than the smallest takt time. If this is not possible then duplicate machines can be used and parts can be alternated between them. The physical Machine Design must ensure that it satisfies the following requirements:

- Narrow face print – The front of the machine should be narrow to minimize the walking distance between machines.
- Raw material fed from the rear – In order to minimize the interference with the worker, the incoming materials should be fed from the rear. Chip and waste should be fed from the rear.
- Ergonomic design – Machines should be designed with good ergonomic principles in order to minimize wasted motion and worker stress. Height, distance and ease of access should be considered for each aspect of the machine.
- Machine should be "right-sized" – This typically means that the machine is designed for single piece flow rather than batch processing.
- Walk Away Switch – The machine should be designed with a switch that allows the operator to start it as he is walking to the next operation.

Because a cell must have all of the necessary machines or stations to fabricate or assemble a part, the workers in that cell must be able to operate various types of equipment. A worker skilled at using several machines or performing several assembly tasks is a Multi Functional Worker. As mentioned previously, process variability can lead to increased need for larger buffer between operations. One of the best ways for reducing variability is to implement standard operations. These are explicit, written steps to be taken by worker and machine at each station. If standard operations are not used flow through the system can vary widely and defects can be hard to trace back to their source. Many feel that standard operations are restrictive, but the reality is that standard operations can be changed and improved at any time as long as all workers are informed of the change. Suggestions for improvement and approval should typically come from the workers.

Design cells for small (ideally zero) changeover time.

Cells with small changeover time help in lead time reduction enabled by setup times of 10 minutes or less. Setup time is the time from the last good part of the previous setup to the first good part of the new setup. The following steps and techniques for setup reduction are adapted from the following three resources: [Toyota Production System, Monden], [The Design of the Factory With a Future, J. T. Black], and [A Study of the Toyota Production System, Shigeo Shingo].

- Identify Internal vs. External setup: Internal setup is that which can only be done when the machine is stopped. External setup can be performed at any time.
- Separate Internal and External setup: Once the internal portion of the setup has begun it should not be interrupted by setup operations that could be performed externally.
- Minimize the Internal setup: This requires reducing the time to change tooling at the machine, and converting as much as possible of the changeover operation from internal to external setup.
- Eliminate the adjustment process: Changing tooling or dies may be quick, but if the required adjustment time is long then setup time is too long.
- Eliminate the entire setup: This can be done by using the same part in multiple products, or by producing multiple parts at the same time. Multiple parts can be made at the same time for example by punching two parts with the same die, or by using to less expensive multiple machines to create the parts.

Operate the system with leveling and pacing.

A balanced production flow means that every day the exact number of products or parts are produced in every work cell, right through final assembly as are demanded by the customer. Balance introduces cycle time which deals with the rate of production and ‘level production flow’ which deals with the frequency of production.

With balanced production, all operations or cells produce at the same cycle time. In a balanced system the cell cycle time is less than the takt time. In an unbalanced system the operations or cells produce at different rates and cause the system buffers to fill up unevenly. When the operations are properly matched production is even and there is no buffer build up.

In Leveled Production, all operations make the quantity and mix of products demanded by the final customer within a given time (demand) interval. The production run size is greater than one unit, but equal to the quantity pulled by customer during the demand interval. Level production flow thus means that large lot production is replaced by 1 piece production (if possible) and that the same quantity is produced every day. This means that every day you produce a day's worth of each product, based upon customer requirements. Level production is compared with unleveled production in Figure 5-5. Figure 5-6 shows the impact level production has on throughput time.

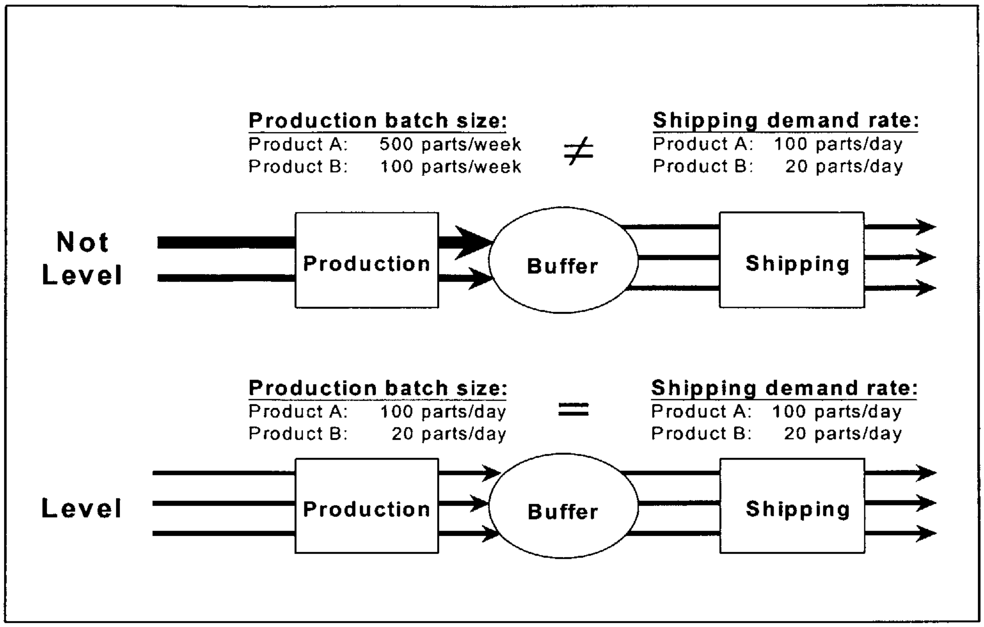


Figure 5-6: A simple production system showing an unleveled vs leveled system [Cochran, 98].

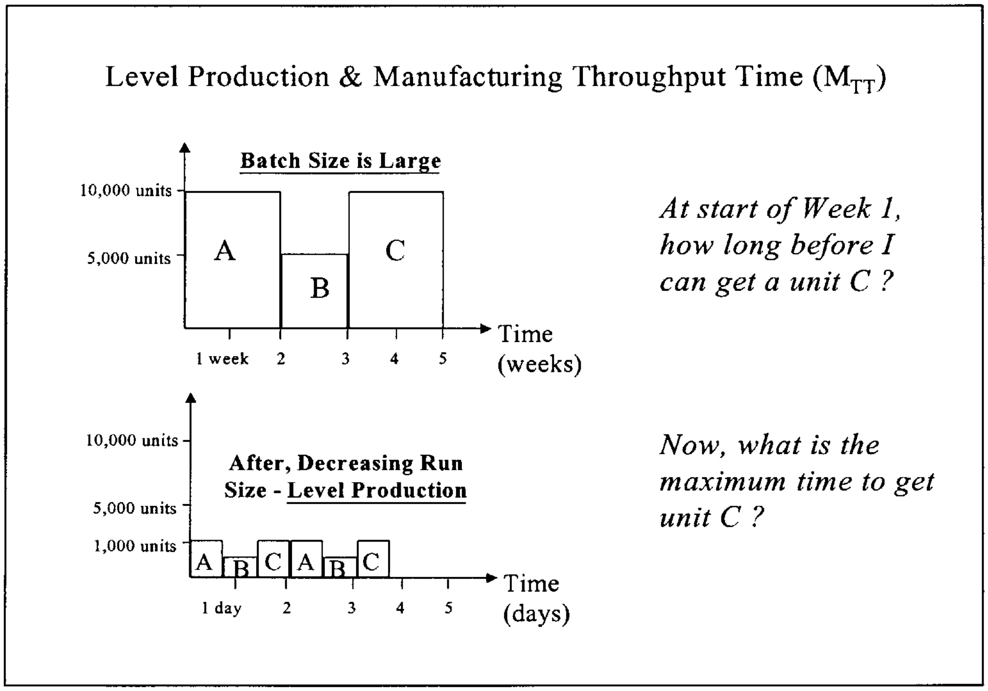


Figure 5-7: The effect of level production on manufacturing throughput time.

In Synchronized Production all operations produce exactly the same sequence of parts demanded by the customer (e.g. same mix, rate, and quantity). The run size and lot size of production is truly one unit. With synchronized production buffers are not needed.

Synchronized Production requires instant changeover and run size of one unit without degrading the system performance. The system design uses single piece flow.

5.3.4 Continuous Improvement

The steps covered here are aimed at improving quality and reducing variability that is detrimental to dynamic systems. Continuous Improvement is the hallmark of world class manufacturing systems as it helps the system evolve ever so gradually to operationally superior systems that reduce costs through identification and elimination of waste.

Evaluate the system with respect to the functional requirements of the MSDD in order to determine the weaknesses in the design and areas for root cause problem solving.

The achievement of FR's is crucial to attaining stability in the manufacturing system. There are a variety of reasons why the FR's from the system design may not be achieved during implementation. The choice of the DP may be flawed or may not be best suited to satisfy the FR. The MSDD based evaluation highlights all the weaknesses in the system design and focuses attention on problems with the operation and their root causes. This evaluation motivated root cause problem solving aimed at achieving the system FR's .

Systematically reduce SWIP between cells

Establishing a Standard Work In Process (SWIP) [Black, 1991] inventory between operations, also sometimes called a marketplace helps in the implementation of a pull system. The SWIP acts to decouple the variation within operations from subsequent downstream operations. The purpose of the SWIP inventory is to ensure the stability objectives of the manufacturing system are achieved in spite of the variation unique to individual operations. The SWIP may be reduced to *expose* the sources of variation (waste) and therefore, cost, that exists within the manufacturing system [Schonberger, 1986]. The gradual and systematic reduction of SWIP between cells forces reduction in variation of the output by improving reliability of machines and operator's work. Efforts are also directed at improving capability of machines and mistake proofing processes. However, special attention must be given to this step and should not result in drastic or complete elimination of SWIP without the system having reached the state of stability where it can handle these changes. Often this step is interpreted as operation with zero inventory and even slight variations in demand or output quality can destabilize the system unless the sources of variation that caused the SWIP to exist in the first place are reduced.

Continuously reduce the run size.

Reduction in run size is made possible by continuously focusing attention at reducing the changeover times in cells. Through reduction in the run size there are greater opportunities of leveling in the final assembly that allows manufacturing systems to follow customer demand more closely and produce the desired mix and quantity over shorter intervals. There is greater flexibility and control over the manufacturing system output resulting in better quality and shorter lead times.

Constantly improve the work.

True cost cannot be reduced by eliminating the piece-part contributors of cost through the indiscriminate application of cost reduction targets [Johnson, 2000, Profit Beyond Measure]. Improving the *work* and the *processes* that support the work in manufacturing reduces true cost. There is always some part of the system that can be improved that will positively affect the entire system. Continuous Quality Improvement or Total Quality Management or Kaizen is further made possible through the increased use of Poka-yoke (mistake proofing) and Autonomous defect detection devices. Machine uptime and reliability can be improved through Total Productive Maintenance (TPM).

5.4 Conclusions

The case study in the previous chapter established how rigor in system design is a necessary but not sufficient condition for superior operational performance. The leadership must help align the incentives of the enterprise system as well as demonstrate through training and physical simulation the benefits of change. It also illustrates value of having a performance evaluation system that is consistent with manufacturing strategy and stabilizes the system before standardizing improvements. Most importantly the case study serves to illustrate the authors assertions on the causes of poor systemic performance and emphasizes the importance of preparing the system for change. Almost no comprehensive system design methodology exists that combine elements of strategy with a rigorous system engineering approach to design and implementation. Most do not addresses enterprise issues that affect manufacturing performance. The steps and phases to design suggested in this chapter in conjunction with the MSDD, as well as additional tools developed at PSD, MIT for system evaluation, is an attempt to address all the levels of the system design pyramid.

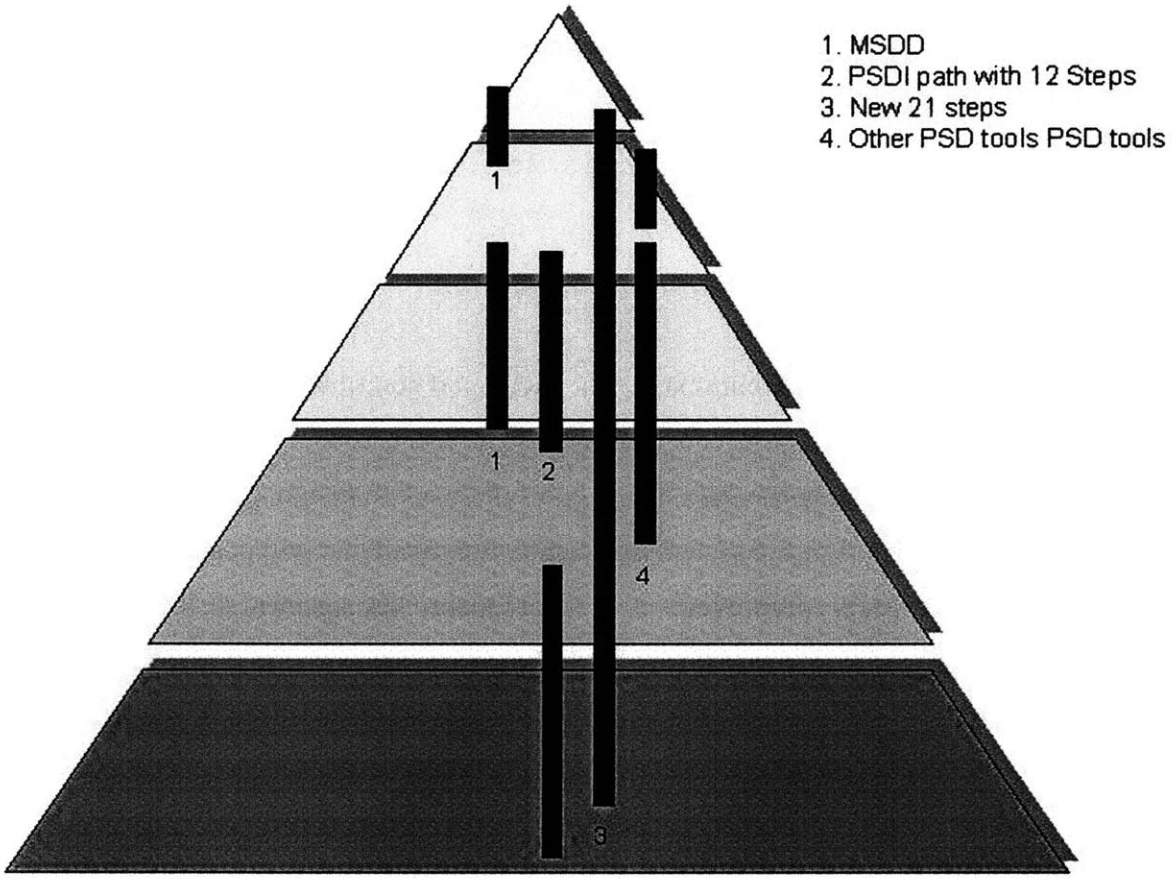


Figure 5-8: Mapping proposed steps and PSD research tools with the system design pyramid

Chapter 6 Conclusions

The thesis focuses attention on the aspects of enterprise issues that influence the ability of system designers and engineers to implement and operate a stable manufacturing system. The thesis proposes a new model for the manufacturing system design process. The leadership is shown to have accountability for preparing the system for change by aligning enterprise interfaces and removing organizational barriers. The actual implementation and operation process involves a series of system engineering phases followed by an evaluation phase that determines the action items for improvement. Continuous Improvement based on performance evaluation is key to enable the system design to evolve into a stable manufacturing system that satisfies the functional requirements of the Manufacturing System Design Decomposition.

The MSDD helps separate objectives from means, and by relating the low-level design choices to high-level objectives it serves to highlight the inter-relationships between the design choices at different levels. The MSDD in conjunction with the literature on systems engineering and the tools developed at PSD provides a conceptual framework to guide the design process. However there are system preparation steps that must precede design efforts to ensure that the system is ready for change and to facilitate the implementation process. The thesis helps in integrating these areas of research into a comprehensive methodology for designing and re-designing manufacturing systems and proposes steps that help in integrating the manufacturing strategy to the design process and recommending ways to prepare the system for change. Emphasis has been placed on physical simulation as a key way to 'win hearts and minds' of people by comparing the simulation of the current state with that of the proposed future state value stream.

The Enterprise interfaces have shown to play an important role in determining the success of implementation. In the case study discussed, leadership and their focus on financial metrics for performance measurement resulted in the project not achieving the scale and scope of benefits that the design and pilot project implementation offered. Financial metrics often tend to drive departmentalization and personal incentives and camouflage the true operational performance of the manufacturing system. To ensure co-operation from all sources in the enterprise, it is crucial to orient the actions of all personnel towards the sought after system design that achieves manufacturing system objectives by aligning incentives accordingly. Leadership can influence the organizational structure and set performance management systems that value operational metrics like WIP and throughput time. The leadership must not solely emphasize reduction of direct labor and unit cost of operation over broader systemic thinking and must guide the implementation process successfully.

References

A.T.Kearney (2000), Global Excellence in Operations Awards

Aggteleky, B. (1970), *Fabrikplanung. Optimale Projektierung, Planung u. Ausführung von Industrieanlagen*; München, Hanser, 1970

Alreck, P. L.; Settle, R. B. (1985), *The Survey Research Handbook*, R.D. Irwin

Arinez, J.F., *An Equipment Design Approach for Achieving Manufacturing System Design Requirements*, Ph.D. Thesis, Massachusetts Institute of Technology

Askin, R.G. (1993), *Modeling and Analysis of Manufacturing Systems*, New York: Wiley

Benton, W C., Shin, Hojung. (1998), "Manufacturing Planning and Control: The Evolution of MRP and JIT Integration", *European Journal of Operational Research.* 110(3): 411-440.

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

Blanchard, B.S.; Fabrycky, W.J. (1998), *Systems Engineering and Analysis*, Upper Saddle River, N.J. : Prentice Hall, 3rd edition

Bonvik, A.M. (1996), *Performance Analysis of Manufacturing Systems Under Hybrid Control Policies*, Massachusetts Institute of Technology, Sloan School of Management, Dissertation

Bruns, Michael (1988), *Systemtechnik*, Springer Verlag, Berlin

Chambers, A., Rand, G. (1997), *The Operational Auditing Handbook - Auditing Business Processes*, John Wiley & Sons, New York

Chin, Louis. Rafuse, Bonnie A.; (1993) "A small manufacturer adds JIT techniques to MRP"; *Production & Inventory Management Journal.* 34(4): 18-21. 1993 Fourth Quarter

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

Clausing, D. (1989), "Quality Function Deployment: Applied Systems Engineering", *Quality and Productivity Research Conference*, University of Waterloo, June 6, 1989

Cochran, David S. (1994), *The Design and Control of Manufacturing Systems*, Ph.D. Thesis, Auburn, Alabama

Cochran, D.C.; Arinez, J.F.; Duda, J.W.;Linck, J. (2000); "A Decomposition Approach for Manufacturing System Design"; submitted to *Journal for Manufacturing Systems*

Cook, J.D., Hepworth, S.J., Wall, T.D., Warr, P.B. (1981), *The Experience of Work - A Compendium and Review of 249 Measures and their Use*, Academic Press, New York, 1981

Corbett, C., van Wassenhove, L. (1993), *Trade-offs? What trade-offs? Competence and competitiveness in manufacturing strategy*, California management Review, 1993, 35, 107-122

Cronbach, L.J., Meehl, P.E. (1955), "Construct Validity in Psychological Tests", *Psychological Bulletin*, vol.52, 1955, 281-302

Cusumano, M. A (1992), *Japanese Technology Management : Innovations, Transferability and the Limitations of "lean" Production*, Cambridge, MA: MIT Japan Program, MIT

Doumeingts, G.; Chen, D.; Vallespir, B.; Fenie, P.; Marcotte, F.(1993), "GIM (GRAI Integrated Methodology) and Its Evolutions - A Methodology to Design and Specify Advanced Manufacturing Systems", *Proceedings of the JSPE/IFIP TC5/WG5.3 Workshop on the Design of Information Infrastructure Systems for Manufacturing*, DIISM '93, Tokyo, Japan, 8-10 November, 1993

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

Felix, H. (1998), *Unternehmens- und Fabrikplanung: Planungsprozesse, Leistungen und Beziehungen*, Carl Hanser Verlag, München

Ferdows, K., De Meyer, A. (1990), "Lasting Improvements in Manufacturing Performance: In Search of a New Theory", *Journal of Operations Management*, Columbia; Apr. 1990; Volume: 9; Issue: 2, pp. 168-184

Filippini, R.; Forza, C.; Vinelli, A. (1998), "Trade-off and Compatibility Between Performance: Definitions and Empirical Evidence", *International Journal of Production Research*, Volume: 36 Number: 12 Page: 3379 – 3406

Flynn, B.B.; Sakakibara, S.; Schroeder, R. G.; Bates, K. A., Flynn, E. J. (1990), "Empirical Research Methods in Operations Management", *Journal of Operations Management*; Columbia; Apr 1990; Vol. 9, Issue 2, p. 250-284

Fox, M.M (1999).; *Factory as a Laboratory*; B.S. Thesis, Massachusetts Institute of Technology

Gomez, D.; Dobbs, D.; Cochran, D. (2000), "Equipment Evaluation Tool Based on the Manufacturing System Design Decomposition", *Proceedings, Third World Congress on Intelligent Manufacturing Processes & Systems*, Cambridge, MA USA, , pp. 17-4, June 28-30, 2000

Graban, Mark R. (1999); *An Inventory Planning Methodology for a Semiconductor Manufacturer with Significant Sources of Variability*; Master Thesis, Massachusetts Institute of Technology, 1999

Grant, D. (1996), "Action Research as a Vehicle for Validating MSD Methodologies", *International Journal of Computer Integrated Manufacturing*, 1996, 9, 5, pp 381-391

Grote, G.; Ryser, C.; Wäfler, T.; Windischer A.;, Weik S.; "KOMPASS: A Method for Complementary Function Allocation in Automated Work Systems", *International Journal of Human-Computer Studies*, February 2000 issue (Vol. 52/no.2)

Hall, R. (1983), *Zero Inventories*, Dow-Jones-Irwin, 1983

Hayes, R. H.; Wheelwright, S.C. (1979), "Link Manufacturing Process and Product Lifecycles", *Harvard Business Review*, Jan-Feb, 2-9

Hayes, Robert H.; Wheelwright, Steven C.(1984); *Restoring our Competitive Edge. Competing through Manufacturing*; John Wiley & Sons, 1984

Hayes, R.H.; Wheelwright, S.C.; Clark, K. (1988), *Dynamic Manufacturing: Creating a Learning Organization,* Free Press, New York, 1988

Hirano, H. (editor) (1988), *Poka-Yoke: Improving Product Quality by Preventing Defects*, Productivity Press, Portland

Hitomi, K. (1996), *Manufacturing Systems Engineering*, Taylor and Francis, 2nd edition, 1996

Hopp, W. J.; Spearman, M.L.; *Factory Physics - Foundations of Manufacturing Management*; Irwin McGraw-Hill, Boston, 1996

Japan Management Association (editor) (1986), *Kanban - Just-In-Time at Toyota*; Productivity Press, 1986

Kettner H., Schmidt J., Greim H.-R. (1984), *Leitfaden der Systematischen Fabrikplanung*; Carl Hanser Verlag München Wien, 1984

Krathwohl, D. R. (1998), *Methods of Educational & Social Science Research: An Integrated Approach,* New York, Longman, c1998; 2nd ed.

Kreafle, Ken (2001), Presentation at MIT Class, April 2001

LAI Workshop (2001), Manufacturing System Design Workshop, Lean Aerospace Initiative, Houston, January 2001

Leedy, P. D. (1997) , *Practical Research : Planning and Design,* Upper Saddle River, N.J. : Merrill, 1997

Liker, J. K.(editor) (1998), *Becoming Lean: Inside Stories of U.S. Manufacturers,* Productivity Press, Portland, Oregon, 1998

Linck, J.; Cochran D.S. (1999), "The Importance of Takt Time in Manufacturing System Design", *Proceedings of the 1999 SAE International Automotive Manufacturing Conference*, IAM99-34, May 11-13, 1999, Detroit, U.S.A.

McKay K.N., Safayeni, F.R., Buzacott J.A.(1995); "Schedulers & Planners: What and How Can We Learn From Them"; *Intelligent Scheduling Systems*, Brown D.E. and W.T. Scherer (eds), 1995, Kluwer Publishers, Boston, 41-62.

Meller, R.D.; Gau, K.-Y. (1996), "The Facility Layout Problem: Recent and Emerging Trends and Perspectives", *Journal of Manufacturing Systems*, 1996, 15, 5, pp. 351

Miltenburg, J. (1995), *Manufacturing Strategy: How to Formulate and Implement a Winning Plan,* Productivity Press, Portland, Oregon, c1995

Monden, Y. (1998), *Toyota Production System - An Integrated Approach to Just-In-Time*; Engineering & Management Press, Third Edition, 1998

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

Nakajima, S. (editor) (1989), *TPM Development Program: Implementing Total Productive Maintenance*; Productivity Press, 1989

Nunnally, J. C. (1978), *Psychometric Theory*, McGraw Hill, New York, 1978

Park, C.S.; Son, Y.K. (1988), "An Economic Evaluation Model for Advanced Manufacturing Systems", *The Engineering Economist*, Volume 34 - Number 1, Fall 1988

Parnaby, J.(1986), "The Design of Competitive Manufacturing Systems", *International Journal of Technology Management*, 1986, 1, 3/4, 385-396

Poschmann, A.W. (1985), *SCORE: Structured Company Operational Review and Evaluation*; New York, NY : American Management Association, c1985.

Reinhardt, G.; (2000), *Technische Betriebsführung II*, Vorlesungsumdruck; Technische Universitaet Muenchen, iwb, 2000

Rother, M.; Shook, J. (1998), *Learning to See; The Lean Enterprise Institute*, Inc.,ISBN 0-9667843-0-8, 1998

Rouse, M.L.; Dallenbach, U.S. (1999), "Rethinking Research Methods for the Resource-Based Perspective: Isolating Sources of Sustainable Competitive Advantage", *Strategic Management Journal*, 20, 487-494

Sakakibara, S., Flynn, B.B.; Schroeder, R.G. (1993), "A Framework and Measurement Instrument for Just-In-Time Manufacturing", *Production and Operations Management Journal*, vol 2, no.3, p.177-194, (1993)

Schonberger, R. (1982), *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*; Free Press, c1982

Schonberger, R.J. (1990), *Building a Chain of Customers: Linking Business Functions to Create a World Class Company*; Free Press, New York, 1990

Sekine, K. (1992), *One-Piece Flow: Cell Design for Transforming the Production Process*, Productivity Press, 1992

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

Son, Young K. (1991), "A Cost Estimation Model for Advanced Manufacturing Systems, *International Journal of Production Research*, 1991, Vol. 29, 441-452

Spear, S.J. (1999), *The Toyota Production System: An Example of Managing Complex / Technical Systems. Five Rules for Designing, Operating, and Improving Activities, Activity-Connections, and Flow-Paths*; Harvard University, Ph.D. Thesis, 1999

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

Strohm, O. (1997; *Unternehmen Arbeitspsychologisch Bewerten*; vdf Hochschulverlag AG an der ETH Zurich, 1997

Suh, N.P. (1990), *The Principles of Design*; New York: Oxford University Press, 1990

Suh, N.P. (2001), *Axiomatic Design – Advances and Applications;* New York: Oxford University Press, to be published December 2001

Suzuki, M. (1999), Tools for Elimination of Muda, TRW Automotive, unpublished document, 1999

Tate, D. (1999), *A Roadmap for Decomposition: Activities, Theories, and Tools for System Design*, Ph.D. Thesis, Massachusetts Institute of Technology

VDI Norm 4004 Blatt 3 (1986): Kenngrößen der Instandhaltbarkeit, Hrsg. Verein Deutscher Ingenieure. Ausg. Sept. 1986

Vernadat, F. (1993), "CIMOSA: Enterprise Modelling and Enterprise Integration Using a Process-Based Approach", *Proceedings of the JSPE/IFIP TC5/WG5.3 Workshop on the Design of Information Infrastructure Systems for Manufacturing*, DIISM '93, Tokyo, Japan, 8-10 November, 1993

VDI Norm 4004 Blatt 3, (1996): *Kenngrößen der Instandhaltbarkeit.* Hrsg. Verein Deutscher Ingenieure. Ausg. Sept. 1986

Wang, A. (1999), *Design and Analysis of Production Systems in Aircraft Assembly*, Master Thesis, Massachusetts Institute of Technolgogy, 1999

Warnecke, H.-J. (1992), *Die Fraktale Fabrik*, Berlin, Springer Verlag

Williams, T.J.; Bernus, P.;Brosvic, J.; Chen, D.;Doumeingts, G.;Nemes, L.; Nevins, J.L.; Vallespir, B.; Vlietstra, J.; Zoetekouw, D.(1993), "Architectures for Integrating Manufacturing Activitities and Enterprises", *Proceedings of the JSPE/IFIP TC5/WG5.3 Workshop on the Design of Information Infrastructure Systems for Manufacturing*, DIISM '93, Tokyo, Japan, 8-10 November, 1993

Williams, T.J. (1993), "The Purdue Enterprise Reference Architecture", *Proceedings of the JSPE/IFIP TC5/WG5.3 Workshop on the Design of Information Infrastructure Systems for Manufacturing*, DIISM '93, Tokyo, Japan, 8-10 November, 1993

Womack, J.P.; Jones, D.T.; Ross D. (1990), *The Machine That Changed the World : The Story of Lean Production*, Macmillan 1990

Wu, Bin (1992), *Manufacturing Systems Design and Analysis*, Chapman and Hall, 1992

Wu, Bin (2000), *Manufacturing and Supply Systems Management: A Unified Framework of Systems Design and Operation*, New York : Springer, 2000

Yin, R. K. (1994), *Case Study Research: Design and Methods*; Beverly Hills, CA: Sage Publications, c1984.

Zipkin, P.H. (1991); "Does Manufacturing Need a JIT Revolution?"; *Harvard Business Review*, Jan.-Feb., 4-11