Evaluation of Design and Operating Criteria for Production System Design and its Constituent Levels

by

Dexter Myles Mootoo

B.S. Mechanical Engineering, Massachusetts Institute of Technology

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Signature of Author...
Department of Mechanical Engineering
May 9, 1997

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

Accepted by...
Ain A. Sonin
Chairman, Department Committee on Graduate Students

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ABSTRACT

Research has been conducted in a variety of manufacturing systems; from small scale production of one product type, to production of a variety of products in a job-shop, to finally mass production of a single component in the automotive industry. Several projects conducted in each of these systems have been used to qualify a framework for Manufacturing System Design and Control. This framework, based on three pillars [Cochran, 1994], emphasizes design and control of a system by applying metrics such as time, inventory, and waste to the system at all levels; the System, the Cell, Machine, and Fixture Level. The methodology is supported by case studies conducted at Lemco Miller Inc., Merlin Metalworks Inc. and an automotive steering gear manufacturer.

The first case study involved a system's analysis of a job-shop supplier to the semi-conductor industry. Process flowcharts are generated for both the repeat-order (Kanban) and single-order manufacturing (SOM) aspects of their business. SOM indicated a lead time average of 47 days versus the desired 21-28 days. Recommendations and implementation of tools to increase production system's efficiency are discussed. At the sub-system level, three cell designs are compared. The first represents a cell that is involved in the manufacture of steering gears. The machining cell at Merlin Metalwork's Inc. is, in contrast, a much smaller, less perfected cell. Using the principles of Axiomatic Design, an analysis of their machining cell indicated coupling and non-fulfillment of certain cell requirements. Finally, an attempt to apply cellular manufacturing in Lemco-Miller's job-shop is described. This last cell design, termed Smart-Cell, demonstrates how industry's constraints often inhibit successful cell design. A custom machine design is then illustrated at the Machine Level. In the final level, the Fixture Level, the impact on jig and fixture design to meet the requirements of the systems level is explored through a series of short case studies conducted at the companies.

It is the intent of this thesis to highlight necessary phases in the design and control of production systems. The case studies presented encompass many of the issues that must be addressed throughout these levels.

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

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CHAPTER 1

THE PRODUCTION SYSTEM

1.0 Introduction

Manufacturing is one of the oldest economic activities of humanity and is full of tradition and craft. Like all important human enterprises, it is subject to scrutiny and to constant technological change. However, in many important areas of manufacturing, ad hoc techniques and intuition are more prevalent than systematic methods.

American manufacturing companies are under enormous pressure to remain competitive. Their emerging counter parts, particularly the Japanese Toyota Production System (TPS), have proven that the manufacturing systems are superior in quality, lead time and costs. This truism is slowly being acknowledged due to the West's edge in design, research and development. However, with every passing product, the Japanese, and those who understand and implement their manufacturing methods, are gaining ground in design. American companies need to realize that they have to change. They cannot rely solely on their novel design tactics. They must integrate design with new manufacturing practices to maintain leadership. The support of management and all others concerned in an organization will continue to be an essential element in the successful adoption of new technologies [Kalpakjian, 1995].

There seems to be a trend in the U.S. that many are attempting to mimic the Toyota Production System, without completely understanding the defining principles. There are certain features that can easily be copied, however the culture and knowledge of workers is one that is difficult to mold. Simply copying one system's attributes and attempting to apply it to another may prove successful for a while. However, no system is perfect, including TPS. The Japanese strongly believe in "Kaizen", or continuous improvement, and thus are not fully content with their system either. Therefore, American companies need to understand that copying TPS may bring them on par with the Japanese, only until the latter improves their manufacturing.

There is a plethora of information documenting what the Japanese have done and just as many outlining how to mimic them. However, what is lacking are strong manufacturing system design-based case studies of American companies who have made a transition to a new system. Therefore, it is essential to consider new design principles and control principles to design an efficient manufacturing system.

Professor Cochran has developed a framework for Manufacturing System Design (MSD) and Manufacturing System Control (MSC). The framework provides a structured guideline for the design process by using Axiomatic Design. This framework, based on three pillars, emphasizes design and control of a system by applying metrics such as time, inventory, and waste to the system at all levels: the System, the Cell, Machine, and Fixture Level [Cochran, 1994].

The goal of this thesis is to qualify these two tools: Axiomatic Design and the framework for Manufacturing System Design and Manufacturing System Control. The thesis implements Axiomatic Design principles within the various levels proposed by MSD and MSC. Evaluations conducted at three companies illustrate the power and utility of the above tools in the analysis and design of manufacturing systems. Since Axiomatic Design is an essential part of the MSD and MSC framework, an introduction to the methodology is dealt with. This chapter also describes the framework for MSD and MSC.

Chapter two involves the first design evaluation, which is a systems analysis of a job-shop supplier to the semi-conductor industry. At the sub-system level, three cell designs are compared. The first represents a “snap-shot” of a manufacturing cell that is involved in the machining of steering gears. The machining cell at Merlin Metalwork’s Inc. is, in contrast, a much smaller, less perfected cell. Finally, an attempt to apply cellular manufacturing in Lemco-Miller’s job-shop is described. A custom machine design is then illustrated at the Machine Level. In the final level, the Fixture Level, the impact on jig and fixture design to meet the requirements of the systems level is explored through a series of short analyses conducted at the companies.

1.1 Introduction to Axiomatic Design

Axiomatic Design represents a new approach to the design process. Developed by Nam P. Suh, the methodology proposes that design, be it of a product, a system, or an organization, can be treated pedagogically like a science instead of its traditional, ad hoc practice. "The ultimate goal of Axiomatic Design is to establish a science base for design and to improve design activities by providing the designer with (1) a theoretical foundation based on logical and rational thought processes and (2) tools."[Suh, Albano, 1995].

The design process can be regarded as consisting of four domains: the Customer domain, the Functional domain, the Physical domain, and the Process domain, illustrated in figure 1-1. During the design process the customer domain is first explored to determine the customer attributes for the design. These attributes must then be interpreted as functional requirements (FR's) in the design domain. During the product design phase the FR's specified in the functional domain must be satisfied by choosing a proper set of design parameters (DP's) in the Physical domain. Similarly, during the process design phase the DP's must be satisfied by selecting an optimum set of process variables (PV's).

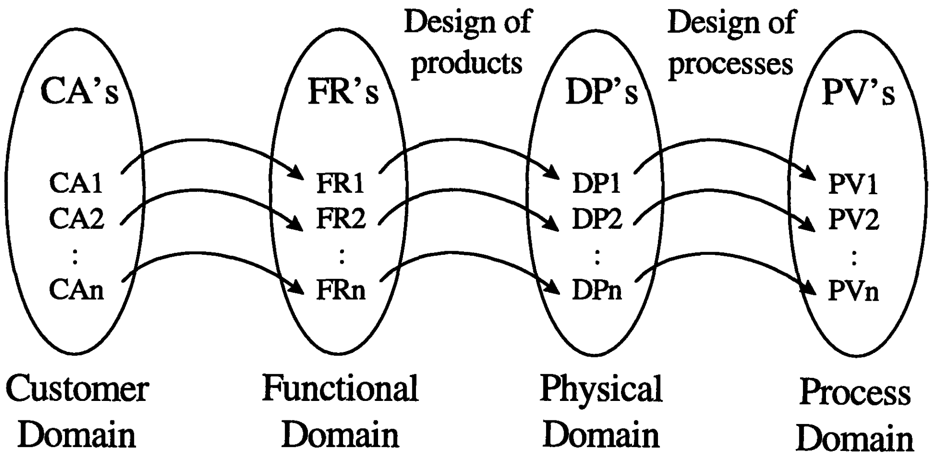


Figure 1-1 The Four Design Domains

In addition to the functional requirements, constraints will appear as a result of translating the customer wants to functional requirements. Constraints have to be obeyed during the entire design process. They refer to functional requirements as well as to design parameters and process variables.

The selection of these design parameters and process variables is typically the ad hoc design process that Suh proposes to structure. Two axioms guide the design process and enable good designs to be identified. The two axioms are stated as follows:

Axiom 1:	The Independence Axiom Maintain the independence of functional requirements (FR's).
Axiom 2:	The Information Axiom Minimize the information content of the design.

1.1.1 The Independence Axiom

To maintain the independence of functional requirements the independence axiom implies two very important, yet subtle characteristics. The first is that functional requirements are defined to be the minimum set of independent requirements that completely characterize the design objectives or needs. By definition, FR's must be independent of other FR's, and thus can be stated without considering other FR's. Secondly, maintaining independence of the FR's corresponds to the relationship between the FR's and the DP's. In selecting DP's to satisfy the FR's, the "needs", each DP must independently satisfy each FR such that any adjustment in a design parameter may only effect its corresponding functional requirement.

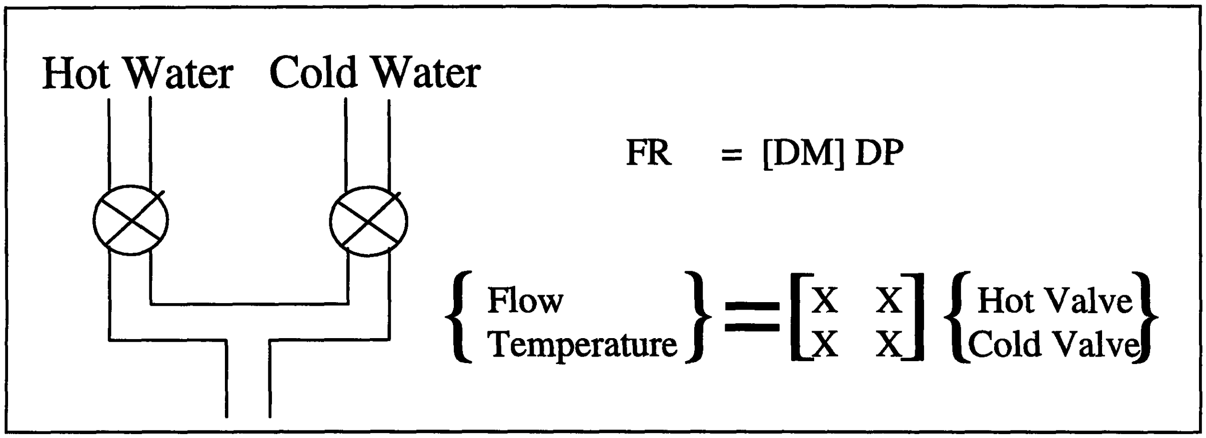
To illustrate the power of this axiom let us evaluate the design of a water faucet. We can model a faucet as having two basic requirements or FR's:

FR1: Control the flow of water.
FR2: Control the temperature of the water.

A particular faucet design, figure 1-2, can then have as it's design parameters the following:

DP1: A hot water valve

DP2: A cold water valve



$$FR = [DM]\, DP$$

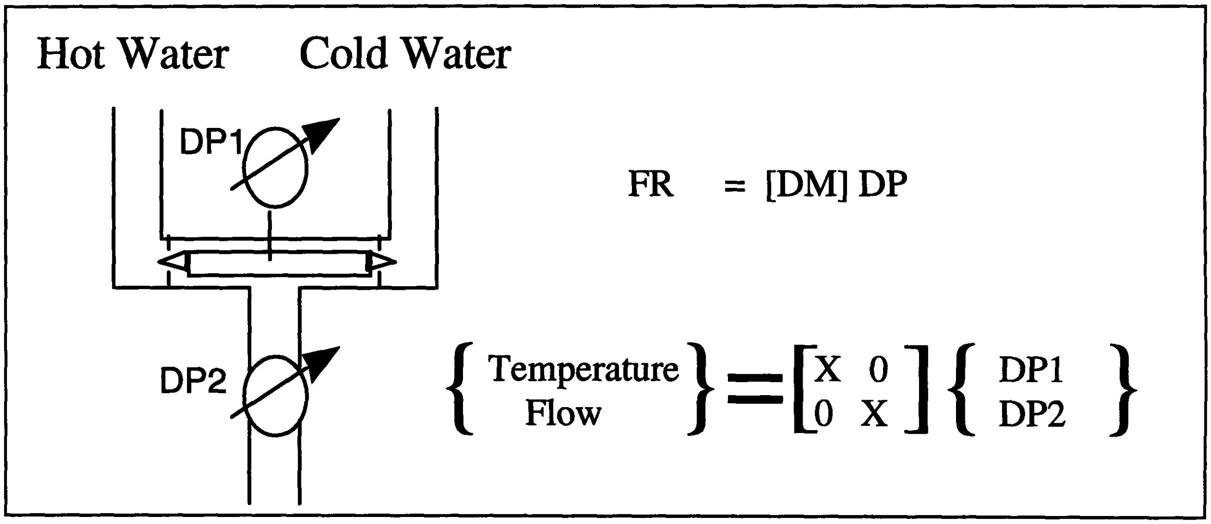
$$\begin{Bmatrix} \text{Flow} \\ \text{Temperature} \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} \text{Hot Valve} \\ \text{Cold Valve} \end{Bmatrix}$$

Figure 1-2 Evaluation of a Coupled Faucet Design [Swensson, Nordlund, 1995]

The relationship between the FR's and the selected DP's can be defined by a matrix as shown. This relationship is derived through a mapping process which essentially attempts to quantify the effects of the DP's on the FR's. A cross of the matrix element A_{ij} expresses that a change of DP_j influences Fr_i. In the example, a change of each valve influences both the flow of water and the temperature. Therefore the design matrix (DM) has crosses for all its elements. What does this tell us about the design?

Looking at the independence axiom, we notice that the independence of the FR's is not maintained and the axiom is violated. We know that manipulating the hot and cold valves to obtain a particular flow and temperature requires iteration. This is referred to as a coupled design and we can conclude that the design is not a good design with regards to satisfying the stated functions. Let us look at another type of faucet, shown in figure 1-3.

With the same functional requirements as the last faucet design we observe that there are also two corresponding DP's that effect the FR's. DP1 is a horizontal twist that regulates the ratio of hot and cold water entering the vertical spout. DP2 is a vertical twist that controls the volume of water leaving the faucet. To obtain a specific flow the user changes only DP2, leaving the temperature unaffected and vice vers. Thus, each design parameter affects only it's corresponding functional requirement, resulting in a diagonal design matrix as shown. This design is said to be uncoupled.



$$FR = [DM]\,DP$$

$$\begin{Bmatrix} \text{Temperature} \\ \text{Flow} \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

Figure 1-3 An Uncoupled Faucet Design

The reader may be familiar with this faucet type and the fact that it only has one lever to facilitate its operation. At first glance, one may be tempted to say that the one lever has to satisfy both FR's and thus it represents a coupled design. An important point to emphasize in the application of the independence axiom is that DP's need not be individual, tangible parameters. For instance, there are many FR's of a soda can; FR1) to contain liquid, FR2) to insulate, FR3) not react nor degrade due to its contents, and so on. Though the tin can is one tangible element, the FR's mentioned above are independently satisfied by; DP1) the can's geometry, DP2) its thermal properties, DP3) its corrosive properties and so on. It is important that the mapping process be conducted to observe the FR-DP relationships.

The first axiom therefore analyzes the design matrix to prove if the functional requirements can be satisfied by the design parameters independently. In addition to the coupled and uncoupled designs, there also exists decoupled designs. These designs are characterized by having triangular design matrices, see figure 1-4. The decoupled design is not necessarily a bad design as success in maintaining independence of the FR's can occur, depending on the order of operation. For example, a look at the DM in figure 1-4 shows that FR1 is only affected by DP1, whereas changes in either DP1 or DP2 affect FR2. Hence, the functional requirements can be independently controlled only by satisfying FR1 through actuation of DP1, and then the second functional requirement, FR2, may be controlled by manipulating DP2. Reversing the order of manipulation of the DP's results in iterating between different values of the FR's and hence failure.

$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$	Uncoupled Design
$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$	Decoupled Design
$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$	Coupled Design

Figure 1-4 The Three Different Kinds of Designs

1.1.2 The Information Axiom

The information axiom states that one must minimize the information content of the design. This axiom is only applied once the independence axiom is satisfied. All designs not satisfying axiom 1 are unacceptable and are not subject to further investigation. The way information is defined here is in the context of probability. The higher the probability of satisfying a requirement the less is the information content. The information axiom may be represented mathematically as follows:

$$I = \log_2(1/p)$$

where "p" is the probability of satisfying a particular requirement.

Let us look at the faucet design example once again. Assuming there were two faucet systems that satisfied the first axiom then we would proceed to evaluate them using the information axiom. Suppose the designer or user wanted to control the temperature to ± 2 degrees while the faucets' capabilities or sensitivities, due to their design and/or manufacturing, were ± 1 degree and ± 3 degrees respectively. The designer's satisfaction tolerance can be defined as the design range, whilst the faucets each have their characteristic system ranges, figure 1-5.

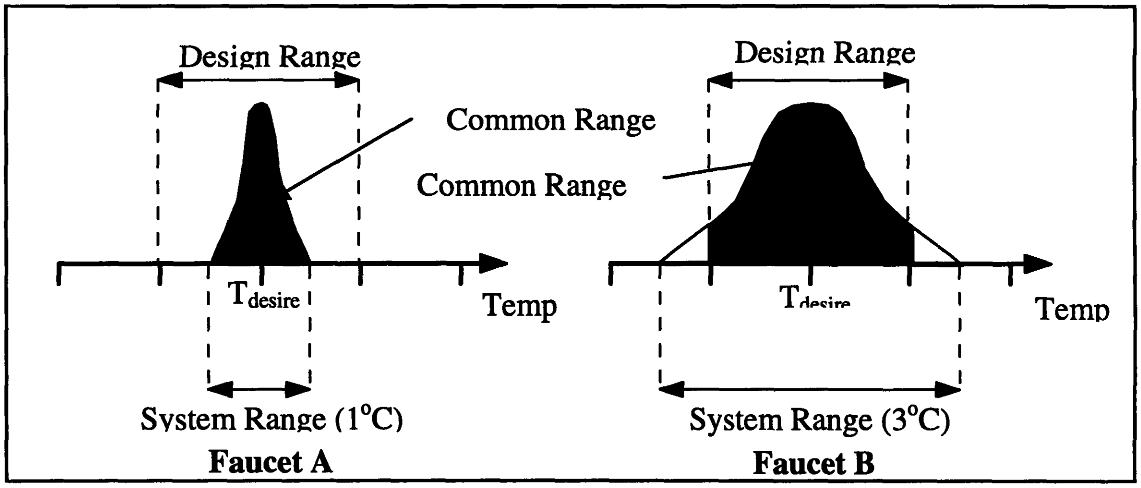


Figure 1-5 Design, System, & Common Temperature Ranges for Two Faucet Designs

The common range represents the overlap of the system range and the design range. If the tolerances of the user are larger than the tolerances of the design parameters, the functional requirements will always be satisfied, provided the design parameters can be calibrated to the mean value. In the example above, the user would like to obtain water from the faucets at the desired temperature, $T_{desired}$. However, the temperature of the water out of both Faucets fluctuate around this mean, as shown by their system ranges. For Faucet A the design range (2°C) is larger than the system range (1°C). The common range is therefore identical to the system range. This means that temperature adjustments will always be within the tolerances of the user. The probability to meet the user's specifications is one. Therefore the information content, the $\log_2(1/p)$, with regards to temperature adjustment is zero. In contrast, Faucet B has a system range (3°C) that is larger than the 2°C design range. In this case, the probability to satisfy the user's specifications is less than one, and thus the information content is not zero.

Minimization of the information content means to maximize the probability of success. If the information content of a design is zero, all specifications will be met all the time. Faucet A therefore is able to satisfy control of temperature all the time, whilst faucet B partially satisfies the requirement.

We have thus compared these two faucet designs with regards to their fulfillment of one functional requirement. They can further be compared, using the information axiom, by analyzing their ability to satisfy the other requirement, control of flow. The net information content of each design may then be compared by summing up the individual information contents pertaining to all the functional requirements.

In most design tasks, it is necessary to decompose the problem further. Figure 1-6 indicates hierarchies in the functional, physical and process domains The development of the hierarchy will be done by zigzagging between domains. The zigzagging takes place between two domains. After defining the FR of the top level, a design concept has to be generated. This results in the mapping process as shown in figure 1-6. The mapping process is then satisfied provided that the two axioms are also satisfied.

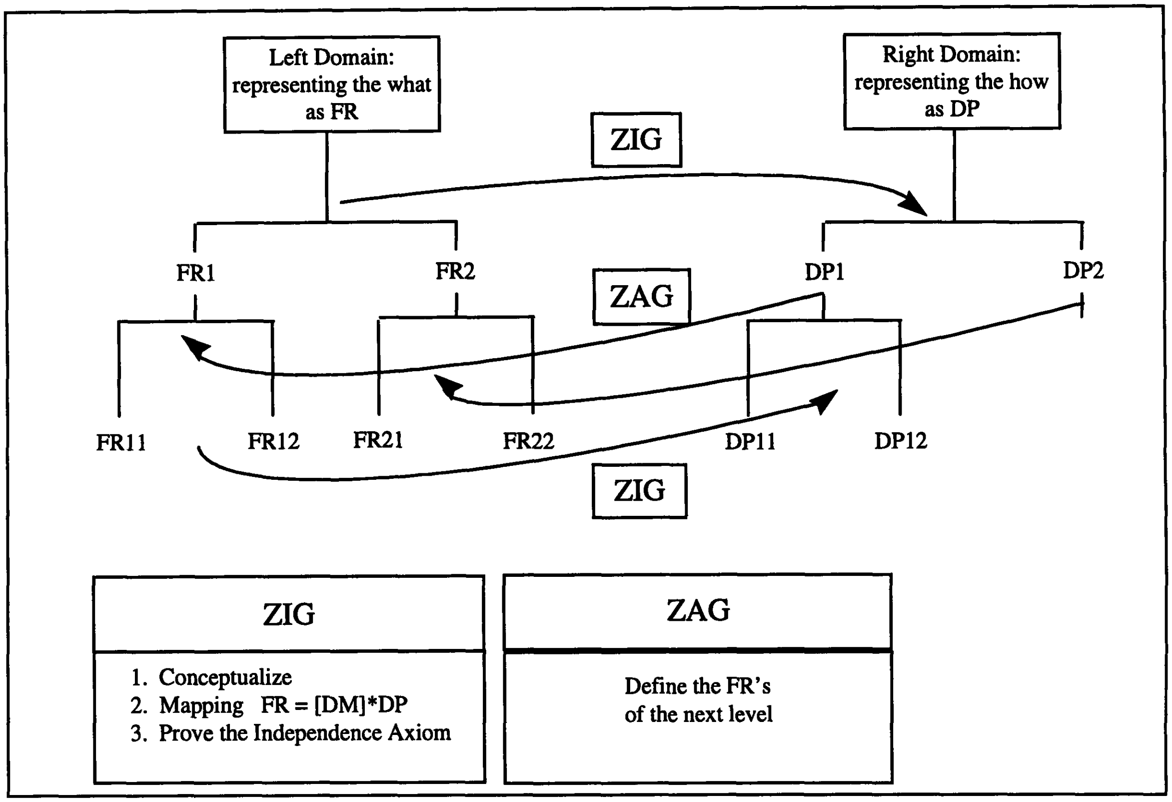


Figure 1-6 Zigzagging Between the Domains to Develop the Hierarchy

1.2 The Three Pillars of Manufacturing System Design and Control

The framework for Manufacturing System Design (MSD) and Control (MSC) enables a new way of designing manufacturing systems [Cochran, 1994]. The development of the framework was motivated by the need for a structured design process for manufacturing systems. The process for MSD and MSC uses Axiomatic Design to simplify the interactions within systems and to reduce the information content necessary for control. The three basic pillars of the framework are:

- the information based control
- the manufacturing control hierarchy
- the process for manufacturing system design and control

1.2.1 Information Based Control

The information based control model describes a general philosophy for the control of manufacturing systems. It defines how information is to be used to control complex systems.

Manufacturing systems are open systems influenced by numerous parameters. The control of a manufacturing system needs a closed loop control model reacting to disturbances [Cochran, 1994]. Figure 1-7 shows the four elements necessary for closed loop control:

1. measurement
2. comparison
3. controller
4. controlled operation or process

The actual output of the system is measured. The actual output is compared with the desired output and the error is calculated. Depending on the error the controller determines the solution. This solution is sent to control the operation or process.

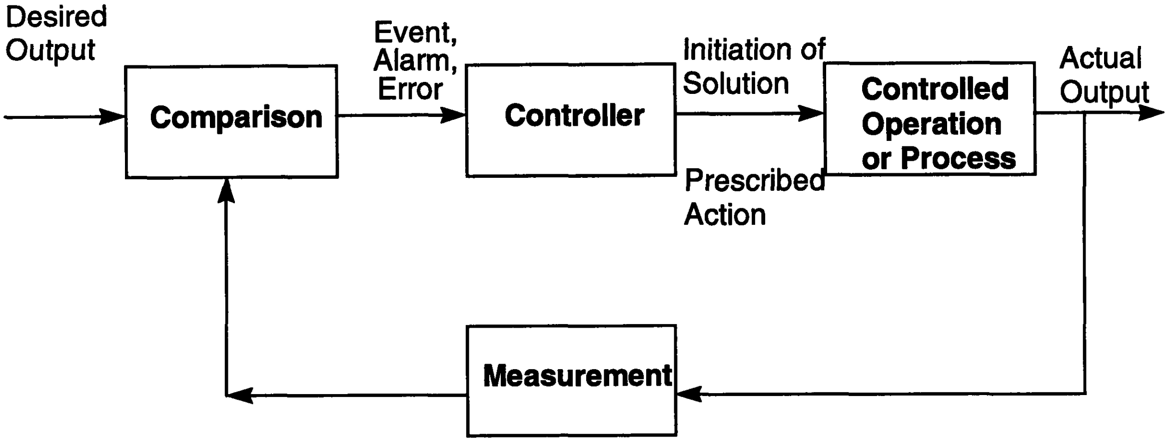


Figure 1-7 Closed Loop Control Model [Cochran, 1994].

The controlled operation or process should be provided with feedback information with a minimum of time delay. If not, it becomes more difficult to stabilize the system due to the longer dead time response. An example of poor control of manufacturing systems is demonstrated by the frequent use of a report-based "control model" shown in figure 1-8 [Cochran, 1994].

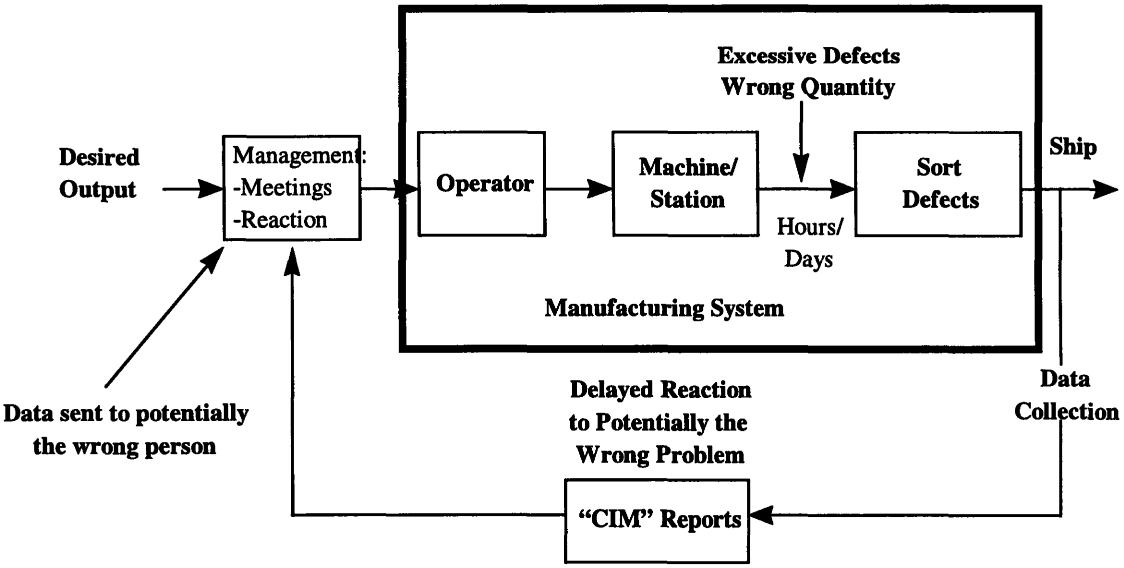


Figure 1-8 Report Based Control [Cochran, 1994]

Two major problems occur by using the report-based control model. First the feedback is separated from the relevant person or from the relevant span of control within the control hierarchy. In figure 1-8 the information is not given to the operator who handles the machine. Therefore the information is not given to the right place. This creates the second problem. The feedback is not real time, instead it is sent to a manager or someone else who may not be available to respond or does not know how to respond.

The information-based control model avoids these problems as shown in figure 1-9. It provides the operator or machine with the information feedback at the right time. The responsibility for control is driven down to the level on which the control action takes place. This type of control includes the identification of the occurrence of an abnormal event, the solution determination and implementation of the solution. In addition, the long term causes for the error may be defined and thus eliminated.

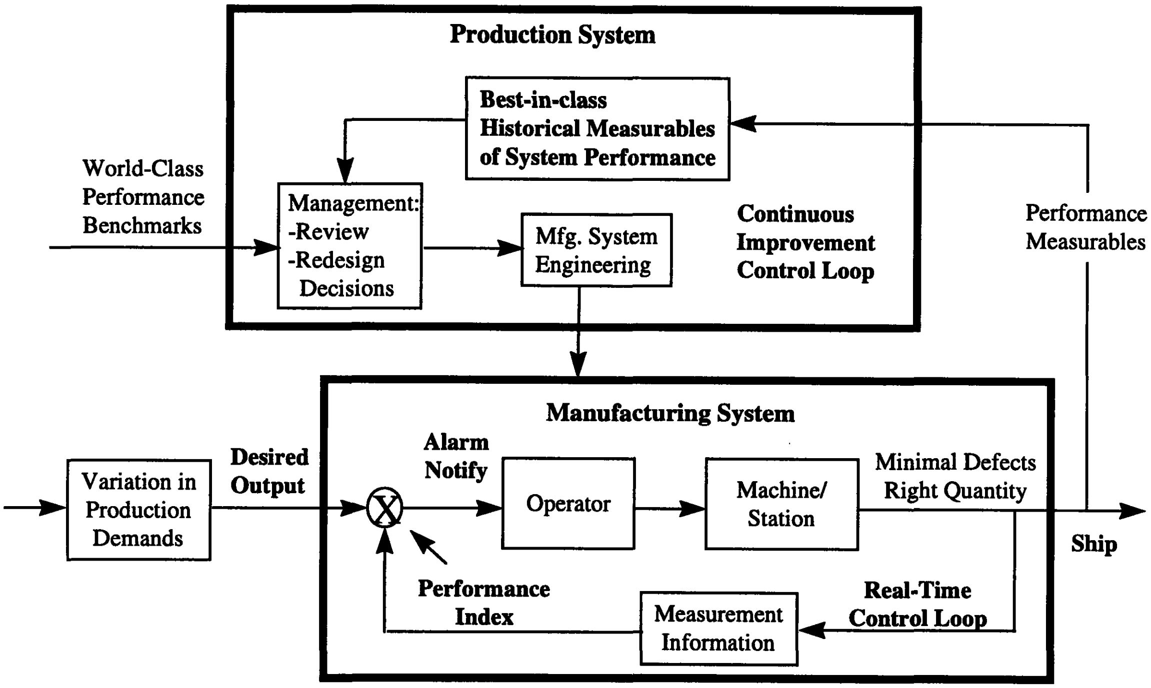


Figure 1-9 Information-based Control Model [Cochran, 1994]

Figure 1-9 also distinguishes between the manufacturing system and the production system. Manufacturing processes are combined to form a manufacturing system. The production system includes and supports the manufacturing system and refers to the total company [Black, 1991]. Since the control is driven down to lower levels of the hierarchy the management of the company can focus on improving the manufacturing system and comparing itself relative to its competitors.

1.2.2 Manufacturing Control Hierarchy

Manufacturing systems can be decomposed into several levels. They are hierarchical in nature [Askin, 1993]. Figure 1-10 shows a modified version of the Manufacturing System Control Hierarchy developed by Cochran. It consists of four levels instead of the original five:

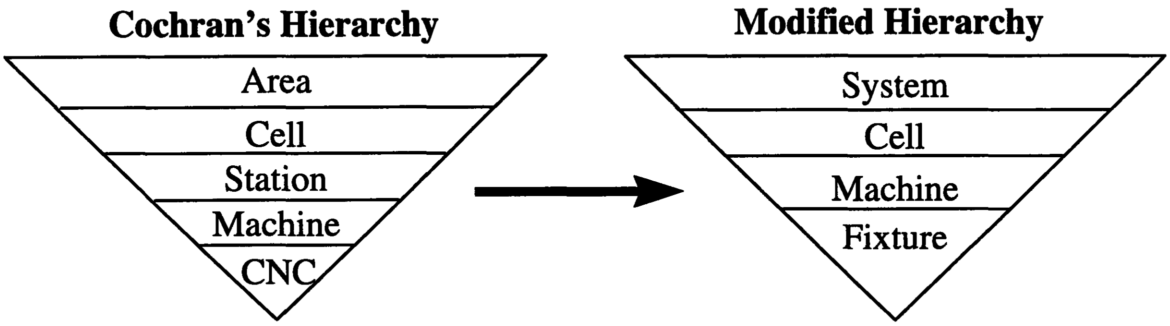


Figure 1-10 The Modified Manufacturing Control Hierarchy

1. The **system** is the largest entity under investigation within a manufacturing system. This layer was previously called the **area** in Cochran's hierarchy. For simplicity and flexibility of application in many manufacturing structures, the area has been renamed as the system. For a product layout the system covers all machines etc. necessary for manufacturing a product. The process layout defines eg. the drilling department as the drilling system. Cellular layouts defines systems according to the conversion flow and forms linked cells if possible.
2. A **cell** consists of logically grouped stations or operations. It is defined consistently in both hierarchies above. Process layouts do not contain cells. The cell level may consist of one or more machines and within one physical location.
3. The **machines** provide specific operations such as welding and drilling. Cochran's

inclusion of a station layer represented groups of machines. This has been neglected in the new model as that distinction between the station level and the machine level was unnecessary.

4. **Fixtures** assist in the accuracy and repeatability of processing steps by effectively locating parts at known positions. This layer replaces the computer-numerically-controlled (CNC) layer used in Cochran's hierarchy. This is due to the fact that not all systems may include control at that level. Fundamentally, however, fixtures represent a more tangible means of controlling the operations at the machines.

The hierarchy can be represented as a system with subsystems. The manufacturing system shown in figure 1-11 consists of the subsystems A1, A2, and A3.

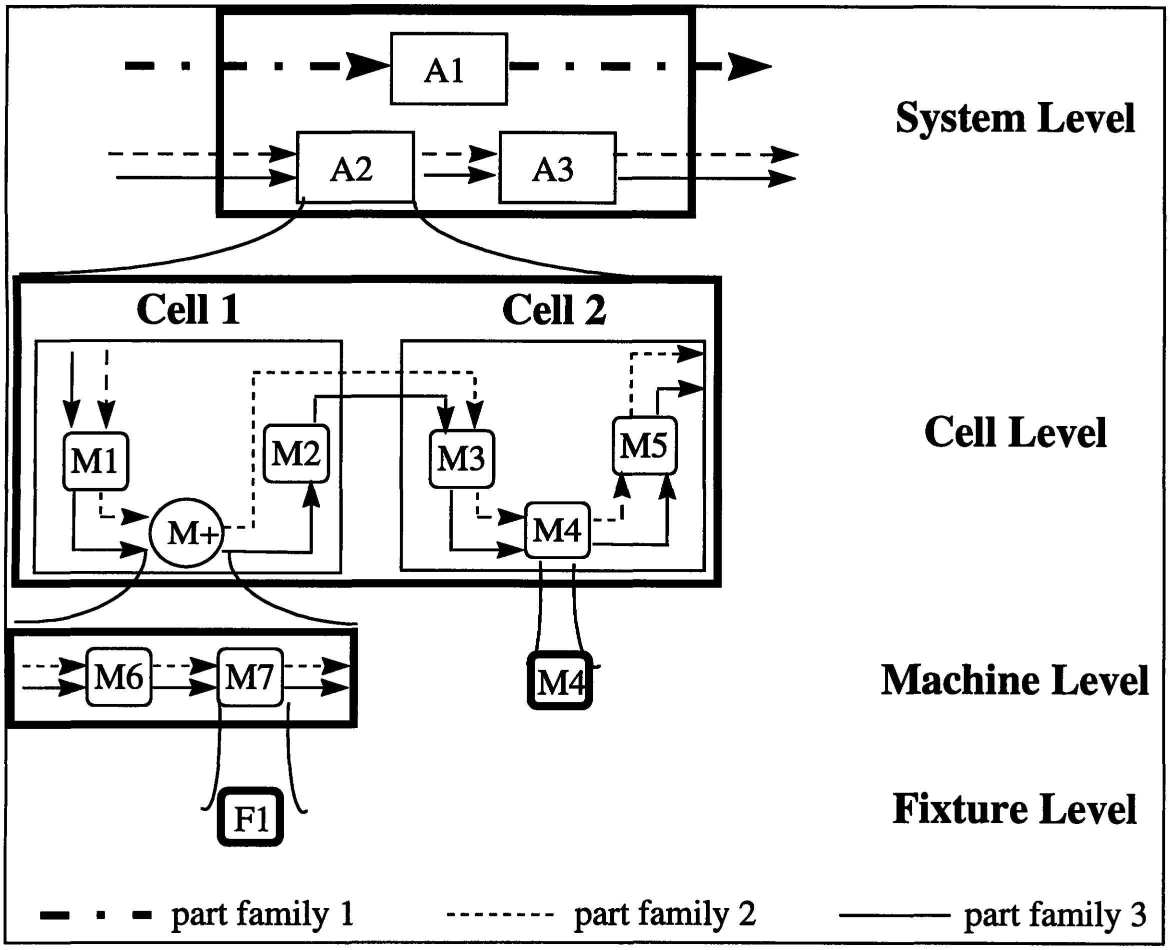


Figure 1-11 The Hierarchy Can Be Represented As A System With Sub-Systems

The system is defined according to three part families, which are the inputs and outputs of the system. Sub-system A1 is only used by part family 1. If part family 1 represents only one product and A1 consists of only one cell, then this sub-system is a pure product layout. Two more part families are also defined. Both pass through the subsystems A2 and A3. System A2 consists of two cells. Within the cell 1 the material flow of part family 2 and 3 is different. Machine M2 is skipped by part family 2. Not all parts produced in one cell have to use necessary all machines within the cell.

The cell 1 consists of four machines M1, M2, M3 and M4. M3 and M4 may be considered as two similar machines . The fixture level follows the machine level. In cell 2, there are no fixtures within machine four. This machine can represent a lathe in which fixtures are not generally utilized. This demonstrates that not all levels of the hierarchy have to be used to structure a manufacturing system.

The relationship between Information-Based Control and the Levels of the Control Hierarchy is shown in figure 1-12. The feedback of the information necessary for control takes place within one level. The information is not transported to a higher level when a lower level is controlled.

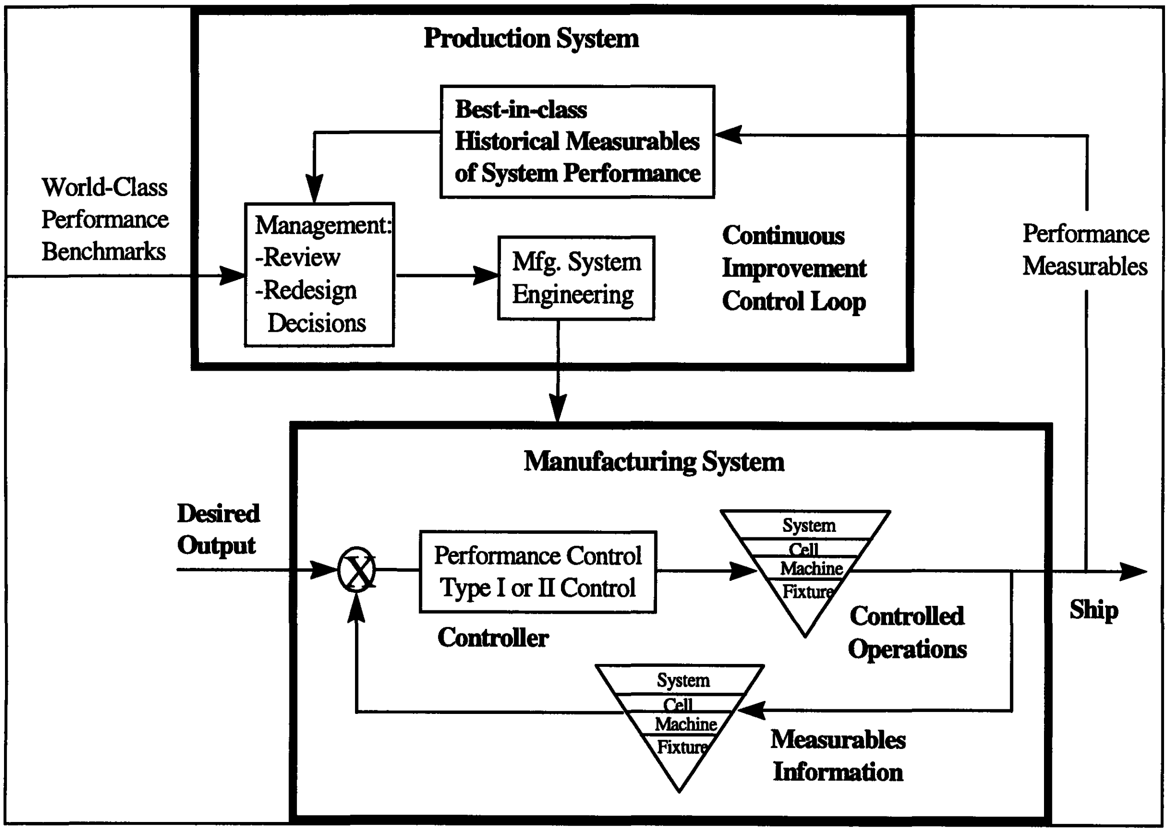


Figure 1-12 Relationship Between Information Based Control & the Control Hierarchy

The relationship between two elements of one level, e.g. between two cells on the cell level, therefore has to be defined. The information measured at this interface enables feedback and control at this level. This relationship may then be exported to the next higher level, the system. The clear definition of the relationships at each level is essential for the physical and logical layout of manufacturing systems

1.2.3 The Process for Manufacturing System Design and Control

The process for manufacturing system design and control is shown in figure 1-13. It applies Axiomatic Design to the design of manufacturing systems. The design is represented in four domains: the customer domain, the functional domain, the information domain, and the manufacturing domain. "The information domain defines the information content that is required to control the manufacturing system." [Cochran, 1994]. The process domain has been renamed as the manufacturing domain.

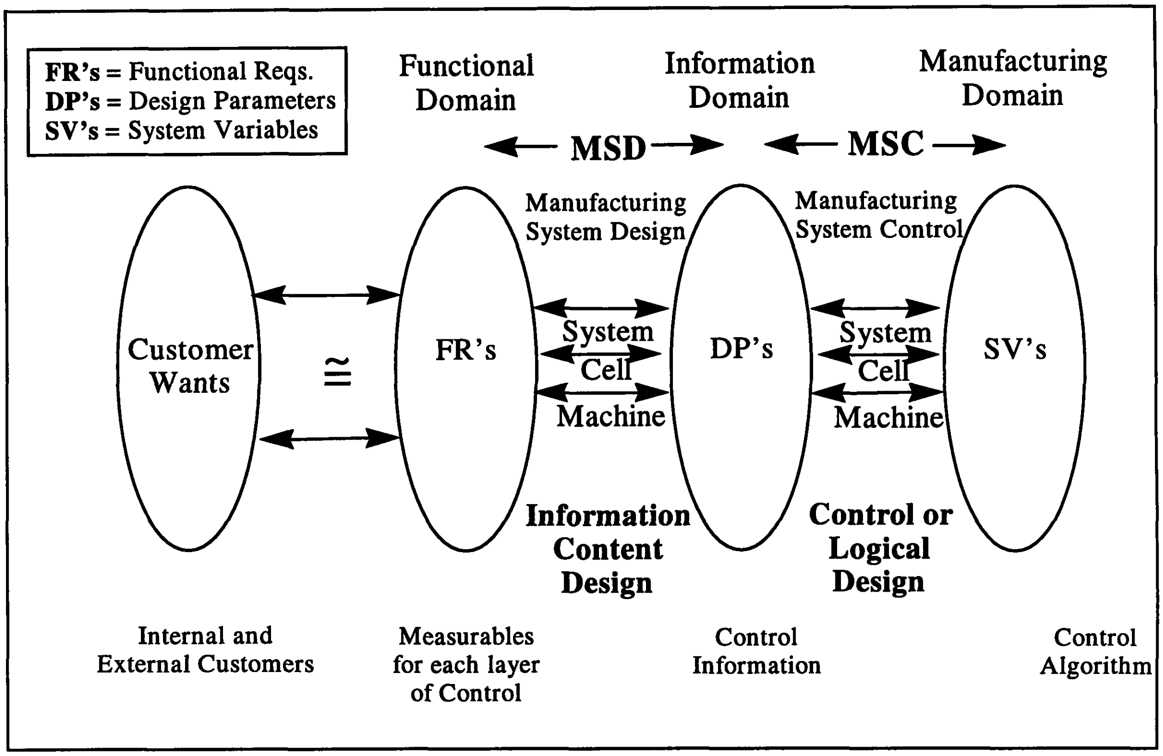


Figure 1-13 The Process For Manufacturing System Design and Control [Cochran, 1994]

The process for manufacturing system design and control requires one translation and two transitions. The customer wants are translated into functional requirements. The functional requirements represent the clear definition of the objectives that the system design must accomplish. [Cochran, 1994]. The functional requirements are translated into design parameters of the information domain and defines the information used to enable the control of the system. The second transition establishes the controllability of the manufacturing system. The system variables are used to define algorithms for the control. The first transition is defined as the manufacturing system design (MSD) process. Axiomatic Design is used for the mapping process between the domains.

There are two different types of customers. The external customer of a manufacturing system is the recipient of the outputs of the manufacturing system. He buys the products manufactured by the manufacturing system. His wants are related to the product he wants to buy. The internal customer of a manufacturing system is the user of the manufacturing system. His wants are related to the working environment.

The customer wants have to be interpreted into functional requirements or measurables for each layer of control [Cochran, 1994]. Using the methodology of Axiomatic Design it is only possible to translate the customer wants into functional requirements of the top level. The functional tree must be developed by zigzagging between the functional and the information domain. This implies that the customer wants have to be structured and ordered to determine the important ones.

System design is an enabler for control [Cochran, 1994]. A system can only be controlled, if the design provides information necessary for its control. This is the major task of the manufacturing system design. The design must incorporate data acquisition and sorting, information flow, and the system control function [Cochran, 1994].

The FR's are transformed into information-element design parameters. The design parameters of the information domain define the information that is necessary for the control of the manufacturing system [Cochran, 1994]. The process of developing the MSD is also called the Information Content Design [Cochran, 1994].

The mapping from the information domain into the manufacturing domain is called manufacturing system control (MSC). The design parameters of the information domain are transformed into system variables of the manufacturing domain. This is also called the control or logical design [Cochran, 1994]. (In one sense these parameters are the control measurables to enable solution determination. They provide the basis for the control algorithms.)

CHAPTER 2

SYSTEM DESIGN

2.1 Introduction

This chapter describes the analysis that was conducted for a job-shop based system. The two primary markets are revealed along with the inefficiencies with which the shop responds to them. The purpose of this work is to provide a structured approach to designing a new system that would more effectively respond to these markets. Recommendations are proposed at the end of the chapter, and a detailed description of one of the sub-systems is described in chapter three.

2.2 Introduction To Lemco Miller

Lemco Miller is a precision machine shop involved in the production of aluminum and steel machined parts for the semi-conductor machine tool industry. The company is a medium-sized job shop of approximately 40 employees with a good mix of manually controlled and CNC machines, both lathes and milling machines.

Lemco Miller's primary customers are the semiconductor equipment manufacturers such as Eaton and Varian. In mid-1996 the semiconductor industry was hit with an unexpected reduction in demand which translated to a huge loss in potential business and part orders for Lemco Miller. The company was faced with several challenges: to reduce their operating costs in order to make the remaining business more profitable, and to try to diversify their markets and bring in new business to make up for the loss in the semiconductor sector.

2.2.1 Problem Statement

Production of parts in a manufacturing system can be categorized into two different types. Type A is the higher volume, repetitive production (standard products) and Type B is the lower volume, non-repetitive production (customized products). Lemco Miller was categorized as a Type A manufacturer when 80% of their business was comprised of two major semiconductor machine companies (Eaton and Varian), who were buying high volumes of repetitively produced parts month after month. Due to a drastic cut in the semiconductor industry, Eaton and Varian decreased demand. This resulted in a change in product mix between the Type A and Type B parts. Lemco Miller thus needed to ramp up in the production of Type B parts, however the manufacturing lead times were too great.

The recommended approach in the short-term to increase sales and be profitable is to increase Type B Ssingle Order Manufacturing parts (SOM), capabilities as well as decrease operating expenses. Figure 2-1 shows the demand forecast defined for companies like Lemco Miller.

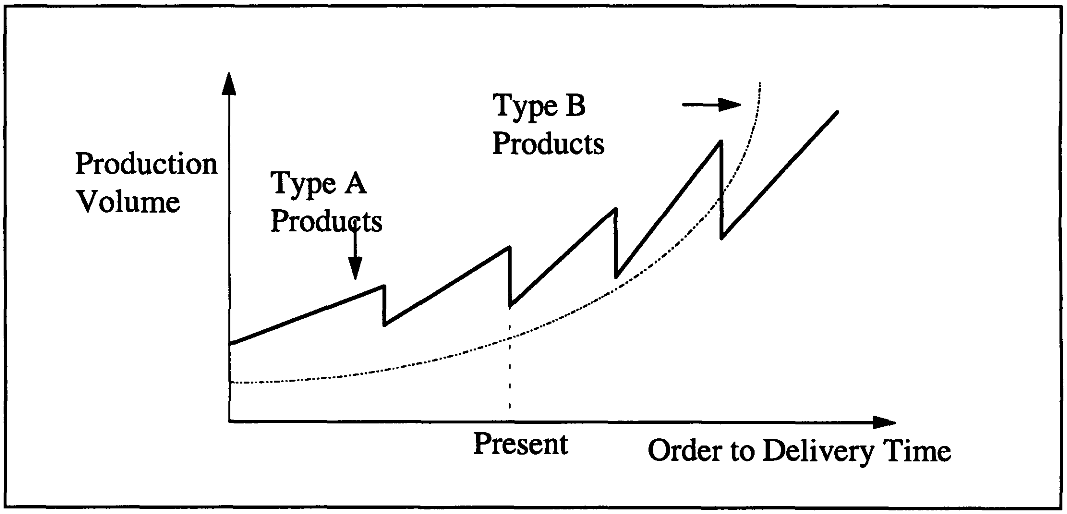


Figure 2-1 Demand Forecast by Product Type

Presently, it is taking twice as long, six weeks, to produce a Type B part as a Type A part. The process of working with new accounts and customers can be described by two major processes, see figure 2-2.

The first process (P1) begins when Lemco Miller obtains a drawing to the time the production of G-Code and the routings are defined for production of the part. The second process (P2) is defined from the time the G-code and routings are defined to the time the part is delivered to the customer. The average time it takes from the beginning of P1 to the end of P2 is six weeks.

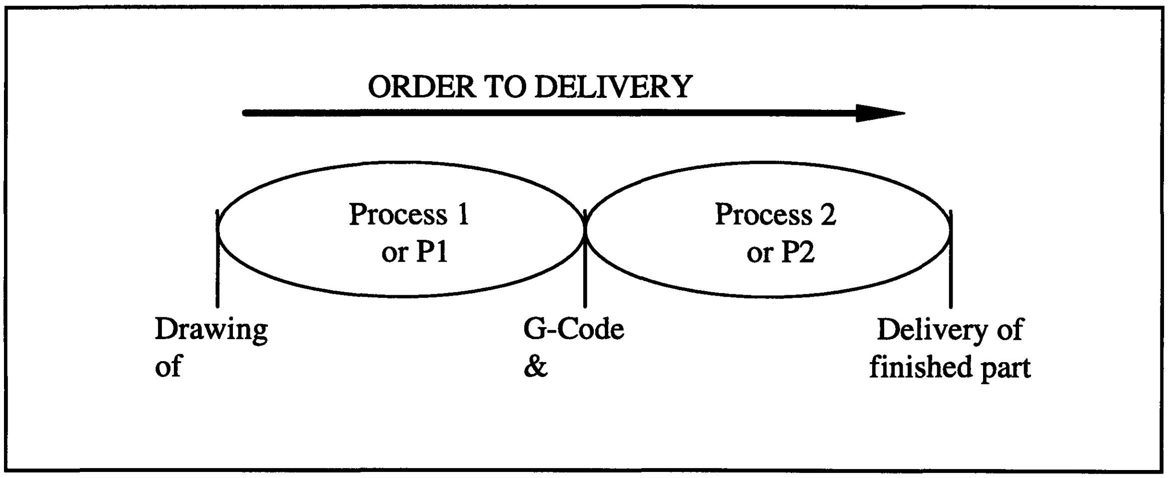


Figure 2-2 Two Major Processes At Lemco Miller

The major problem at Lemco Miller is not only long lead times during both areas (P1 and P2), but also not defining standardized work procedures. By defining standardized work procedures the accuracy in estimating cost and lead time will be improved, thereby eliminating inaccuracies in scheduling of machines. The next section will explain more of what is included in each of the above two processes.

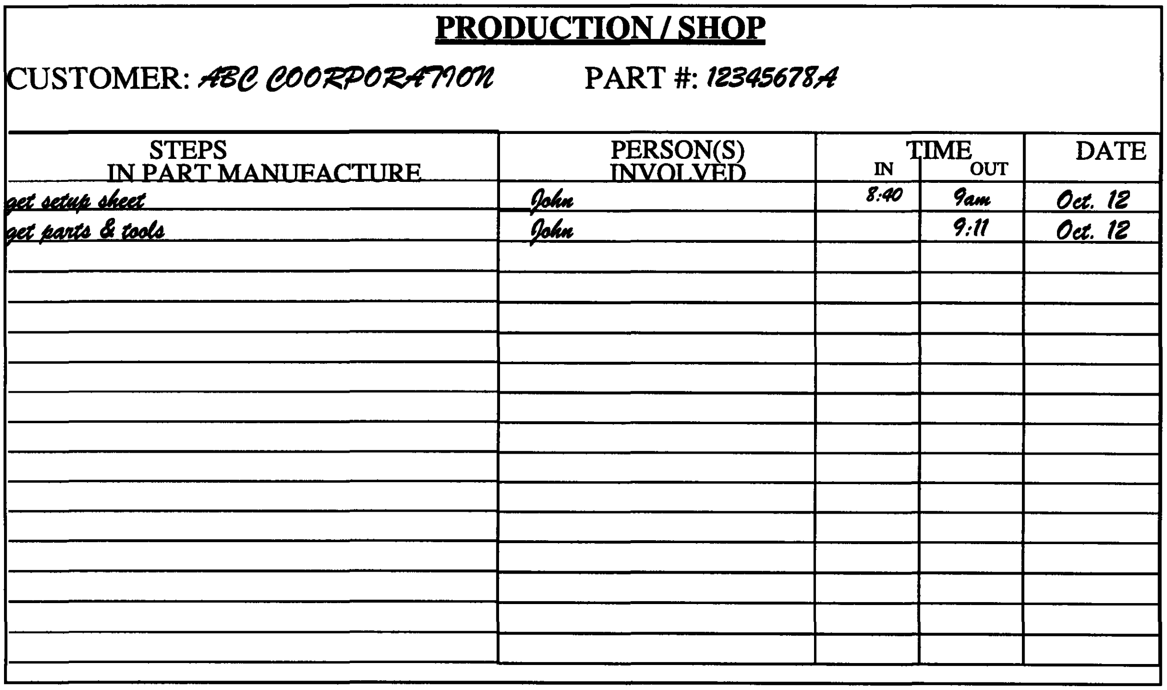
2.2.2 Process Followed To Create A Part

Process P1 is composed of two sub-areas, which are quoting and planning. During the quoting stage, Lemco Miller obtains a blueprint of the part to be quoted. In this stage, production time and pricing are calculated "by experience" to convey to the customer the production lead time of the part and how much it will cost to manufacture the part. After the part is approved by the customer, the second stage will start. In the production planing stage, 1 schedule planner, 1 programmer, 1 engineer, and 2 shop-floor men will meet and discuss issues of routing. This is waste or “muda” in terms of resources [Shingo, 1987]. They will discuss what machines should be used, what tools are needed, the program requirements, and fixturing needs. Routing on "Job Boss" (a scheduling system) is created before this meeting, which means that some machines are pre-allocated before the meeting. A discussion ensues as to whether a pre-allocated machine should really be used or not. Once decided, the part is programmed for the respective machines and material is procured.

The second process, P2, is composed of four major stages; Machining, Deburr/Finishing, Inspection and Delivery. During the machining stage, the part follows the routing developed from the previous stage. When the operator receives a work order, he goes to the digital numerically controlled (DNC) computer, transfers the program and looks for the setup sheet. He will then start working on getting the necessary tools as well as pre-setting them. When a machine is idle, gathering and pre-setting tools by the operator is also "muda". All parts being machined in the shop will go through the Deburring/Finishing area and then through Inspection. Finally, after all operations are completed, the part will go to the packaging area, in which one operator is in charge of packaging all the parts that will be going out to the customer.

2.2.3 Detailed Analysis Of Type A (Kanban) & Type B (SOM) Jobs.

A detailed time analysis was conducted on processes P1 and P2 by instructing all employees to document their activities with regard to certain jobs. Three Type A (Kanban) and four type B (SOM) parts were selected which would highlight quoting, planning and administrative issues in addition to the engineering, scheduling and production activities. This information was documented on two forms, labeled Administrative/Engineering and Production/Shop, which accompanied the shop papers for the four jobs. Figure 2-3 shows the Production/Shop form. In addition, to remind employees to document their tasks red dots were placed on the shop papers. Anytime an employee saw these highlighted jobs they filled out either of the two forms.



PRODUCTION / SHOP

CUSTOMER: ABC COORPORATION PART #: 12345678A

STEPS IN PART MANUFACTURE	PERSON(S) INVOLVED	TIME		DATE
		IN	OUT	
get setup sheet	John	8:40	9am	Oct. 12
get parts & tools	John		9:11	Oct. 12

Figure 2-3 Production/Shop Form Used To Gather Time-Data On Activities In The Shop

The following sections discuss the information that was gathered on Type A and Type B jobs through the manufacturing system.

Process P1 : Inventory inspection to work order release onto shop floor for Type A (Kanban) Job

PERSON A (in: 9:00--out: 11:30)

1. In order to create more parts that are in the Kanban system, person A will print 2 reports:
2. Report A: “Inventory Report,” which states the quantity of Kanban parts available and the reorder quantity
3. Report B: “Active Jobs”, which states all the jobs being set-up or are ready to be produced
4. Person A goes through more than 300 parts one-by-one finding which parts are below the reorder point in order to make more. This is done for all the companies on the Kanban system. On 8/14/89 only one company was studied.

5. Person A writes in another report (report C), the lot size and the due date of parts that are below the reorder quantity
6. Report C will go to Person B

PERSON B (in: 11:30--out: 2:10)

1. Once the reports are with person B, this person will go to the "Job Book" and apply a job number to all the jobs that need to be produced.
2. After writing all the new jobs in the notebook, person B will print out the work orders necessary to produce the required Kanban parts. The work order will contain the Routing and the Direct/Buy information. This is not the correct method for scheduling production of Kanban parts, as will be discussed in section 2.2.4.
3. All the work Orders will go to Person C

PERSON C (in:2:10---out: 3:15)

1. Person C will look for the Blueprints in the file cabinets and prepare the package to go to the shop floor. The package will be sent to the stock room in order to investigate if there is enough material to produce the parts.
2. The package will wait on the "waiting wall" located in the engineering room until the part is ready to be produced.
3. When the part is ready to be produced the package will go to the "scheduling wall" located in the shop.

PROCESS P1: Customer order to job release onto shop floor for Type B (SOM) Job : 8/12 - 8/13

1. Order received by PERSON A (10:15 --- 10:20am, 8/12)
2. Pickup material by PERSON T (5:00pm ---8:30am, 8/12 ---8/13)
    - This customer usually provides the raw stock, however pick-up is burdened by Lemco Miller.

- Note: the customer has provided the stock in the absence of a quote.

3. Login quote by PERSON T (11:10 ---11:15am, 8/13)
    - Customer, delivery date, part number and amount recorded. Job has not been created yet.
4. Engineering, CAD drawings by PERSON G (11:15 ---11:45am, 1:00 ---1:15pm, 2:00 ---2:30pm, 8/13)
    - Redrawing of the part to include the stock-on conditions.
    - Machine programming for this job, as with all lathe jobs, can be performed here, however, this engineering/programming task is passed on to the lathe operators.
5. Quote of job by PERSON F (11:45 ---11:55am, 12:30 ---12:55pm, 8/13)
    - Checks the history of the part to see if the part was previously quoted (part did have a history).
    - Estimates the material, process, and time requirements.
6. Confirm delivery by PERSON A (1:20 ---1:25pm, 8/13)
7. Release or document quote by PERSON F (1:25 ---1:30pm, 8/13)
8. Create job by PERSON B (1:30 ---1:40pm, 8/13)
    - Job number created, receive and mark material with job number.
9. Inspection report created by PERSON G (3:30 ---4:00pm, 8/13)
10. Final review by PERSON B (4:10 ---4:15pm, 8/13)
    - Shop paper and material released to the shop floor.

The P1 process for this Type B job was not typical for all Type B jobs. Due to the urgency and importance of the part, the P1 phase of the entire production process was expedited in one day. Five of the seven administrative personnel were used to perform the above tasks. This is graphically illustrated in figure 2-4.

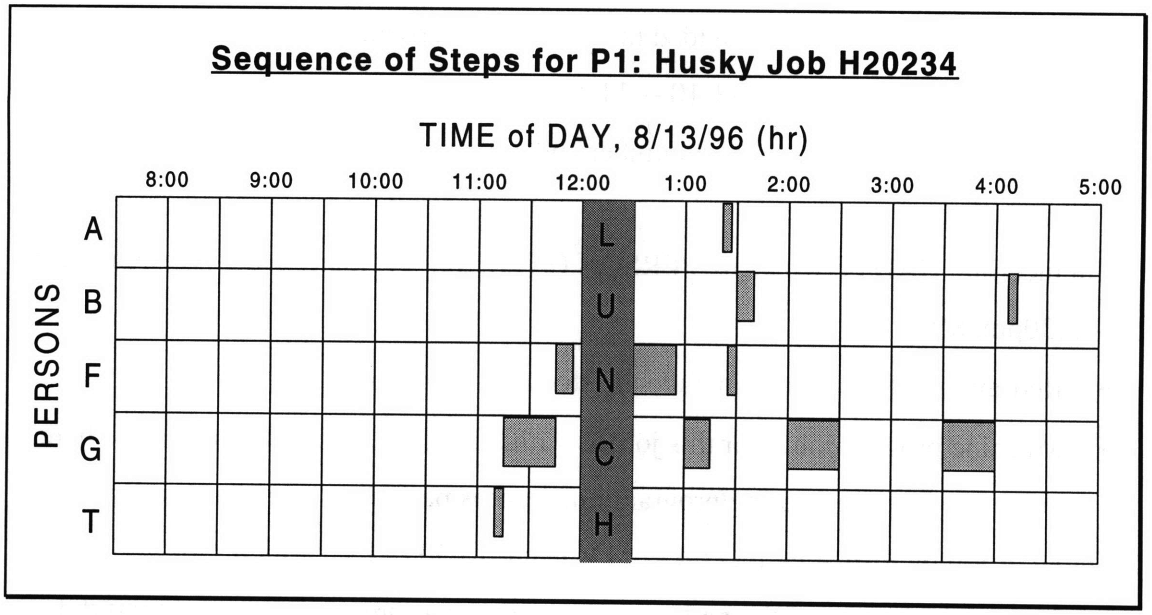
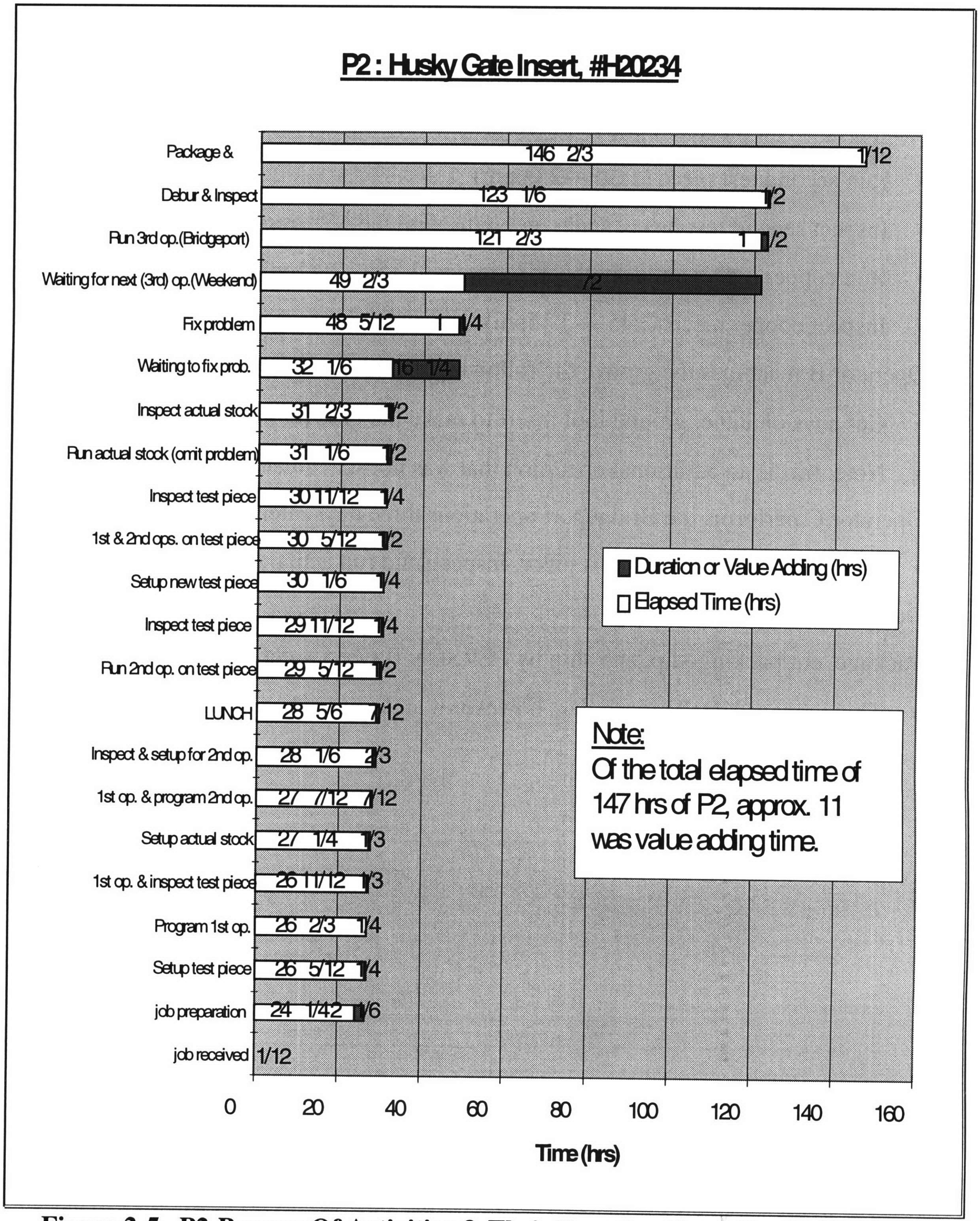


Figure 2-4 P1-Process Completed Within One Day For A Particular Part

PROCESS P2: Production of part to delivery for job H20234 (Husky Gate Insert) : 8/14 - 8/21

1. Job acknowledged by PERSON S (7:00 ---7:05am, 8/14)
2. Job preparation by PERSON S (7:20 ---9:30am, 8/15)
   - Ordered end mills, talked with operators to make special tool, and emphasized that a setup test piece be made. (Special tool made to perform an o-ring groove)
3. Operator A performs some operations on HT25;
   - Cut aluminum and set-up test piece (9:30 ---9:45am)
   - Engineer & Program the first operation. Typically, (9:45 ---10:00am)
   - Run first operation on test piece then inspect (10:00 ---10:20am)
   - Copper stock from customer not same standard size as test stock. As a result, jaws had to be cut two times prior to running the first operation on the copper piece. (10:20 ---10:40am)
   - Run first operation on copper stock; simultaneously engineer and program second operation (10:40 ---11:15am)
   - Inspect copper piece and setup for second operation (11:15 ---12:00pm)

   - Run second operation on test piece (12:30 ---1:00pm)
   - Inspect test piece, had problems with the 45° groove (1:00pm ---1:15pm)
   - Cut new test piece in lathe to fit the jaws (1:15 ---1:30pm)
   - Run second test piece (1:30 ---2:00pm)
   - Inspect second test piece, again problems with the 45° groove (2:00pm ---2:15pm)
   - Run copper piece, omitting the 45° groove (2:15 ---2:45pm)
   - Inspect copper piece (2:45 ---3:15pm)
4. Operator B machines the groove the following day (7:30 ---8:45am, 8/16)
   - Cut jaws on lathe, ground tool insert to make the groove, machine, and inpect.
   - Note: this is an additional operation that was not scheduled in "Job Boss."
5. Operator C performs the Bridgeport operations three days later (8/19)
   - Bore jaws, program, run test piece, inspect, and run actual copper part.
6. Debur and inspect.
7. Package, cut packing-slip, and ship by PERSON B (7:55 ---8:00am, 8/21)
   - This job was "late" by one day, however it took seven days of throughput time.



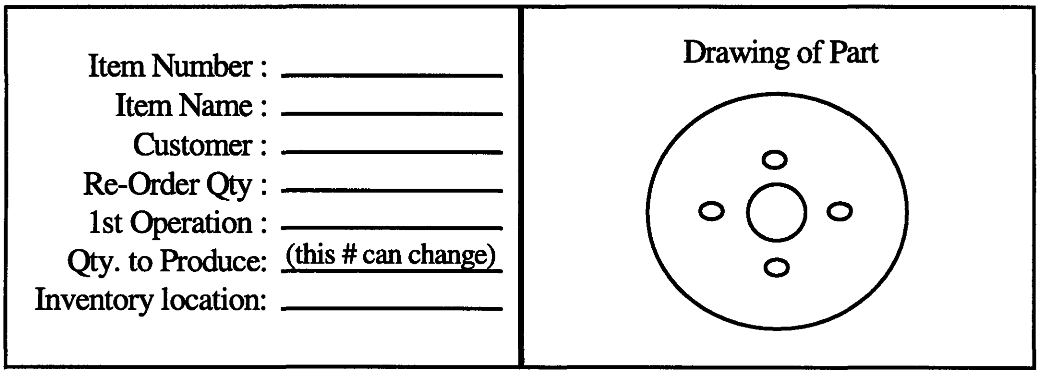
Note:
Of the total elapsed time of 147 hrs of P2, approx. 11 was value adding time.

Figure 2-5 P2-Process Of Activities & Their Duration For A Particular Part.

2.2.4 Results of Analysis & General Recommendations

Type A (Kanban) Parts - P1

Person A wasted around 2 hours trying to find out what Kanban parts were short. Those two hours were only for one customer. This time can be mostly eliminated by creating some Signal/Production Ordering Kanban Cards. These cards will look like the one shown in figure 2-6.



Item Number : ______
Item Name : ______
Customer : ______
Re-Order Qty : ______
1st Operation : ______
Qty. to Produce: (this # can change)
Inventory location: ______

Figure 2-6 Example of a Signal/Production Ordering Kanban Card

For large parts this card will be placed within the parts (see figure 2-7) and for small parts, the card will divide the container into two sections, so that when one section is empty, the card will go to Person A meaning that the reorder quantity has been reached. Two bins can also be used instead of dividing one into two sections.

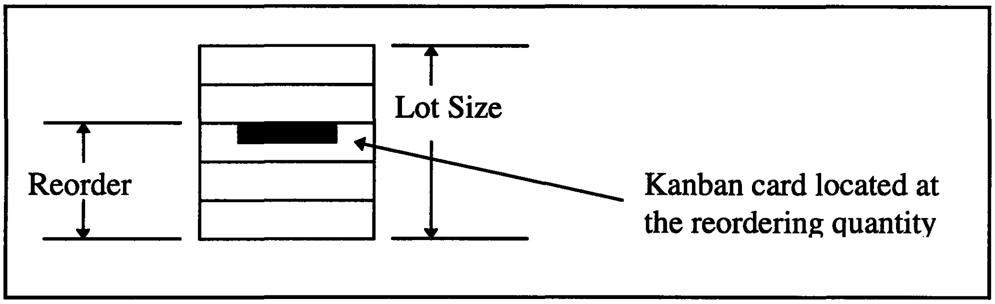


Figure 2-7 Location of Kanban Card for Large Parts

The Kanban card can contain the routing of the part. If this is the case, then the work performed by Person B can be eliminated and that person can dedicate the time of printing the work order/routing to other aspects, like perhaps even taking some responsibilities from person A or person C to free some of their time. Another benefit is the elimination of paperwork in the shop and in the office (the kanban card is reusable)

Time spent by person C can also be eliminated by creating a Material-Requisition Kanban card. This card will be placed in the raw material, so that when it gets to the reorder point, more material will be ordered. The benefits of this card will be the elimination of the time spent during the "stock check" by some of the second shift workers. This will also eliminate paperwork from the waiting wall because one "operation," which is "stock check" will be eliminated. This card will strive to decrease the inventory of raw material and better control of it. The Material-Requisition Card is shown in figure 2-8 in conjunction with the other Kanban Card.

Since it is recommended that the drawings of the part be placed within the machines of use, paper work and no re-printing of the blueprints will be needed, which indeed is a tedious job.

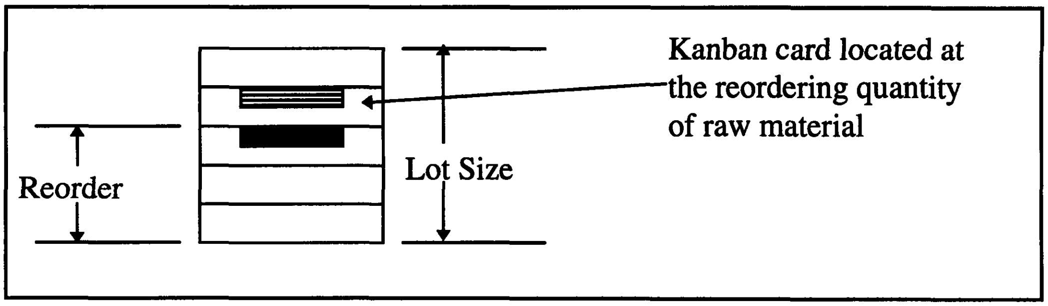


Figure 2-8 Material-Requisition Kanban Card

An example of the Material Requisition Kanban Card can be seen in figure 2-9

Item Number: ______________________
Item Name: ______________________
Supplier: ______________________
Material Size: ______________________
Container Capacity: ______________________
No. of Containers: ______________________

Figure 2-9 Material Requisition Kanban Card

Type A (Kanban) Parts - P2

Monitoring P2, scheduling and production, for the three repeat-order jobs became futile. Changes in due dates by customers due to excess inventory of parts coupled with the shuffling of priority and scheduling with other jobs resulted in placing the jobs on hold, and, for a particular job, even cancellation. Nonetheless, the P2 process for Type A parts witnesses similar production/ scheduling inefficiencies and problems as Type B parts. These issues and proposed solutions are discussed below.

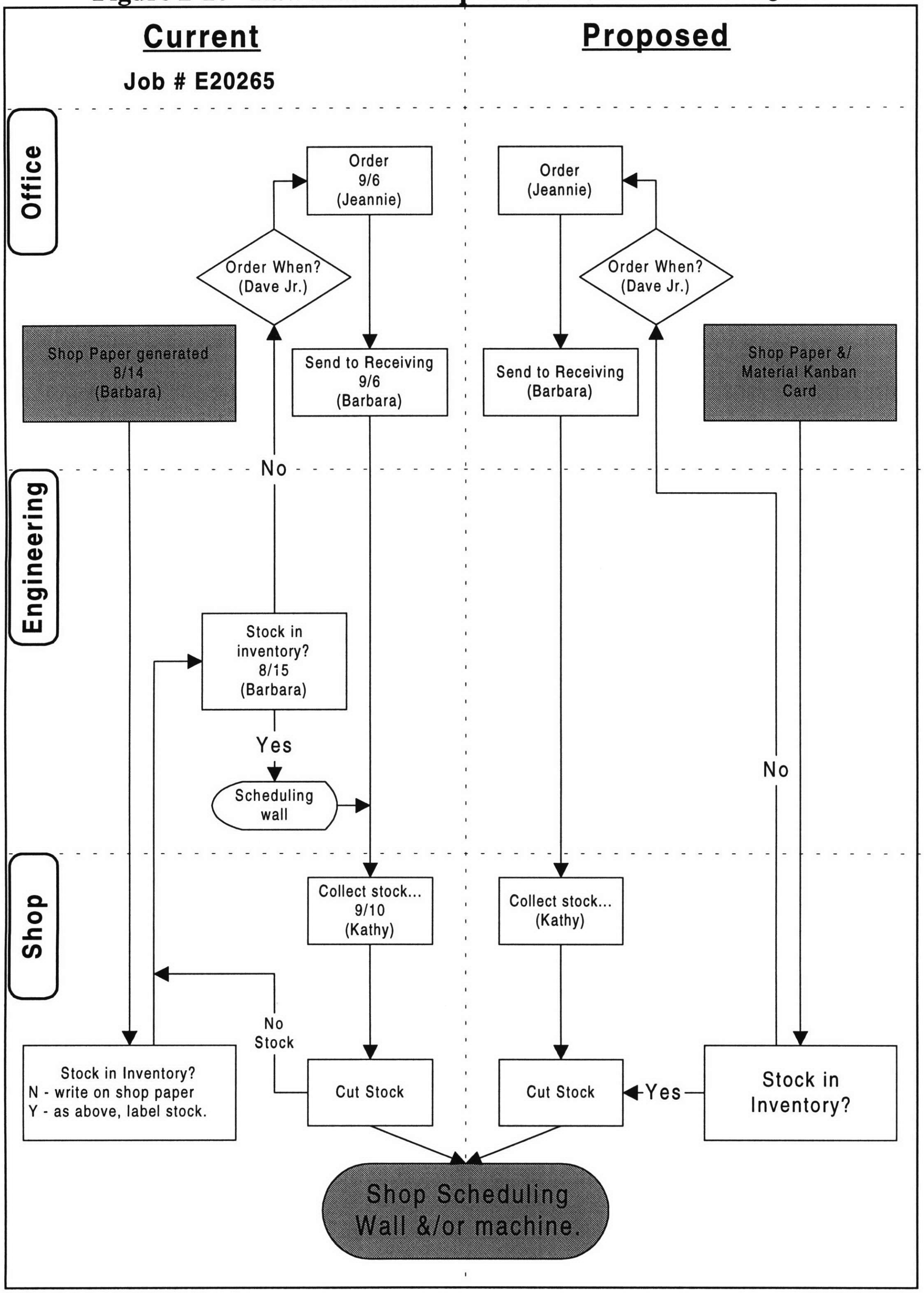
Type B (SOM) Parts - P1

1. Of the 4 SOM jobs, the approximate lead times (from when the job was created to the date of shipment) was an average of 47days; 6 days being the minimum for the Husky gate insert job, and 67 days being the longest for the Husky-P job. The two other jobs had lead times of approximately 53days and 60 days respectively. Generally, Lemco Miller would like to keep within a 21-28 day lead time.
2. Engineering is still programming extensively with Genesis software although the superior merits of the Virtual Gibbs package are apparent. According to the engineering manager, "the Gibbs software is easier to use and for the most part, can produce a part faster. However, he and the others have not had the time and training to become fully acquainted with it." For example, only 2 of the 3 engineers use

Virtual Gibbs from time-to-time. The third engineer, engineer C, has never used it, and I do not think he plans to. In addition, of the four computers in engineering, there are three that have the software installed on them, but there are only two keys. Also, the machine that one of the programmers is seated at would not be powerful enough to run Gibbs. In the meantime, there's a computer that's sitting in engineering, with the Gibbs software, but no one is using it. Perhaps a third key should be purchased to utilize the third machine and then, if willing, engineer C's tasks would be made easier and faster. With this in place, engineer C's previous computer may be placed at the MAM 600 to facilitate an operator's engineering/programming that currently is undertaken at the machine.

3. Often ignored is the programming proposed by engineering. Engineering is performing machine-specific programming that generally is being reprogrammed on the shop floor. This is wasted work and the operators should not be re-programming, or the engineers need to know why their programs are inappropriate.
4. As demonstrated in the P1 process for Type A (Kanban) parts, there is a lot of unnecessary paper travel and processing steps. The raw material requisition process currently checks the inventory for stock. If stock exists, administration is notified so that they would not order additional material. Meanwhile, the required amount of material is not cut nor put aside, but may be tagged and left in inventory. The problem that has arose several times is that 3 weeks later, when the job is ready to be manufactured, the stock has already been consumed for either another job, or for fixtures. The current job must then be delayed until material is ordered and delivered. The recommended approach is to cut, label and put aside stock specific to a job when raw material inventory is checked. In addition, inventory control with raw material requisition cards (see figure 2-9) should be implemented to cut down on unnecessary inventory inspection and paper travel. The current and proposed methods of operation are illustrated in flow-chart form in figure 2-10.

Figure 2-10 Raw Material Requisition Process for SOM Jobs.



Notes: 1. Reduce paper travel and unnecessary procedures.

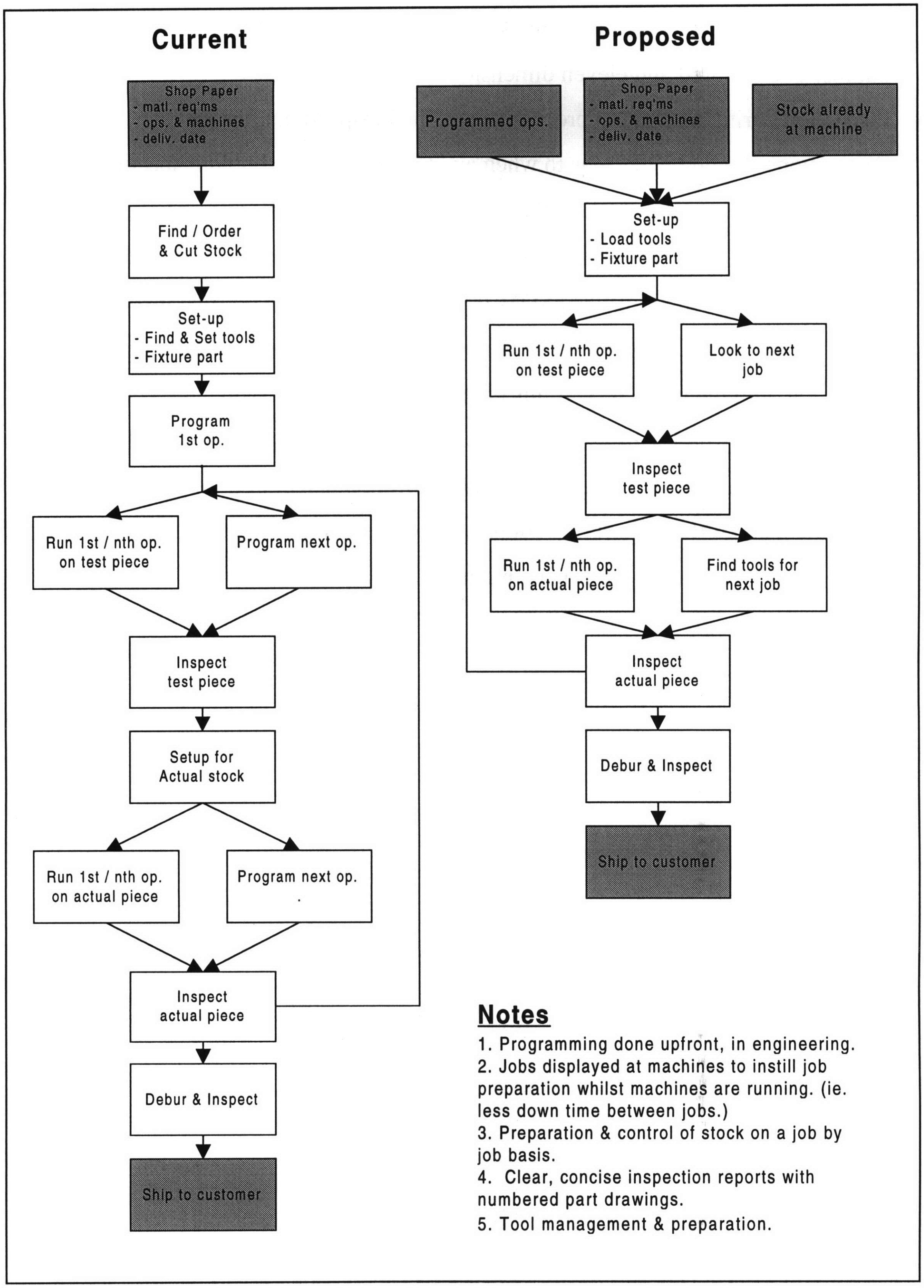
2. Eliminate opportunity for stock already dedicated to a job to be consumed by another.

Type B (SOM) Parts - P2

1. The lathe programming should be performed with the CAD package in engineering. Engineering prepares the jobs and becomes familiar with the part and how it should be machined. Leaving the programming for the machinist essentially repeats the familiarization process and thus wastes time. There are currently 6 lathe operators, 3-4 of whom are capable of programming a part depending on it's complexity. These machinists vary in their expertise, programming skills, and styles, and particularly with Kanban jobs, they have difficulty producing a part that was previously performed by another operator. The final analysis is non-standardized part production, increased lead times, and greater room for error.
2. In addition to having the programming for lathe jobs conducted in engineering, the operators need to prepare for upcoming operations or the next job while the machines are running. In addition, they should inspect the part after every operation prior to moving onto another operation. These principles are flow-charted in figure 2-11.
3. There should be a Tool Requirement List that informs the Tool Crib Requisitioner as to which tools are needed prior to the machine operator receiving the setup sheet. Currently, machinists are also performing tasks such as tool ordering and allocation which is additional waste.
4. There seems to be a problem with the generation of inspection reports. Although it's well accepted in engineering, in inspection, and by the machinists that their part drawings should be numbered to the inspection reports, many times this is not being performed. On two occasions it was observed that the prints were not numbered. On the first, Friday 27th of September, job # H20484, there were 60 dimensions to be inspected. The total machining time for the job, which consisted of a lot size of 2, was approximately 3hours, while the inspection after the machining process occupied an additional 1.5hours. Thus, a 3-hour job became a 4.5-hour job, which must then go to inspection **again** for final inspection. There is thus a redundancy in the inspection of parts. A second circumstance was observed a few days later, on the 1st of October. This job was however a Varian repeat, part # E17016700 and job # P19647. All the

repeat jobs should technically be marked up correctly, yet the machinist had to number one hundred and eleven dimensions for this job.

5. Inspection during machining process versus final inspection after the fact. Distinctions should be made as to when and to what degree should inspection be performed at the machine versus that done at final inspection. As was pointed out by the lead man of the Bridgeports, many times he and his operators would perform all the inspection on small lot sized SOM jobs that they run, and no final inspection would be performed. Apparently he attributes this to his experience and good reputation with the inspectors. If this practice has been successful, and there have been few quality problems as a result, the merits of final inspection should be reassessed. Strangely enough, it is felt that inspection is required for all CNC jobs, while the manual Bridgeport operations are regarded as more accurate and repeatable. Given today's technology, this perception is unfound and inaccurate.



Notes

1. Programming done upfront, in engineering.
2. Jobs displayed at machines to instill job preparation whilst machines are running. (ie. less down time between jobs.)
3. Preparation & control of stock on a job by job basis.
4. Clear, concise inspection reports with numbered part drawings.
5. Tool management & preparation.

Figure 2-11 Current & Proposed Operating Procedures for SOM on Lathes

2.2.5 Goals of the New Proposed Manufacturing System Design

Having defined and refined P1 and P2, and the standardized work that is necessary to enable predictable and efficient processes, the challenge now lies in their implementation. The new manufacturing system at Lemco Miller will be able to perform very efficiently with Type A & B parts by tailoring sub-systems that can respond to their unique requirements. The previous analysis focused mainly on manufacturing of type B parts with recommendations concluding the section. However, as indicated in the introduction and in the problem statement, the bulk of Lemco Miller's business deals with Type A, Kanban parts. It is, therefore, recommended that the new system should comprise of approximately 60% cells that will respond to the Kanban parts, and the remaining 40% of the SOM parts in the revised job-shop environment, as discussed previously. With regards to a cellular layout, the benefits are described below. In addition, a pilot cell is being setup by Lemco Miller and is evaluated in the upcoming chapter, Chapter 3, Cell Design.

In the cellular layout, Lemco Miller will be working under the Single Piece Flow environment. Single piece flow will reduce queuing time from operation-to-operation since the next operation will no longer have to wait for the entire batch. As an effect of reducing this queuing time, throughput times will be reduced as well as work in process inventory and finished good inventories. Quality of parts will be improved since the feedback of errors will be internal.

The layout of the shop will be redefined in order to increase effectiveness and efficiency so that one operator will work on more than one machine at a time. This change will result in better space utilization, while process planing will be more simple. Worker's morale will increase as well as their satisfaction and communication because they will no longer be bored by staring at one machine, while the machine is working. Operators will be responsible for inspecting as well as deburring some of the features on the parts. This will help to eliminate the current bottleneck, which is the deburring/finishing stage.

Standardized work and standard tooling will be used in order to reduce the complexity of making a part. This standardization will also reduce some of the tooling and fixtures currently used. The programming practices will also need to be revisited in order to reduce the number of tools.

CHAPTER 3

CELL DESIGN

3.0 Introduction

At the cellular level, three cell designs are compared. The first represents a cell that is involved in the manufacture of steering gears. Following this, the machining cell at Merlin Metalwork's Inc, a much smaller, less perfected cell, is contrasted. Using the principles of Axiomatic Design, an analysis of this machining cell indicated coupling and non-fulfillment of certain cell requirements. Finally, an attempt to apply cellular manufacturing in Lemco-Miller's job-shop is described. This cell design, termed Smart-Cell^{TM} by Lemco Miller, demonstrates how industry's constraints and mis-interpretation of manufacturing system design principles often inhibit successful cell design.

3.1 A Rack-Bar Machining Cell

The rack-bar machining cell at an automotive steering gear manufacturer demonstrates many important characteristics of cellular manufacturing. These characteristics are listed, and the cell's layout is shown in figure 3-1, below.

The cell is manned by three operators. It is synchronous with the upstream elements because its cycle time is designed based on the 52 seconds takt time and also because the machine and operator work are both standardized. As observed, the operators' cycle time were constantly being achieved during the shift. The cell cycle time can be quickly altered to respond to changes in customer demand by adding or removing workers. The cell cycle time does not depend on the machining time. Flexible work-holding devices, and tool changes in programmable machines allow rapid changeover from one component to the other. The machine and operator times are independent or uncoupled.

Raw bar stock placed in front of the first machine in the cell is loaded manually into the first machine. This first machine processes eight bars at a time as the machine's cycle time is eight times that of the cell's takt time. Nonetheless, single piece flow production is practiced as bars move one-by-one to downstream machines in the cell. The first six machines implement automatic material handling or transfer between themselves. From then on, operators transfer, load and unload, one bar of work-in-process for every cycle. Space is also allocated for standard-work-in-process, thereby preventing high inventory.

The level of sophistication and control in the cell is illustrated at the machine level. Each machine is equipped with both quality checks and safety switches. Quality checks, also referred to as poka-yokes, mistake-proof parts one at a time as they are processed. If a defect occurs, an alarm is immediately sounded, and the problem treated. Similarly, safety switches protect the operators from getting hurt while machines are running.

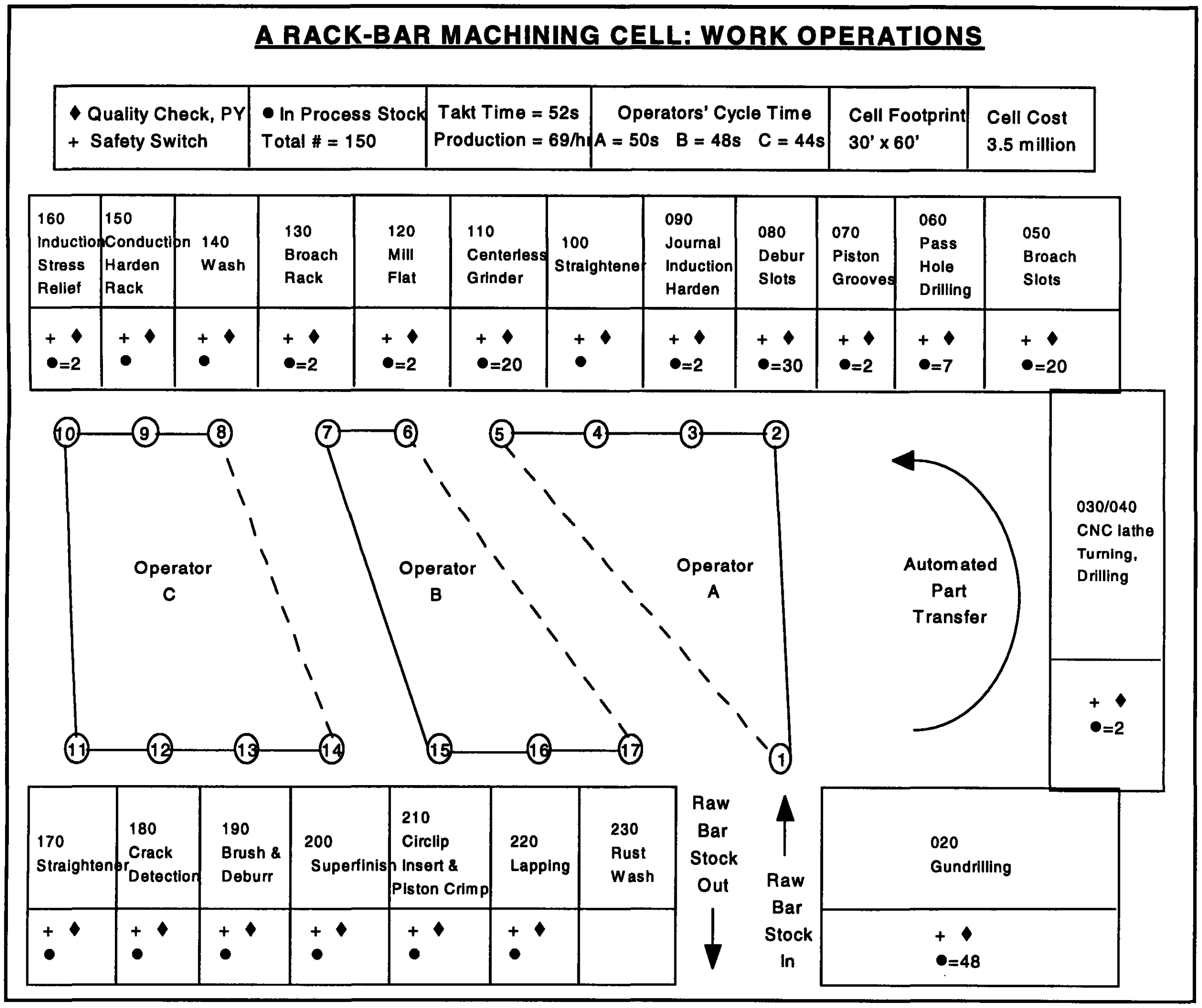


Figure 3-1 Example Of A Machining Cell

Cell Attributes:

1. Small cell footprint, 30 ft wide by 60 ft long.
2. Cell has 21 machines, each with similar form factor, approximately 4 ft wide.
3. Cell typically run by 3 workers, however number of workers can vary, to increase or decrease production volume.
4. Production is single-piece-flow. The majority of the machines process parts one at a time, with the exception of the gun drilling operation. The machine's cycle times for this operation was greater than the cell's takt time, however, parts were still passed one at a time to the downstream operations.
5. Standard work operations are defined for every part processed by the cell.
6. Standard WIP of 150 parts.
7. With a Takt time of 52 sec, the lead time is approximately 2 hr.
8. Standing, walking workers (90-95% utilized)
9. No workers are isolated. Each worker can see each operation and there are no obstructions to operators' walking paths.
10. Operators rotate jobs every two hour in an 8hour shift, 3 shifts per day.
11. No rework lines.
12. No "buffers" to compensate for long changeovers.
13. Every assembly task and machining operation 100% mistake proofed.
14. Machines built on casters for portability and modularity in the cell layout.
15. Material loading from rear of cell (along aisle).
16. Chips fed to rear of cell (along aisle).
17. 3 hour inventory between machining and assembly.
18. Operators rotate or change between the respective work loops.

3.2 Evaluation of Machining Cell at Merlin Metalwork's Inc.

Merlin Metalwork's Inc. is a titanium bicycle frame manufacturer. Historically, the company made frames in huge batches in a job shop layout. Within the last few years, however, the company has been trying to improve their manufacturing cost and customer response by adopting a cellular manufacturing layout, but with little success. In particular, they have been trying to perform single-piece-flow for some time. In making the transition from batches to single-piece-flow a "machining cell" has been set-up to facilitate the flow of the parts. There were, undoubtedly, a number of problems that arose. One of the issues that has received the most attention has been the problem of reducing set-up time on a number of the existing operations, such as the drop-out mitering operation explained in Chapter 6, Fixture Design. The benefits of reducing set-up time are immediately apparent and thus very attractive as a solution to many of the problems. However, simple observation of the process hints that there may be more fundamental problems that may not be resolved by set-up reduction. A preliminary analysis of the machining cell was conducted using the principles of Axiomatic Design and the Time-Based-Management (TBM) & Kaizen approach. The results are presented in the next section.

3.2.1 Background

The machining cell primarily consists of small, manual machines like drill presses, horizontal and vertical mills, a lathe, and Bridgeports. Raw material, titanium tubes of varying diameters and wall thickness, are stored on the outside of the cell, close to a manual lathe. The lathe, custom built with a Scroll chuck for quick and easy insertion, is used to cut the tubes to approximate lengths which would later be used to make the top tube (TT), down tube (DT), seat tube (ST), head tube (HT), bottom bracket (BB), seat-stays (SS) and chain-stays (CS), respectively (see figure 3-2).

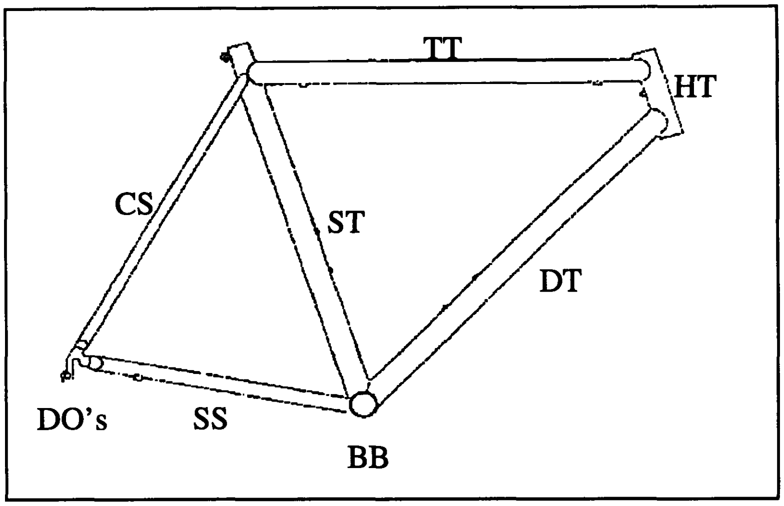


Figure 3-2 Bike Frame and Constituent Tubes

The tubes are then placed in a box from which the cell operators would pull individual tubes that require specific operations, such as the bending, drilling and mitering. These tubes are eventually fitted onto a jig that is used to secure the tubes for welding.

The layout of Merlin's machining cell is shown in figure 3-3. The layout is not actually that of an ideal U-shaped cell layout in which the machines are arranged in order of the part/ stock flow. Instead, to accommodate the iteration between cutting tubes to the correct length and securing them to the jig for welding (described in 3.2.2) the mills have been placed closer to the jig, on the west side, while other machines that are generally used first, are placed closer to the raw material inventory. Machines have also been assigned arbitrary numbers, which do little in facilitating the smooth understanding and operation of the cell.

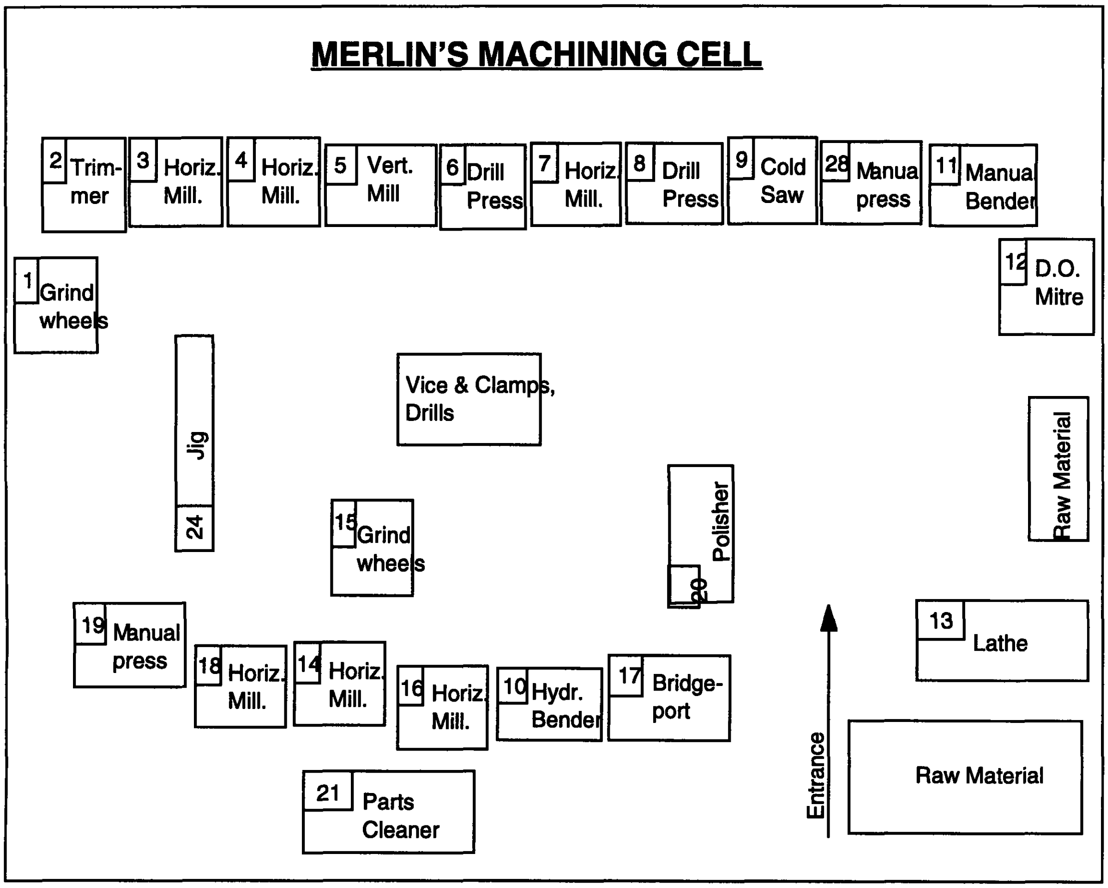


Figure 3-3 Merlin's Machining Cell Layout

The cell is operated by 5 workers who perform the same tasks throughout the one 8hr shift per day. The foot print of the cell is approximately 20ft wide and 50 ft long, relatively large as it has to accommodate 5 workers, the machines, and the travel paths of the workers to the machines. The workers' paths are displayed in figure 4 below. It shows that there is a lot of confusion in the operation of the cell. Operators A and B both have fairly clear, uninterrupted paths, while the paths for C, D, and E are overlapping. In addition, there is not much space in these areas.

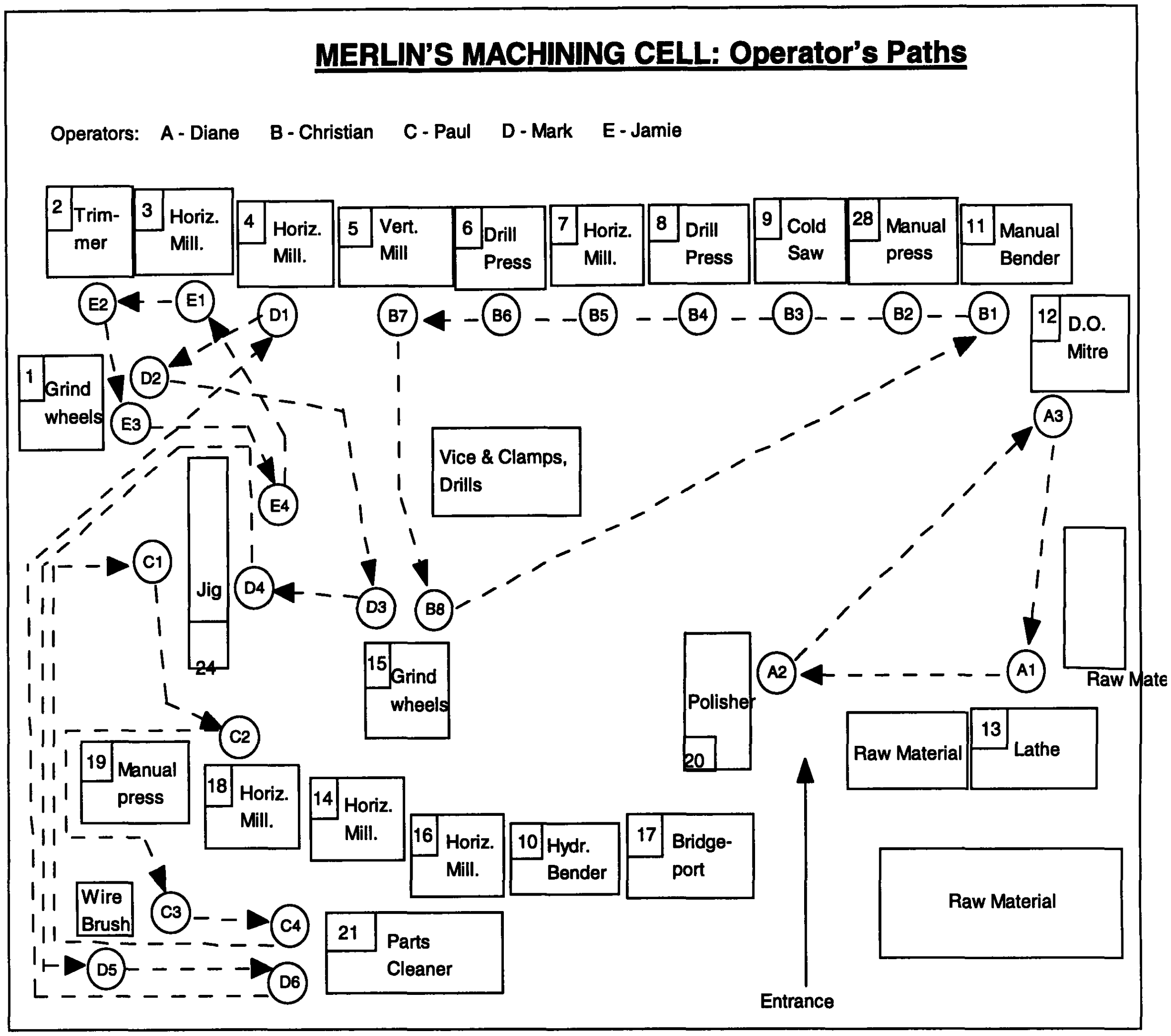


Figure 3-4 Operators' Paths for Merlin's Machining Cell

3.2.2 Axiomatic Design Approach

The machining cell may be viewed as a system with many functional requirements (FR's) corresponding to the total number of styles of bike frames that must be produced [2]. Each of these styles has its own corresponding subset of functional requirements:

- Standard Road Frame (FR1, FR2, FR4, FRn)
- Road Frame model A (FR2, FR3, FRm)
- Road Frame model B (FR1, FR3, FRn)

- Standard Mountain (FR1, FR3, FRo)
- Mountain model A (FR3, FR4, FRp)

At any given point in time, the system is required to satisfy different subsets of FR's. A set of design parameters (DP's) must be chosen to independently satisfy the sets of FR's. This means that the system must reconfigure or switch to satisfy {FR1, FR2, ... , FRx} independently, and at an acceptable speed [Suh, 1990].

At the highest level of abstraction, the system can be seen to have four main FR's for each of the various bike styles:

FR1: Cut tubes to specified length
FR2: Bend seat-stays and chain-stays to specified angles
FR3: Miter tubes as specified
FR4: Fixture tubes for tack-welding

The DP's that satisfy the FR's are shown below:

DP1: Lathe used to cut tubes
DP2: Manual tube bender
DP3: Hole-saws used to create miter
DP4: Jig used for securing tubes.

The design matrix (DM) that shows the qualitative relationship between the FR's and DP's is:

$$\begin{Bmatrix} Length \\ Bend \\ Miter \\ Fixture \end{Bmatrix} = \begin{bmatrix} x & 0 & x & x \\ 0 & x & 0 & x \\ 0 & 0 & x & x \\ x & x & x & x \end{bmatrix} \begin{Bmatrix} Lathe \\ Bender \\ Hole-saw \\ Jig \end{Bmatrix}$$

The design matrix may be interpreted as follows. The length of a tube is first achieved through cutoff on a lathe according to a spec-sheet. This linear length may then change when a miter is put in the tube. Finally, when placed on the jig, the tube may not fit correctly and so must then be mitered once again until the fit is correct. Similarly, angular bends are placed in the tube with a bending machine according to the spec-sheet, but when the tube is placed on the jig, it may not fit and so must be operated on again. Mitering of the tubes is performed at a variety of simple manual horizontal mills, but this operation is also usually repeated after checking the tubes against the jig. Finally, when the tubes are to be secured for tack-welding, many times they would not fit correctly and thus the stops on the jig are adjusted depending on the lengths, bends and miters performed on the tubes.

The design matrix indicates coupling between the DP's and the FR's. For instance, a perturbation in the jig setting affects the required length, bend, miter, and position of the tubes. The implication is that the functional requirements are not being satisfied independently nor precisely, but only through a series of iterations. The cutting, bending, and mitering operations are supposed to be performed according to the specifications outlined on each of the frame's spec-sheet. The jig however, is not set-up precisely according to these specifications, but according to master-frames that are close in specifications to the bike that is to be made. Although there is quite an inventory of these master-frames to cover a range of bike styles and sizes (which incidentally could be regarded as enormous inventory-waste) the frames are never exact due to their own imperfections in machining and wear and tear. As a result there is usually a discrepancy in what the spec-sheet dictates and what the jig has been set to accommodate. The machinists then iterate between the specifications on the spec-sheet and what has been set on the jig by the incorrect master frame.

Axiomatic Design tells us that if the functional requirements are not being independently satisfied by the chosen design parameters then new DP's must be selected. From the company's point of view, that may not be simple. Nonetheless, if the jig system could be quickly and easily set up or configured according to the actual specifications of any bike size and style, then there would be no need to use master frames, and therefore, no discrepancy. Similarly, all machining operations would need to become under control. In other words, cutting, bending and drilling can not be controlled unless the machines and machinists are first able to measure or sense what they are doing. Simply stated, if one cannot measure it, one cannot control it.

3.2.3 TBM - Kaizen Approach

Time Based Management (TBM), and more specifically Kaizen, is concerned with organizational tasks and the design of production systems, processes, and system integration. Many times Kaizen describes a phenomenon or a result of the application of a good design principle. However, if the system that is under analysis is fundamentally a poor design, the improvements predicted by Kaizen would be small, and the underlying problem would not be highlighted. The power of Kaizen is therefore essentially continuous optimization; reducing costs and increasing revenue. This is conducted by observing the existing machining process or flow and its individual operations with regards to:

- operator cycle time and path
- machine cycle time/ cell Takt time
- value adding operations
- setup reduction
- waste management

and then to improve on these. This is a continuous improvement process that can be applied in the short term. The preliminary analysis of Merlin's machining cell with regard to some of the above metrics is shown in table 3-1, below. It is important to mention that production in the machining cell is performed in a semi-single-piece-flow manner. Due to the relatively large setup times on some of the operations, single-piece-flow is not always feasible. Depending on the product mix on any given day, frames may be made one at a time, in batches of two, termed "double-piece-flow" by Merlin's operators, or in batches larger than two. The measurements listed in table 3-1 will reflect times for processing of parts in varying batch sizes.

Processing Times

Operation	Time/part (min)	# Parts	Total Time (min)
Jig Setup	10' - 20'	1	10' - 20'
Cutting (Lathe)	1' - 1.5'	8 tubes	8' - 12'
Bending CS & SS	5'	2 pairs	20'
Slashing CS & SS	1'	2 pairs	4'
Mitering CS & SS	5' - 8'	2 pairs	20' - 32'
Mitering TT	5' - 7'	2 sides	10' - 15'
Mitering DT	4' - 7'	2 sides	8' - 15'
Mitering ST	2'	1 side	2'
Mitering DO's	8' - 12'	1 pair	8' - 12'
Water bottle holes	0.5'	2 holes	1'
Relief holes	2'	3 sets	6'
Crimp SS	1'	2 tubes	2'
Degreaser	10' - 15'	1 set	10' - 15'
		Total Time = 109' - 165'	

Table 3-1 Processing Times in Merlin's Machining Cell

Value Added

Operation	Time/operation (sec)	# Parts	Total Time (sec)
Cutting (Lathe)	5" - 7"	18 cuts	90" - 126"
Bending CS & SS	1" - 3"	5 bends & 2 bends	7" - 21"
Slashing CS & SS	5"	2 pairs, each 1 side	20"
Mitering CS & SS	17" - 23"	2 pairs	34" - 46"
Mitering TT	27"	2 sides	54"
Mitering DT	63"	2 - 3 times	126" - 189"
Mitering ST	60"	1 side	60"

Mitering DO's	31"	2 ends	62"
Water bottle holes	6"	2 holes	12"
Relief holes	30"	3 sets	90"
Crimp SS	5"	2 tubes	10"
		Value Added = 10.2 mins - 12.1 mins	

Table 3-2 Value Adding Times for Merlin's Machining Cell

Takt Time

Merlin's Takt time was calculated using the equation below. The operating time used in the calculation was based on a typical 8 hour 15 minute work day, with deductions of 45 minutes for lunch and 30 minutes for other sporadic breaks and delays throughout the day. The customers' daily demand requirement was estimated by production personnel at Merlin. This figure varied quite a bit and was determined according to the amount that was needed to replenish late orders as well as to accommodate new orders. The figure that is used here is 14 bike frames per day.

$$\text{TaktTime} = \frac{\text{Net Operating Time / Period}}{\text{Customer Requirements / Period}}$$

$$\text{TT} = \frac{\text{420 mins. available}}{\text{14 units}}$$

$$\text{TT} = \text{30 mins}$$

The Takt Time can then be used to determine how many workers would be necessary to fulfill the customer demand. Since the average processing times have been calculated, the necessary number of operators is given by the following:

$$\text{No. of Operators} = \frac{\text{Processing Time}}{\text{Takt Time}}$$

$$= \frac{165}{30} = 5.5 \text{ workers}$$

We thus see that with the current implementation of 5 workers in the cell, Merlin is unable to meet the 30min Takt time. This can be overcome by eliminating 15mins (30mins x 0.5) from the total processing time, either by increasing speeds and feeds for instance, or reducing setups, or even eliminating certain operations altogether.

3.2.5 Conclusions on Merlin's Machining Cell

The Kaizen approach enabled measurements of the cycle time and value adding operations of the system. Again, preliminary measurements indicated that the value adding operations were a very small proportion of the total processing time, approximately 6 - 11%. In addition, the desired takt time was calculated, and then, to achieve this with 5 workers, 15 minutes would have to be eliminated from the existing process.

The first axiom of Axiomatic Design leads to the conclusion that the machining cell system is a highly coupled system. The four basic operations of cutting tube lengths, bending, mitering and then securing the finished tubes are not independently achieved by the existing design parameters. The main culprit of this operation is the jig system. Currently, they are implementing a jig that is set by master bike frames, and then the cut parts must be mounted on the jig. The problem arises as perturbations in the jig setting affects the required length, bend, miter and position of the parts. The jig is being used as a mounting system for the parts as well as a gauge. To achieve the desired output, one must iterate between the four operations of cutting, bending, mitering and positioning. Many times, the final output is actually a compromise of the original specifications and what was dictated by the master frame.

The two approaches, Axiomatic Design and Kaizen, have their own relative strong points and weak points. In the evaluation of processes and systems, Axiomatic design focuses on the objectives of the system and therefore highlights the root causes of any deficiency. On the other hand, TBM and Kaizen focuses on monitoring the system and, consequently may chase symptoms instead of staying true to the system's objectives. Unfortunately, depending on the complexity of the system, determining what minimum number of FR's an existing system is supposed to satisfy can be very difficult and timely. This may result in an incorrect Axiomatic Design evaluation. However, further studies must be conducted to maximize the feedback from the two approaches described above, and then implement them in the design and control of manufacturing systems such as this.

3.3 Introduction to Lemco-Miller's Smart-Cell^{TM}

The "Smart-Cell^{TM}" project conducted at Lemco Miller Inc. was a joint effort by Lemco Miller employees, Valuetech Engineering, and M.I.T. to design and build a standardized manufacturing system in a job shop environment. M.I.T.'s intent was to design an ideal cell with characteristics similar to those of the steering gear manufacturing cell, described earlier in this chapter. Due to constraints in Lemco Miller's environment and their inability to critically evaluate and adhere to the design principles defined later on in this chapter, this goal was not achievable. The following is an evaluation of the project.

3.3.1 Steps In the Design of the Smart-Cell^{TM}

In designing the Smart-Cell^{TM}, the following steps were undertaken:

1. Recover/ Review Existing Engineering Processes, Tooling and Fixture data. A clear understanding of the current organization had to be achieved to know what would be possible. The traditional batch process was observed along with the plethora of tools, dedicated fixtures and vises.
2. Review/ Evaluation/ Selection of Part Numbers for manufacturing system. The cell was targeted to manufacture repeat or Kanban parts. Of Lemco Miller's selection of over 100 Kanban parts from 2 prime customers, 35 parts were eventually selected. They were chosen on the basis of size, similar geometry and manufacturing processes.
3. Review/ Evaluation/ Selection of Key Workcenters for manufacturing system. Initially, 6 machines were proposed for the cell on the basis of availability and presumed necessity. The machines were 2 lathes, one being CNC and the other a manual one, 3 machining centers, and one CNC Bridgeport. Eventually, however, part programming and routing indicated that the manual machines, the lathe and the Bridgeport were unnecessary. Other criteria for selection of the machines involved high spindle speeds and control for tapping, wide range of x-y-z machining travel, large machine table sizes and a fairly large tool capacity. The selected machines are

shown in table 3-3.

	VM40	VK45	L. Comet	HT25
Machine Type	V.mill	V.mill	V.mill	CNC lathe
# of Machines	1	1	1	2
# of Axes	3 axis			2
Table/Chuck Size	16"x30"	19"x44"	20"x50"	10"
X-travel	22"	40"	41.2"	9.3"
Y-travel	16"	20"	20.4"	20"
Z-travel	16"	20"	20.4"	24.4"
Indexable	<--------- Rotary --------->			
Fixturing	<--- T-slots & Sub-plate --->			
Spindle HP	7.5	10	15	25
RPM	6000	8000	8000	3600
Tool Capacity	20	30	20	10
Max. Tool diam.	3.7"	4.3"	6"	
Max Tool length	9.8"	11.8"	15"	
Touch Probe	x	x		
Tool Length Meas.	x	x		x

Table 3-3 Smart-Cell^{TM} Machine Data

4. Review/ Evaluate/ Select Standardized Tooling. All tools for the 35 jobs were documented. The list consisted of over 170 tools that posed a problem for the selected machines with small tool capacities on the order of 20 and 30 respectively. The implication was that tools needed to be swapped in and out depending on the job that was being run at the time. This would increase setup times to an extent that would not warrant single piece flow in a cellular manufacturing system. In addition, it was suspected that many of the tools were unnecessary. For instance, many could be eliminated by using smaller diameter tools to circle interpolate the tool paths of the larger tools. Many tool setups were required in producing a part as the majority of the machining would typically be performed on one machine. By implementing three or four machines in the manufacturing process, and having all parts flow through these machines, all the necessary tools could now be distributed in the four machines. The final tool selection, 70 tools, for the three machining centers is shown below in table. 3-4.

MACHINE 1: VM40 VERTICAL MILL (20 TOOLS)

	Dia.	Description		Dia.	Description
1.	3.000	Facemill Insert Cutter	11.	0.093	Endmill 4 Flute Carb. Ctrcut
2.	1.250	Endmill 4 Flute Carb Ctrcut	12.	0.359	Drill (23/64) 2 Flute Carb
3.	1.000	Endmill 4 Flute Carb Ctrcut	13.	0.332	Drill (LTR "Q") 2 Flute Carb
4.	0.750	Endmill 4 Flute Carb Ctrcut	14.	0.328	Drill (21/64) 2 Flute Carb
5.	0.500	Endmill 4 Flute Carb Ctrcut	15.	0.281	Drill (LTR "K") 2 Flute Carb
6.	0.375	Endmill 4 Flute Carb Ctrcut	16.	0.250	Drill (1/4) 2 Flute Carb
7.	0.250	Endmill 4 Flute Carb Ctrcut	17.	0.500	Spot Drill ½" x 90° Carb
8.	0.134	Endmill 4 Flute Carb Ctrcut	18.	0.500	Spot Drill ½" x 120 ° Carb
9.	0.125	Endmill 4 Flute Carb Ctrcut	19.	0.306	Dovetail Cutter (20 °) Carb
10.	0.109	Endmill 4 Flute Carb Ctrcut	20.	0.189	Dovetail Cutter (30 °) Carb

MACHINE 2: VK45 VERTICAL MILL (30 TOOLS)

	Dia.	Description		Dia.	Description
1.	0.266	Drill (LTR "H") 2 Flute Carb	16.	0.228	Drill (#1) 2 Flute Carb
2.		M8 x 1.25 Bottom Tap	17.	0.125	Drill (1/8) 2 Flute Carb
3.	0.257	Drill (LTR "F") 2 Flute Carb	18.	0.0995	Drill (#39) 2 Flute Carb
4.		5/16-18 UNC-2B Btm Tap	19.	0.750	Countersink ¾" x 90^0 Carb
5.	0.207	Drill (#7) 2 Flute Carb	20.	0.375	Countersink 3/8" x 90^0 Carb
6.		¼-20 UNC-2B Btm Tap	21.	0.2495	Reamer 4 Flute Carb
7.	0.159	Drill (#21) 2 Flute Carb	22.	0.500	Chamfer Endmill ½" x 90^0
8.		#10-32 UNC-2B Btm Tap	23.		
9.	0.136	Drill (#29) 2 Flute Carb	24.		
10.		#8-32 UNC-2B Btm Tap	25.		
11.	0.106	Drill (#36) 2 Flute Carb	26.		
12.		#6-32 UNC-2B Btm Tap	27.		
13.	0.250	Spot Drill ¼" x 90^0 Carb	28.		
14.	0.375	Spot Drill 3/8" x 120^0 Carb	29.		
15.	0.238	Drill (LTR "B") 2 Flute Carb	30.		

MACHINE 3: COMET-LG VERTICAL MILL (20 TOOLS)

	Dia.	Description		Dia.	Description
1.	5.000	Facemill Insert Cutter	11.	0.219	Drill (7/32) 2 Flute Carb
2.	1.000	Endmill 4 Flute Carb Ctrcut	12.	0.203	Drill (13/64) 2 Flute Carb
3.	0.750	Endmill 4 Flute Carb Ctrcut	13.	0.187	Drill (3/16) 2 Flute Carb
4.	0.625	Endmill 4 Flute Carb Ctrcut	14.	0.180	Drill (#15) 2 Flute Carb
5.	0.500	Endmill 4 Flute Carb Ctrcut	15.	0.177	Drill (#16) 2 Flute Carb
6.	0.3125	Endmill 4 Flute Carb Ctrcut	16.	0.140	Drill (#28) 2 Flute Carb
7.	0.187	Endmill 4 Flute Carb Ctrcut	17.	0.375	Spot Drill 3/8" x 90° Carb
8.	0.1719	Endmill 4 Flute Carb Ctrcut	18.	0.375	Spot Drill 3/8" x 120 ° Carb
9.	0.156	Endmill 4 Flute Carb Ctrcut	19.	0.306	Dovetail Cutter (20 °) Carb
10.	0.0625	Endmill 4 Flute Carb Ctrcut	20.	0.189	Dovetail Cutter (30 °) Carb

Table 3-4 Standard Tools Implemented in the Smart-Cell™

5. Select/ Design/ Manufacture Quick Change/ Standardized Fixturing. The work holding devices that have been implemented are discussed in chapter 5, Fixture Design. They consist of a combination of interchangeable sub-plates that attach to the tables of the machines, and Chick Qwik-Change fixtures and standard jaws that are mounted on the sub-plates.
6. Develop/ Standardize Engineering Process Routers for specific parts. The current process routers are generated by a multi-purpose software system called Job Boss. This package is used for quoting, scheduling production, documenting the routing, keeping track of inventory, and in general, monitoring the status of the production system. A number of assumptions and simplifications have been made to encompass all of these functions and as such, the software does not provide very true nor accurate data. Nonetheless, the software is very much tied into the running of the shop and thus is still being maintained for the routing. With regards to specifically standardizing the process routers for the Smart-Cell, the new router would display the typical flow of parts in the cell. These paths have been determined by considering the tools that should be loaded onto the machines to enable part flow and attempting to balance the amount of time and operations that are performed at each of the machines. The initial feedback is that there will be two paths that would be followed, either 1) VM40 to Comet to VK45 or 2) HT25 to VK45. The implementation of these two paths may actually create some confusion and is not recommended for cellular systems. In essence, the cell should simplify operations to the extent that all parts produced in the system follow one consistent route. Having two product-flows that culminate at one machine can lead to scheduling problems and bottlenecking. The decision to operate in this manner was based on the fact that the last machine has, thus far, a machine cycle time that is less than half that of the preceding machines and Lemco Miller prefers to have machines running than waiting. This is a direct violation of a cellular manufacturing system design principle. Perhaps another cell should be designed that would produce only the parts that require the route of turning first, on the HT25, and then machining on another VK45. This would allow the two cells to be independently

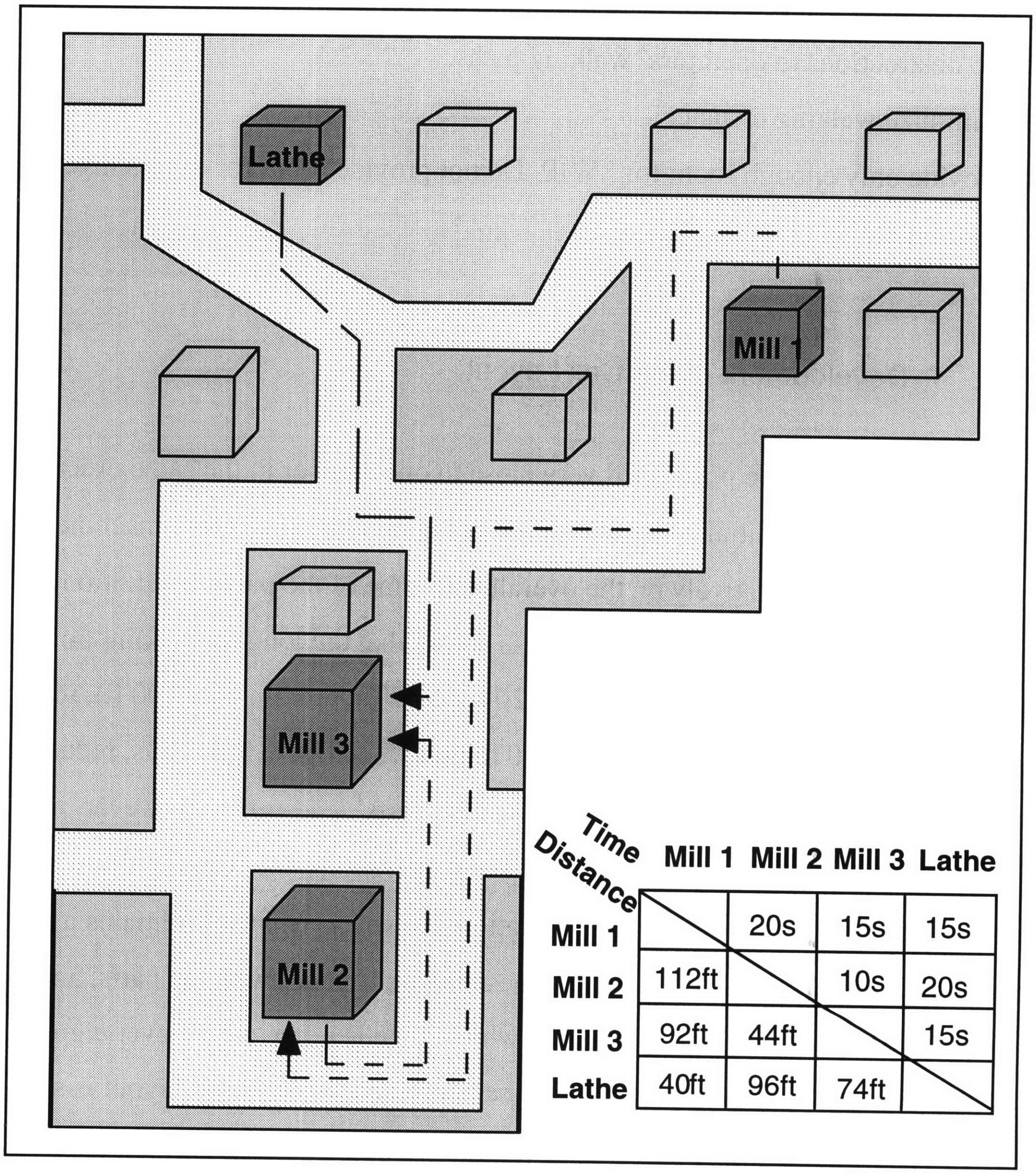
optimized to those families of parts instead of compromising one to accommodate both.

7. Develop/ Standardize Part Programs to incorporate standard tooling/ fixturing. Traditionally, programming was conducted with an old, text based system called Gemini. This software has now been replaced by a 3D-rendering CAM (Computer Aided Machining) package called Virtual Gibbs. The software allows users to scroll through the standard tools list, shown in Table 2, and not have to choose from an infinite library. Also, the software allows standard machining cycles, like drilling and tapping, to be saved and then accessed with the touch of a button. Knowing the standard fixture and sub-plate locations before hand also allows the programmer to more accurately and more quickly program the tool paths.
8. Prepare CAD (Computer Aided Design) Drawings incorporating new process/ tooling and fixturing. New CAD drawings for the 35 parts had to be prepared for purposes of importing into Virtual Gibbs, the CAM software. The idea behind this was to test the feasibility of programming tool paths in the CAM package directly from the customer supplied CAD drawing. This was a success. In addition, tooling and fixturing drawings had to be prepared and documented. Some of these drawings are found in chapter 5, Fixture Design.
9. Establish Standard Procedures for manufacturing system**.** Some of the standards that have been conveyed by M.I.T. are discussed below. Lemco Miller's Smart-Cell^{TM} does not adhere to any of these:
    1) One part type seizes all of the cell's resources at a time.
    2) A part may skip a machine in the cell, but there should be no backtracking.
    3) It is acceptable for some machines to wait.
    4) Always perform single piece flow.
    5) Conform to standard work operations for each part, regardless of their sequence of production.
    6) Rolling changeover is allowed, abiding by rule 1).
    7) Perform External Setup (while machine is running) as much as possible.

8) Volume flexibility by varying number of workers.
9) Standing, walking workers as opposed to seated, stationary workers.
10) No workers are isolated.
11) Each worker can see each operation.
12) No obstructions to operators' walking paths.
13) Minimize walking distance.
14) Provide only enough room for SWIP. Do not provide room for excess inventory to accumulate.

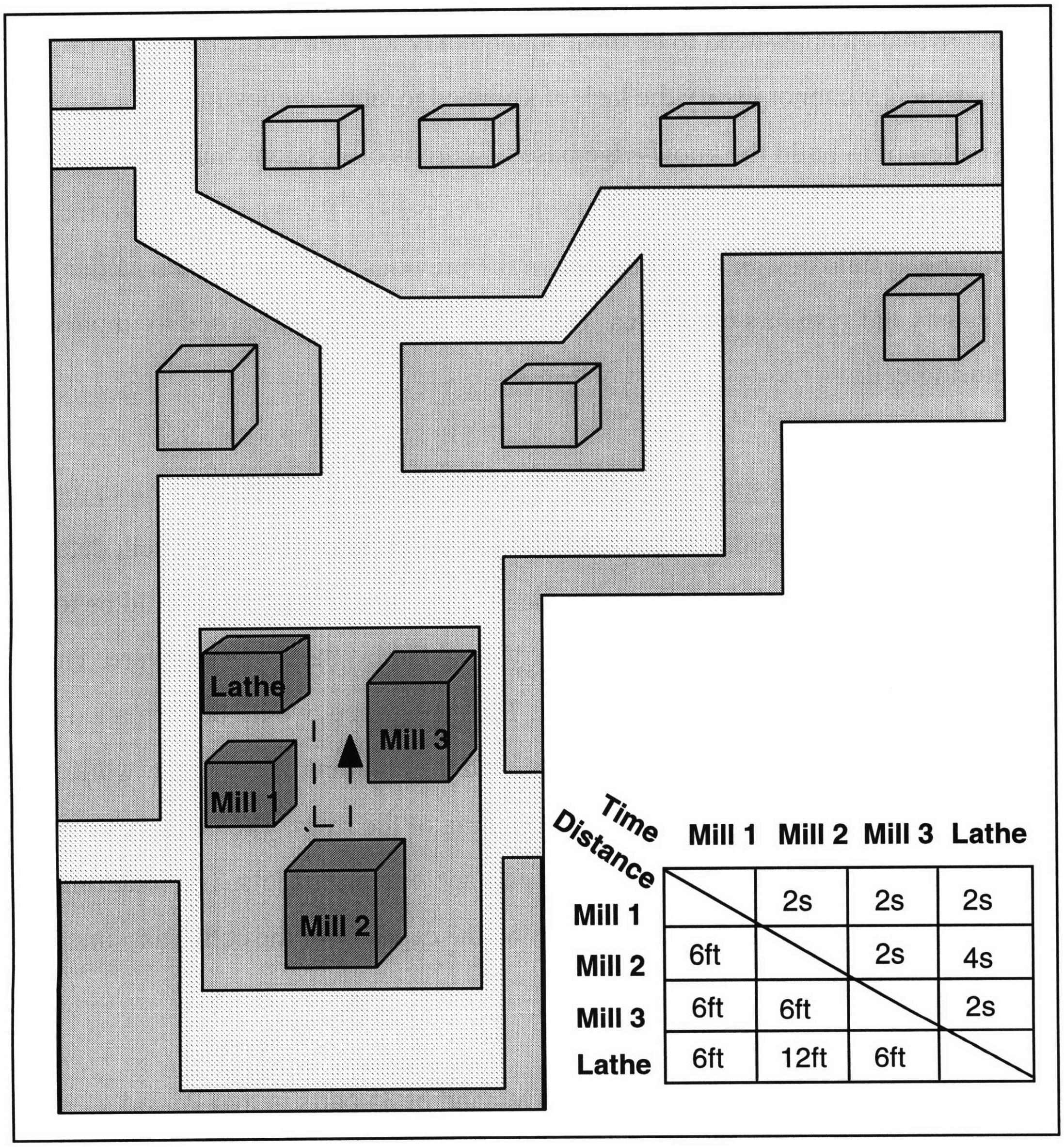
3.3.2 Development of the Cell Layout.

Ideally, machines should be positioned very close to one another in the same order as the processes. However, the initial constraint of not being able to move these machines closer together would impact negatively on the overall lead-time of the parts, in addition to wearing out the operators. Preliminary analysis shows that the longest walking time between any two machines is approximately 20 seconds (approximately 100 ft), relative to a present machine/operator cycle time of 10 minutes, see figure 3-5. Thus, reducing this walking time would not significantly reduce the parts' lead-times. However, if the cycle time were to be reduced later through Kaizen operations, the walking times may become more detrimental to the "cell's" operation. However, what still remains a problem is the stress on the worker to walk these large distances with the parts, and, in some cases, with the fixtures and sub-plates, which, together, can weigh over eighty pounds. Material handling therefore needs to be addressed. A proposed layout is shown in figure 3-6.



Time / Distance	Mill 1	Mill 2	Mill 3	Lathe
Mill 1		20s	15s	15s
Mill 2	112ft		10s	20s
Mill 3	92ft	44ft		15s
Lathe	40ft	96ft	74ft	

Figure 3-5 Current Cell Layout



Time / Distance	Mill 1	Mill 2	Mill 3	Lathe
Mill 1		2s	2s	2s
Mill 2	6ft		2s	4s
Mill 3	6ft	6ft		2s
Lathe	6ft	12ft	6ft	

Figure 3-6 Proposed Cell Layout

3.3.3 Conclusions on Smart-Cell^{TM} and Future Work

The design of large manufacturing systems is not trivial. Problems arise as companies acknowledge that changes need to be made and quickly introduce concepts on an ad-hoc basis. "Expediency cannot justify the lack of knowledge, and urgency must not sidetrack an honest attempt to build the knowledge base. Rigorous discussions must prevail over quick judgements in efforts of this kind" [Suh, 1990, p 391]. By not adhering to the manufacturing system design steps outlined in the previous sections, Lemco Miller has failed to satisfy the system's objectives. The following steps are proposed to improve the manufacturing cell:

1. Development of Excel spreadsheet on a Tool-Machine specific basis relative to part numbers. In an effort to determine the "drum-beat" or Takt time of the cell, data must be gathered on the machining times for the 35 parts. One possibility would be to analyze the cut time per tool generated by Virtual Gibbs, the CAM software. This data may be compared in an excel spreadsheet. The spreadsheet would be formatted such that the machines and corresponding tools head the columns of the sheet, while the part numbers descend on the left at the beginning of the rows. The cut-times would fill the cells corresponding to a particular part and one of its tools. The total times may then be compared and used to determine the capacity of the cell. Takt time according to the equation:

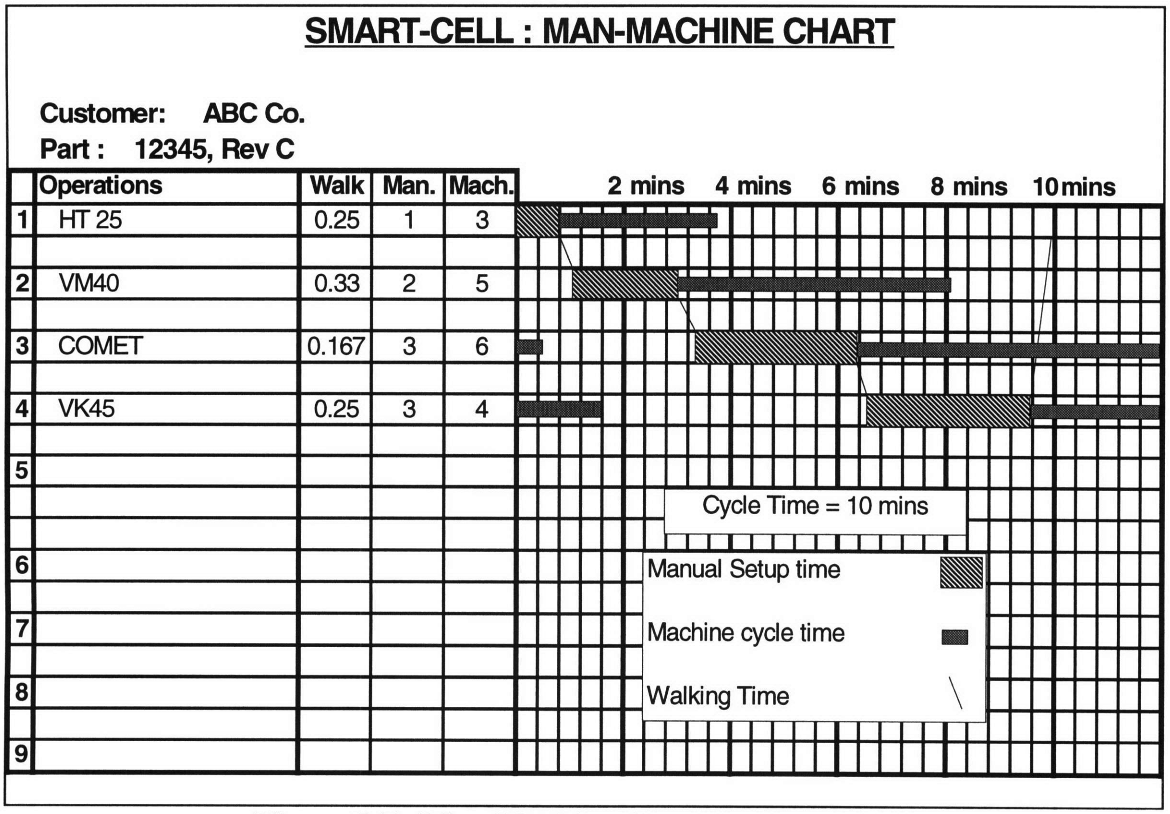
   Takt Time = Available Time per Period/ Demand of 35 parts in that Period

   may be calculated by considering the 35 parts' monthly demands, their machining times, and the available run times of the cell. This value can be used to help schedule parts to the cell and identify excess capacity.

2. Development of man-machine charts for the 35 parts in the cell. A man-machine operating sequence chart is needed to illustrate the sequence and timing of manual

operations, such as loading, unloading, walking, and setup, as well as the machines' processing times. An example of this chart is illustrated in figure 3-7.

- Estimate load/unload times and thus determine need for quick-change tools and fixtures.
- Estimate walking time between machines.
- Estimate machining time (Input from CAM system & matrix in number 2)



SMART-CELL : MAN-MACHINE CHART

Customer: ABC Co.
Part : 12345, Rev C

	Operations	Walk	Man.	Mach.
1	HT 25	0.25	1	3
2	VM40	0.33	2	5
3	COMET	0.167	3	6
4	VK45	0.25	3	4
5				
6				
7				
8				
9				

Figure 3-7 Man-Machine Chart for Smart-Cell

1. Look upstream and downstream of the 35 identified parts. For many of the parts additional operations are necessary, both prior to and after processing through the cell. These operations include both internal ones (such as preparing, deburring, grinding inspection) and external ones (raw material purchase, and coating). How these operations are tied in to the single-piece-flow, Kanban operations need to be determined.

2. Conduct Pilot Run in phases. Like most new concepts and systems, it takes time and effort to implement. The new manufacturing cell should be implemented in phases, starting off with the targeted 35 parts. The cell should be optimized for these parts before it is benchmarked and applied to all parts in the manufacturing system.

3. Identify Training Requirements. It is essential to understand that workers are the greatest obstacles to overcome in the implementation of new manufacturing systems. Machines may be purchased, processes changed, and flows reconfigured. However, in the end, the operators need to be trained to operate the system, not the managers.

4. Conduct Training as required. Simply acknowledging workers inefficiencies and incapabilities is not sufficient. Effort must be made to educate them.

5. Transition to Manufacturing. Once the concepts have been proven successful and both operators and managers are content with the pilot cell can there be a transition to manufacturing. If this transition is conducted prematurely customer attributes, such as quality, delivery time, and cost, may not be satisfied. The result is the obvious, damaging reputation, lost of customers, and even closure of the business.

3.4 Conclusions

This chapter presented three examples of manufacturing sub-systems at a cellular level. The first represented a brief description of a "picture-perfect" cell that is involved in the manufacture of steering gears. Following this, the machining cell at Merlin Metalwork's Inc. was evaluated using two tools: Axiomatic Design and Time Based Management. The principles of Axiomatic Design indicated coupling and non-fulfillment of certain cell requirements. Time Based Management proposed metrics that may be used to quantify inefficiencies in the cell, however there was no distinct solution to the problems. However, further studies must be conducted to maximize the feedback from the two approaches described above, and then implement them in the design and control of manufacturing systems such as this. Finally, the third evaluation was conducted on an attempt to apply cellular manufacturing in Lemco-Miller's job-shop. This attempt demonstrated how industry's constraints and mis-interpretation of manufacturing system design principles often inhibit successful cell design. Principles and guidelines were proposed to aid the process of designing and evaluating the new manufacturing system. Sufficient time, critical analysis, and a thorough understanding of the principles for manufacturing system design are recommended for success.

CHAPTER 4

MACHINE DESIGN

4.0 Introduction

This chapter representes a description of a custom machine design that the author conducted for Merlin Metalworks Inc. The case study demonstrates issues that companies must address in deciding on making or buying any machinery that will be used in their manufacturing process.

4.1 Background

Due to the concern of the apparent depletion of the ozone layer in our atmosphere, the Clean Air Act has eliminated production of ozone depleting chemicals in 1995. The Freon that was used in Merlin's vapor degreaser was one such chemical. The vapor degreaser was instrumental in cleaning the titanium parts prior to welding of the bike frame. Merlin was thus faced with the following options:

1. Retrofit the old vapor degreaser so that it could utilize solvents that are not banned. The downside to this approach is that these solvents are classified as hazardous and require special handling and health considerations. In addition, it will be costly to upgrade the system to include increasing temperatures and vapor retention. In the long run, high solvent costs may also impact on the operating costs of the company.
2. Another option would be to purchase an aqueous or semi-aqueous cleaning system. These systems essentially use soap (cleaners with surfactants) to attack and loosen dirt and water to rinse it away. Most of these systems also have heaters or vacuum equipment to dry parts because aqueous cleaners evaporate slowly. The aqueous cleaning process however is a lengthier process than vapor degreasing, and the final quality of cleanliness is usually less.
3. The third option would be to custom build an aqueous cleaner. These systems are relatively simple and inexpensive to build, as opposed to purchasing one that generally is very expensive, long lead time, and not necessarily suitable for the cell's parts or layout.

The third option was considered the most feasible one to pursue. The first two would require substantial capital investment, long turn around time, and unnecessary features and options.

4.2 The Design & Development Process

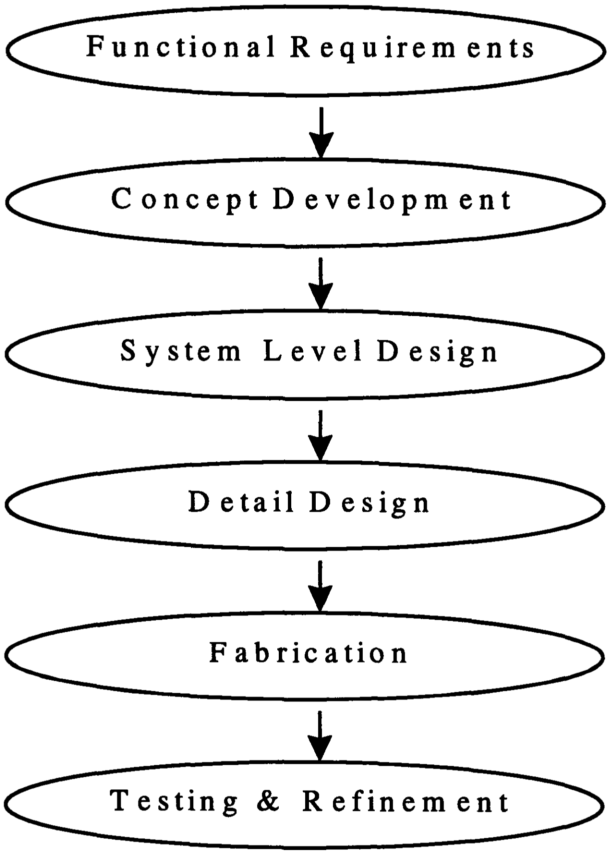


Figure 4-1 The Design & Development Process

The first stage, and probably most important, of the design process consisted of understanding the functional requirements of the cleaning system, for instance what level of cleanliness was desired. A cleaning and testing protocol was set up that determined the cleanliness levels indirectly. This protocol simulated the manufacturing process of contaminating the titanium parts, cleaning them, and then welding them together to make up the bike frame. The sample tubes were cleaned under various conditions and with different cleaning solutions, welded, and then subjected to tensile tests to observe their breaking points. The results from these tests were untimely however, and the development process proceeded based on perceived cleaning requirements.

The next phase, the concept generation phase, consisted of prescribing preliminary design parameters for the design requirements. Many existing aqueous cleaning systems were studied to aid the development of ideas. Having decided on a particular concept, a system-level design was conducted. At this point, an understanding of how the various components would interface with one another and their impact on the entire system was made. Contact with suppliers and pricing of components was also performed. The timeline for the project was very aggressive and thus vendors needed to be contacted early. In the detail design phase machining and assembly drawings were made. The design fabrication phase consisted primarily of assembly as many of the components were purchased and cut to size. Assembly operations also involved welding, which was performed in house by one of Merlin's welders, and soon after, tests and adjustments were made.

This entire process spanned two months with a total expenditure of under ten thousand dollars. Comparable systems were priced at approximately fifteen thousand, with a six month turn around period.

4.3 The Design

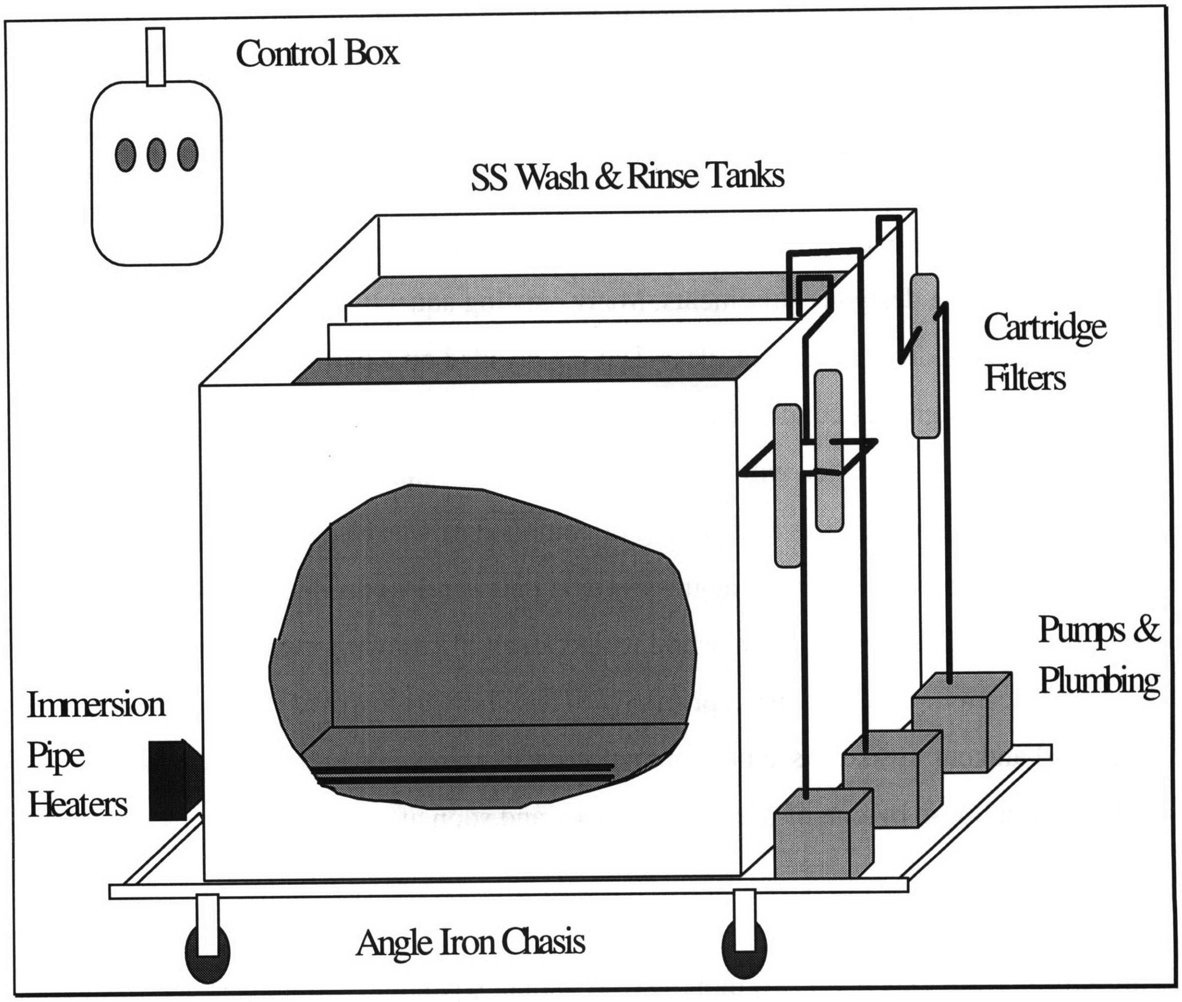


Figure 4-2 Custom Designed Aqueous Cleaning System

The custom-designed cleaning system essentially consisted of a wash tank and a rinse tank. Parts, mounted on a basket, were placed in a soap solution in the wash and then rinsed in the rinse tank. To aid the cleaning process, both tanks were heated, agitated and filtered constantly. A reverse osmosis water system was also installed to supply the tanks with clean, de-mineralized water. These components are described in detail below, followed by the operating instructions.

A. Parts Container / Basket

The basket for supporting the parts in the cleaner was designed to satisfy the following functional requirements:

FR1: Must be able to contain all the parts that comprise a bike frame (Road or Mountain bike frame)

FR2: Must support the tubes vertically to facilitate draining of solution on removal.

FR3: Must be able to contain small parts such as drop-outs, brake bosses etc.

FR4: Must not allow tubes or other parts to escape the basket whilst inside the cleaning system.

On investigation, the tubes that comprised both road and mountain bike frames were never longer than 26 inches, implying a basket height in that range. A typical frame consisted of 3 straight, long (<26"), large diameter tubes; four bent, smaller diameter, medium length (13" - 17") tubes; and 2 other short (approx. 6"), but large diameter (2") tubes. Finally, there were smaller parts that needed to be cleaned as well; such as the drop-outs (see bike frame figure 3-2). The design of the parts basket that held the above frame components is illustrated below. The basket is approximately 8" x 8" square, and 40" tall, for easy insertion into the deep tanks. There are three horizontal grid patterns in which tubes are located. Tall tubes are placed vertically in the four middle squares, whilst the shorter, bent tubes are placed on the outside squares. Two wire mesh baskets (not shown) are attached at the bottom and top, for holding smaller tubes and parts.

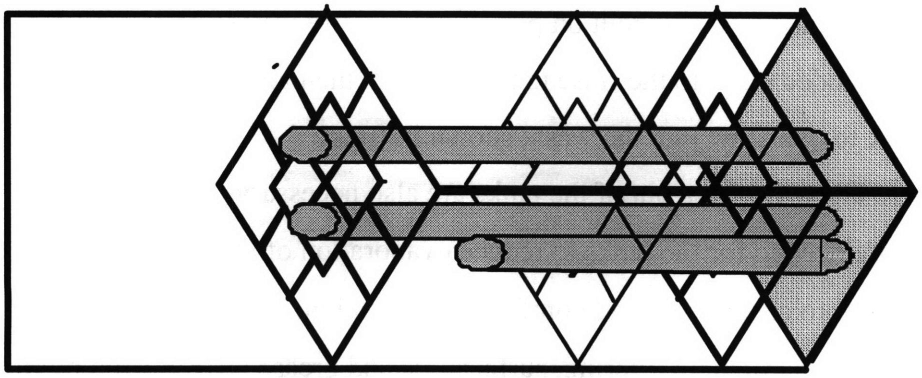


Figure 4-3 Stainless Steel Parts' Basket

B. The Wash & Rinse Tanks

The primary function of the wash tank was to clean the parts in the aqueous cleaning solution. The rinse tank was used to remove any remaining particles and soap solution from the parts after they were removed from the wash. These functions were accomplished by decomposition into several other sub-functions:

1. The wash and rinse tanks must contain sufficient cleaning solution to allow complete immersion of the parts. The geometry of the tanks was therefore determined by the fact that the longest tube was approx. 26", and the tanks needed to accommodate half of an already assembled bike frame. These were the main factors that drove the current design to be a rectangular tank, 3' long, 2' wide, and 4' deep, with a separating wall in the middle for the wash and rinse compartments.
2. The wash and rinse solutions needed to be heated and maintained at a temperature of approx. 150°F to facilitate proper cleaning and drying of parts. (See the Heating System section)
3. The solutions needed to be agitated to aid the cleaning of the parts. This was achieved by using a 1/3 HP pump for each compartment to recirculate the solutions at high velocity.
4. Recycling and filtration of the solution must be performed to remove dirt particles (See the Plumbing Section)
5. The need for water and soap replenishing systems to compensate for their removal due to evaporation and dragout on part removal. Pure water, from a reverse osmosis system, is added daily to the rinse tank. A "weir" then allows pure water from the rinse tank to overflow into the wash, shown in figure 4-4.
6. Drains to allow flushing out of the tanks are also necessary features.
7. Covers are needed for the tanks to reduce evaporation of the solution and, more importantly, to ensure safe and comfortable operation.
8. In addition to particulate filtering, surface oils and grease are removed by runoff into the weir, figure 4-4.

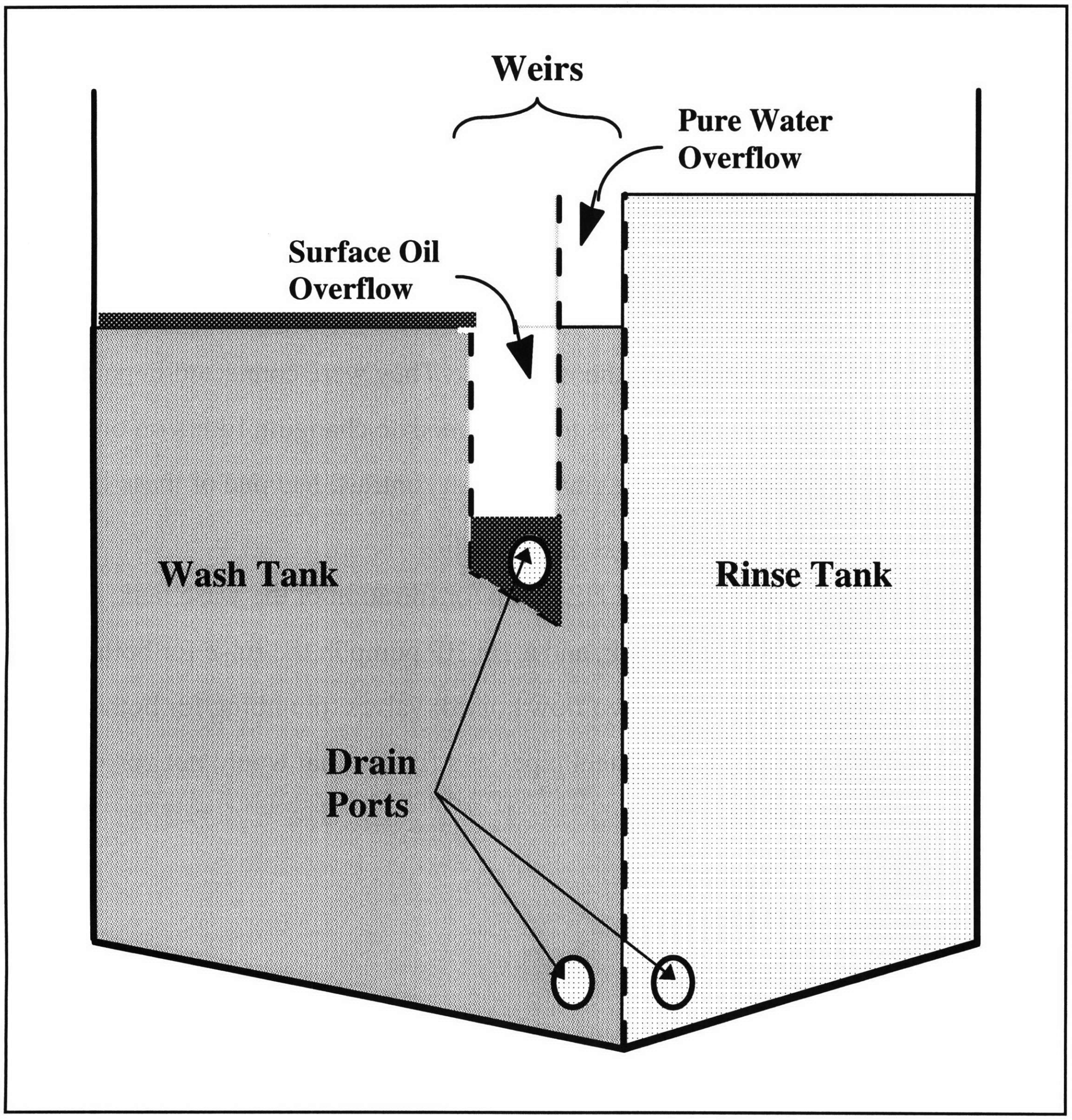


Figure 4-4 Cross-Sectional View of Wash & Rinse Tanks

D. The Heating System

Heating of both the wash and rinse tanks were achieved by pipe-plug immersion heaters. Strip heaters were also considered, however, their lower relative efficiency as well as the greater inaccuracy in holding steady state temperatures did not warrant their lower initial costs. The pipe-plug heaters, one in each tank, were mounted horizontally near the bottom of the tank. The electrical connections were placed on the left side of the tanks while the plumbing, pumps and filters were on the right. These heaters were purchased from

Merrimac Industrial Sales Inc.

E. The Filters, Pumps & Plumbing

Both the wash and rinse tanks required filtration of particulates such as dirt and other insolubles. The wash tank will see more oils and particulates than the rinse tank. Due to this, more filtration was performed in the wash tank. Two cartridge filters, 20 micron resolution, were used for filtration on the wash tank. They were connected in parallel to allow high filtration flow rates as well as to accommodate changing filters on one whilst the other would be allowed to run. The rinse tank, in contrast, had one of these filters.

Three pumps were implemented; a 1/2 HP pump for filtration of the wash tank, a 1/3 HP pump for the agitation of the wash tank, and a 1/3 HP pump in the rinse for both filtration and agitation. With the exception of two flow control valves, plumbing for both the wash and rinse tanks consisted of stainless steel pipes and fittings that would not corrode and thus not contaminate the tanks.

F. Control Panel

A NEMA enclosure was used to house the electrical circuits. It contained a main breaker for the entire cleaning system, an automatic timer, and switches for the pumps. The timer was used to automatically switch the heaters on 5 days a week, 2 hours prior to the work start time. This ensured that the wash and rinse solutions were at the optimum temperature when the workers arrived. In contrast, the pump switches were attached on the outside of the enclosure for quick and easy access. These pumps would only need to be switched on when parts were being washed.

G. RO Water System

A reverse osmosis water treatment system was installed to provide water of the required purity level. This system ran continuously off the main water supply, and stored the treated water in a bladder vessel. When full, the unit would shut down. The bladder vessel would then be used for adding pure water to the tanks. This system was provide and will be supported by Atlas Water Systems.

H. Cleaning Solution

A Daraclean soap was prescribed by W.R. Grace & Co. for conducting the necessary cleaning. The soap is non-toxic and non-foaming when used at 10% concentration with pure water. Cleaning capacity of the soap is fairly high and fresh batches can probably be added once a month, depending on the contaminants. integrity of the wash

OPERATION

- Make sure the pumps are on and the wash and rinse tanks are at 150 degrees.
- Only stainless steel and titanium parts should come in contact with the wash and rinse solutions. Anything else may react with and contaminate the solutions.
- Load the basket with titanium parts that are to be cleaned. Care should be taken not to overload or poorly place parts in the basket as they may fall into the tanks.
- Remove cover from wash tank, place basket with parts into the tank, and recover. Leave in wash for approximately 10 mins.
- Remove cover from rinse tank, place basket with parts into the tank, and recover. Leave in rinse for approximately 1min.
- Remove basket with parts, recover tank and allow parts to dry. (Fan or other drying system may be used to expedite the drying process)
- Turn pumps off at the end of the day. (Heaters automatically shut down)

4.4 Conclusions

This chapter provided a technical description of a custom-machine-design that the author conducted for Merlin Metalworks Inc. The custom-design had the advantages of low cost, on the order of ten thousand dollars, and a short lead time of two months, respectively. Implementation of the cleaning system has also been successful, satisfying the fundamental needs of a production cleaning system. The decision to make a right-sized, custom-designed cleaner was a correct one. Purchasing a cleaning system would have resulted in either an unsuitable system or one that would have had an enormous lead time and high expense.

Although the design and development process progressed without the implementation of the principles of Axiomatic Design, the exercise was conducted methodically, as shown. However, in the absence of the axioms there was no formal way to evaluate the design throughout its design and development stages. Only when proposed designs can be analyzed will the design process converge to a solution quickly.

CHAPTER 5

FIXTURE DESIGN

5.0 INTRODUCTION

This chapter presents some fundamental issues involved in the design of jigs and fixtures. The fixture is a device for holding and locating work while operations are being performed, whereas the jig is not only a device for holding and locating work, but it also guides the tool performing the operation. The approach is to provide the criteria for appropriate design observations and examples, followed by concluding remarks and rules. With this in mind, a detailed study on the design of a fixture to facilitate a machining operation will be initially presented. The case study also implements the Axiomatic Design methodology as a tool to facilitate the design process. Following this, another example will be presented on some of the work-holding issues encountered in a job-shop. The chapter will then conclude with some basic rules on the design of jigs and fixtures.

5.1 Fixture Design at Merlin Metalworks Inc.

Merlin Metalwork's Inc. is a titanium bicycle frame manufacturer. Within the last few years the company has been trying to improve their manufacturing cost and customer response by adopting a cellular manufacturing layout, as discussed in chapter three, cell design. One of the issues that has received the most attention has been the problem of reducing set-up time on a number of the existing operations. The benefits of reducing set-up time are immediately apparent and thus very attractive as a solution to many of the problems. The following section addresses a design of a fixture for set-up reduction. The principles of Axiomatic Design are implemented to illustrate the analytical power and decision making capabilities of Axiomatic Design.

5.1.1 Background & Problem Definition

A bike drop-out (DO) is that part of the bike at which the rear wheel is attached. The dropout is fixed to the frame by welds at the seat-stays (SS) and chain-stays (CS) respectively, see figure 5-1. The drop-outs are generally of two types, those for road bikes and those for mountain bikes. Depending on the size of the particular type of bike, the relative location of the stays with the drop-out may vary, particularly in the angles between the seat-stay and the chain-stay. To ensure proper alignment and fit between the stays and the drop-out, the latter must be machined accordingly. Figure 5-2 illustrates the necessary alignment between the stays and a machined drop-out. This machining is referred to as mitering.

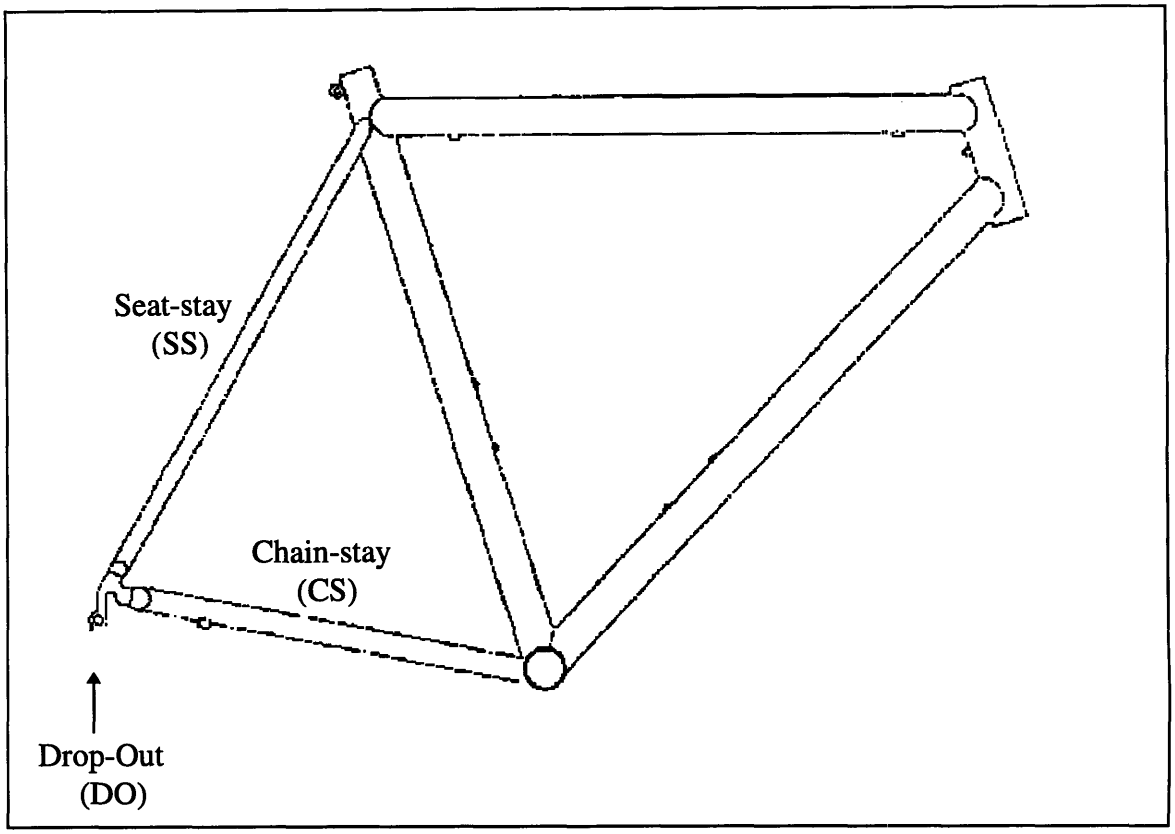


Figure 5-1 Drop-Out Location on Bike Frame

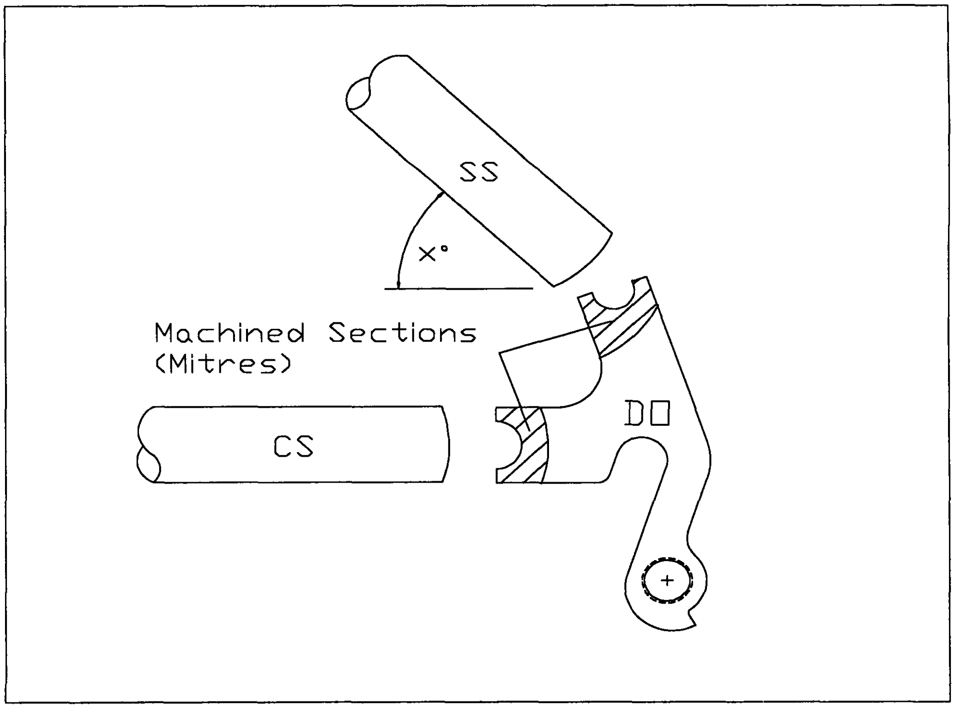


Figure 5-2 DO-SS-CS Match-up

Previously, many aspects of the mitering operation were performed in the absence of accurate tools. Depending on the particular diameter of the SS or CS that was to mesh with the drop-out, a hole-saw of corresponding diameter was chosen. Two DO's were placed together, face-to-face, so that a pair may be mitered simultaneously **and** consistently. A spacer may be required to separate the DO's to the correct width that was equivalent to the diameter of the hole-saw, see figure 5-3. The pair of DO's and the spacer would then be positioned between the jaws of a vice, adjustments continuously being made to align the DO's with each other, as well as with the hole-saw. The angle between the axis of the hole-saw and the surface of the DO's had to be set, usually by eye, however, from time-to-time, a protractor was used. In addition, the DO-pair had to be positioned in the center of the hole-saw and then mitered to a particular depth, again, all of which was performed by eye-balling.

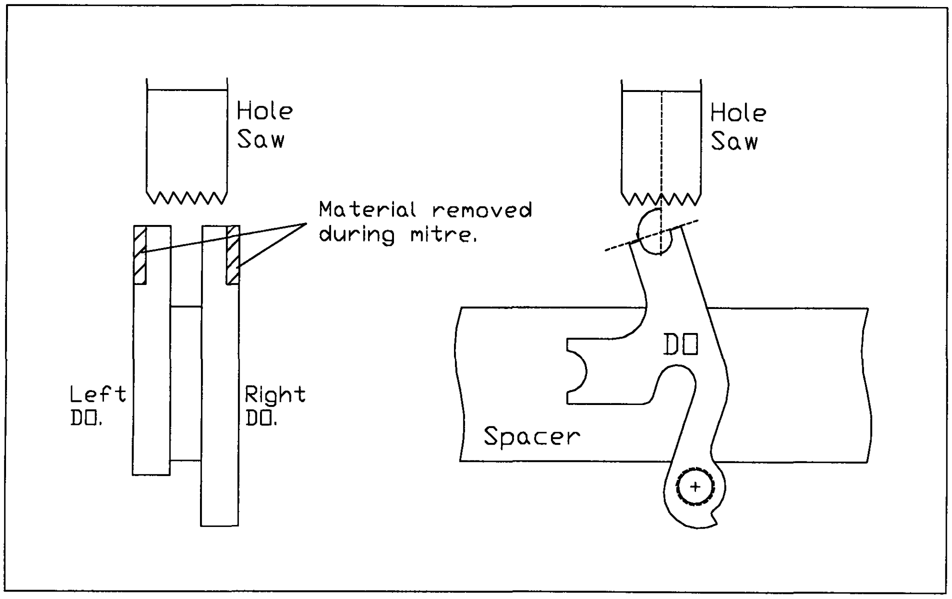


Figure 5-3 Typical DO Mitering Operation

The previous mitering operation had several fundamental problems. Due to the lack of utilization of tools, the mitered part was often imperfect; wrong depth, incorrect miter angle, and off-center miter were some typical problems. Thus, a lot of time went into positioning. Iterations between cutting, re-orienting the Drop-Outs, and moving the table were very common, and this resulted in long cycle times between 6-12 minutes.

To reduce the cycle time and increase accuracy, a fixture design was proposed. It is important to emphasize that the effort to solve the problem was focused on utilizing the existing parts and practices. One may be tempted to redesign the drop-outs and/or the interface between the stays. In fact, new DO's have been designed such that they do not require mitering; they comprise of small tabs at the ends which simply fit into pockets in the stays, the relative angle between the DO and the stay accounted for by pivoting about the tab. However, the objective here was not to redesign the product but to design a fixture to improve the process. Thus, to state concisely, the objective here was to design a fixture that allowed accurate mitering of the existing drop-outs as well as reduce the cycle-time to approximately one minute.

5.1.2 The First Design Approach

Design has always been perceived as a creative, ad-hoc process. It is one of the few technical areas where experience is more important than formal education [I}. In solving the problem outlined above, there was no formal methodology that was adopted. Instead, the following may be regarded as a general practice and one which was adopted by the author.

- Study of the Existing Operation. As already described, the existing operation was extremely inaccurate and under-designed. Nevertheless, there was valuable information to be gained, such as major requirements for the new design and resolving the issues of integrating the new fixture into the flow or process in the cell.
- Formulate Major Design Goals. These were specified by the customer, in this case, the manufacturing company, as well as deduced from studies on the existing system, as explained above. They can be stated as:
    - *Orient DO's appropriately (i.e.: no machine adjustments)*

- *Allow for both Mountain & Road DO's*
- *Clamp drop-outs (DO's) securely*
- *Be unable to load incorrectly*
- *Ease of loading & Unloading*
- *Minimal pieces of tools required to operate*
- *CS miter @ 90 degrees, 0.3" depth*
- *55 miter 80 - 100 degrees, 0.3" depth*
- *Miter for varying diam. stays (i.e.: use spacers...)*
- *Total Cycle Time approx. 60 secs.*

- Brainstorm, Conceptualize. Knowing the requirements of the new design, we then began the brainstorming phase. The problem that was encountered here, however, is knowing which requirements should be focused on initially, and knowing when certain ideas should be pursued and when they should be neglected. It is this phase of the entire design process that is least understood and which is mostly attributed to the creativity and experience of the designer. It will be shown later that the principles of Axiomatic Design prove to be very useful in structuring and systematically navigating through this phase.

5.1.3 The Final Fixture Design

The final fixture design consists of one main fixture in which four other sub-fixtures mount. The main fixture is fixed in the jaws of a vice on a drill press. The sub-fixtures then drop vertically into a pin-slot in the main fixture. The primary purpose of this main fixture is to enable rotation of the sub-fixtures about the pin slot. There is also a graduated steel insert that has pin holes in 1 degree increments. The sub-fixtures can then be positioned with respect to these holes, see figure 5-4.

Three of the four sub-fixtures are used for mitering the seat-stay ends of the drop-outs. The fourth one is used for chain-stay mitering only. The primary purpose of these sub-fixtures is to align and secure the drop-outs, for both road and mountain bikes, prior to their mitering operation. The sub-fixtures contain locating pins and locking pins that enable this. In addition, the design is mistake-proofed to prevent the incorrect loading of the drop-outs. Figures 5-5 and 5-6 illustrate these sub-fixtures.

The three seat-stay mitering fixtures have handles that are used to align with the pin-holes on the steel insert of the main fixture. These are used to select the angle of miter on the seat-stay ends of the drop-outs; between 80 - 100 degrees. The chain-stay drop-out fixture does not have a handle to adjust its angle as chain-stay mitering is always performed at an angle of 90 degrees. There are three sub-fixtures for the seat-stay operations as this job requires three different spacings between the drop-outs. This spacing is provided by the shims. Similarly, the chain-stay mitering sub-fixture contains a shim that sets the spacing between the drop-out parts.

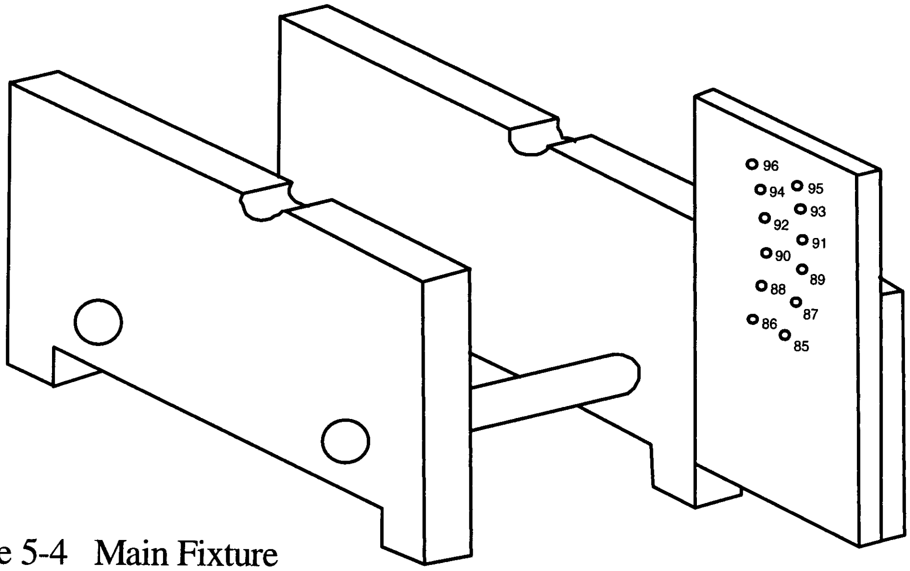


Figure 5-4 Main Fixture

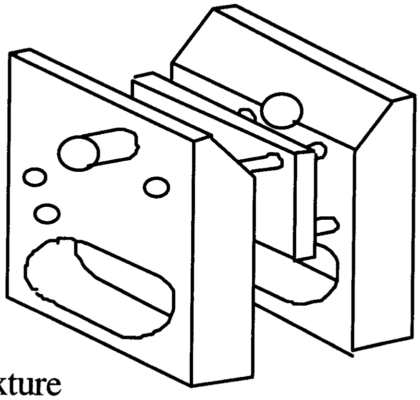


Figure 5-5 CS Sub-fixture

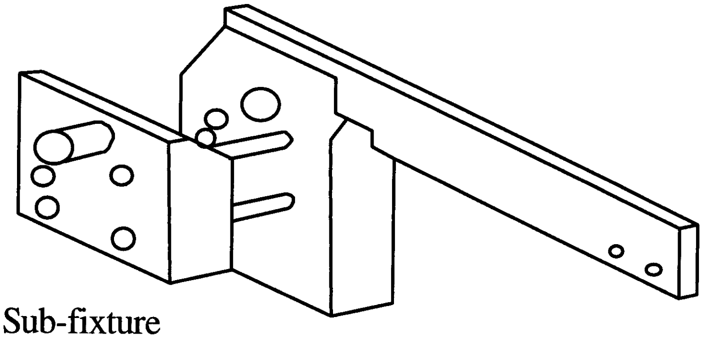


Figure 5-6 SS Sub-fixture

5.1.4 Axiomatic Design Analysis of Fixture Design

The drop-out fixture design may be decomposed into the top level functional requirements as follows:

FR1: Position DO's
FR2: Vary angle
FR3: Miter DO's
Constraint 1: Reduce cycle time to 60 secs.

These FR's can be independently satisfied by choosing the following design parameters:

DP1: DO Positioner Sub-fixture
DP2: Angle Adjuster System
DP3: Vertical Hole-Saw Cutter

The rigors of the first axiom, that is, maintaining independence of the functional requirements, allows the DP's to be chosen so that an uncoupled design matrix connecting the two is obtained. In this analysis however, the DP's have already been determined and are being mapped onto the desired FR's to check their validity. The current design may be represented as:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$

After deciding on the upper-level DP's as above, the upper-level FR's may be decomposed into more specific FR's. These are then mapped onto the appropriate DP's according to the first axiom. This decomposition is repeated to form a hierarchy, the size of which, is determined by the desired specificity. The results are as follows:

The DO Positioner Sub-fixture (DP1):

FR11: Position DO's for CS Miter	DP11: CS Sub-fixture

FR12: Position DO's for SS Miter	DP12: SS Sub-fixture
FR13: Secure DO's for Miter	DP13: Clamp (vice)
FR14: Prevent Incorrect Loading	DP14: Poka-Yoke Pins

Constraint 2: Prevent Table Movements/ Adjustments

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \end{Bmatrix} = \begin{bmatrix} X & O & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \end{Bmatrix}$$

The CS sub-fixture (DP11) and the SS sub-fixture (DP12) contain similar sub-levels:

FR1x1: Position for Road DO	DPlxl: Locating Pins	
FRlx2: Position for Mountain DO	DP1x2: Locating Pins	(x = 1, 2)
FRlx3: Correctly space DO's	DPIx3: Shims (spacer)	

$$\begin{Bmatrix} FR1x1 \\ FR1x2 \\ FR1x3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1x1 \\ DP1x2 \\ DP1x3 \end{Bmatrix}$$

The locating pins mentioned above, DP1x1 and DP1x2, were physically integrated, as per corollary 3 of the Axiomatic Design methodology. This does not imply the occurrence of functional coupling. The positioning of road DO's and the positioning of mountain DO's are never performed simultaneously and thus are still being independently satisfied by the same locating pins in the sub-fixture. This is an example of physical coupling or integration of DP's.

Decomposing the Angle Adjuster System (DP2):

FR21: Vary SS angle between 80^0-100^0	DP21: Pin to cavities at selected angles
FR22: Fix CS angle at 900	DP22: Rest sub-fixture perpendicular to table
FR23: Fix virtual center of DO with respect to the hole-saw axis	DP23: U-shaped Virtual Center locator

$$\begin{Bmatrix} FR21 \\ FR22 \\ FR23 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP21 \\ DP22 \\ DP23 \end{Bmatrix}$$

Decomposing the Hole-Saw Cutter (DP3):

FR31: Cut to 3 different diameters	DP31: 3 hole-saws of desired diameters
FR32: Cut to 0.3" depth	DP32: Set 0.3" stop on cutter

$$\begin{Bmatrix} FR31 \\ FR32 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP31 \\ DP32 \end{Bmatrix}$$

The design matrix obtained for the hole-saw sub-system is a decoupled one. This is due to the fact that the 0.3" depth cut, FR32, is influenced by both the size of the hole-saw, DP31, and where the stop is set on the drill machine, DP32. There are three hole-saws employed in this operation, and thus three different stop set-points needed. Nonetheless, this decoupled scenario indicates that success is still obtained by adjusting the stop after determining the size of the hole-saw, and not vice-versa.

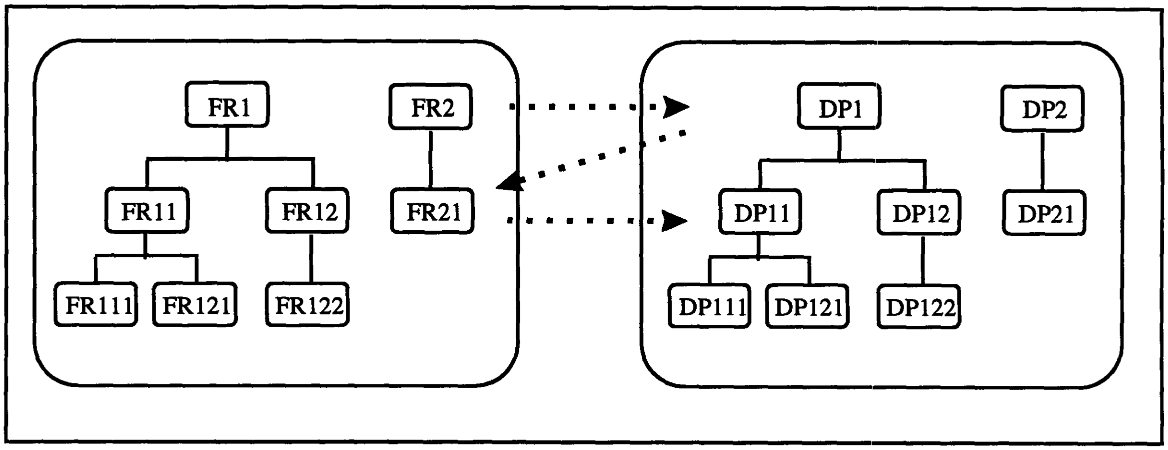


Figure 5-7 Hierarchical Tree Structure of Functional Requirements & Design Parameters

5.1.5 Conclusions On Drop-Out Fixture Design

Axiomatic Design illustrated that the drop-out fixture design described above was uncoupled and therefore acceptable. The fixture's performance in the machining cell has also been admirable. The fixture satisfied all the major targets, while achieving enormous improvements in accuracy and cycle time reduction.

There were a few issues that were not addressed by the design. The mitering operation undoubtedly produces burrs, yet this interaction or interference with the fixture's operation was not anticipated. For instance, a build-up of the shavings in the various pin-holes as well as between mating surfaces resulted in clogging and mis-alignment. This would occur fairly rapidly and time was required to clear these burrs. In addition, the overall mitering operation previously required a grinding operation immediately after it. Again, due to the unanticipated interference between a partly mitered drop-out and its subsequent loading in the fixture, it became necessary to perform the grinding operation during the mitering operation.

Nonetheless, the Axiomatic Design approach provided a step-by-step procedure for developing, documenting, and evaluating the design. Unlike the first approach of basing design on experience, Axiomatic Design provides decision making criteria as to what constitutes a good design. This becomes extremely important in the conceptualization phase, as wrong decisions made here adversely biases the effort and all subsequent decisions, making them difficult to correct [Kim & Suh, 1991].

5.2 Fixtures in the Job-Shop

In the production of low-quantity lots of small parts, such as in a job-shop, the loading, unloading, and handling of the parts can require significantly more time than the actual machining time. This is particularly true of precision parts which require more than one machining operation and which are smaller than .250 inch in diameter or thinner than .010 inch. With parts such as these, which require milling, drilling, and grinding operations, the loading and unloading time constitutes up to 75% of the total production time. Thus, the minimization of cutting time, which is the traditional approach in improving productivity, is less effective than other approaches. Clearly, one of the alternate approaches to the reduction of production lead time is refining how well and how long it takes to locate a part or tool.

In the job shop, fixtures typically vary depending on the size and shape of the parts that they are to hold, the precision with which they must be secured for machining, and, of course, on the machines that will be operated. All machines require a method of holding the work-piece, regardless of the operation (e.g. a turning operation on a lathe, a grinding operation, a milling operation, and so on). Lathe fixtures typically are comprised of a series of machined jaws that either secure the work-piece on its outer diameter or the inner diameter about the axis of rotation. Due to the rotational symmetry of the parts processed in turning operations, these fixtures are relatively simple. In milling operations, however, securing the work piece becomes complicated. Lack of consistency exists in the type of milling machine, for instance 3-axis, 4-axis, 5-axis, horizontal, and vertical machines. These machines have different preferred fixture methods. In addition, the different positions on the part that are planned to be machined in any given fixture leads to many opportunities and complications in how the part should be secured.

Fixtures implemented in milling operations include simple vices, usually found on Bridgeports, clamps and braces that secure the part to the machine, and dedicated fixtures that must also be secured to the machine. The first two practices may be termed generic fixtures as they may be applied to a variety of parts, however they never hold the parts in the same position relative to themselves or with respect to the same machine datum [Cochran, 1990]. A dedicated fixture uses pins, cavities or “nests” that coincide with the geometry of the part such that it may only be placed in one precise orientation every time.

In the job shop environment, fixtures have not received as much emphasis as they should with regards to system attributes. The design and operation of these fixtures becomes a major issue as the part mix and quantity increase. Industry has expended much effort into reducing the time taken to setup and breakdown fixtures, leading to quick change systems similar to the Chick Qwik-Change Jaws, described below. However, much of this effort has resulted in further support of the batch production method as an attempt to amortize the setup times over a number of parts instead of working to completely eliminating setup. This practice encourages long system lead times as each part has to wait on every other part in a batch before being moved to the next operation. An example of this practice has been observed and is described in the next section.

5.2.1 Fixtures in the Operation of Lemco Miller's Smart-Cell^{TM}.

In an effort to improve the manufacturing system, Lemco Miller decided to design a manufacturing sub-system, called the Smart-Cell^{TM}. The Smart-Cell^{TM} was designed to accomplish only several of the cellular manufacturing systems' objectives, as explained in chapter three, cell design. One of the design's requirements was for the sub-system to build to customer demand rate or Takt Time. The shop's traditional method of batch production was unaware of daily demand. The production lead times are long and the pace of production is unknown to the operator. The perceived solution was to implement single piece flow in a "cellular" layout.

To accomplish this objective, machining operations were divided among several machines so that each of the individual machine's cycle times would be less than the Takt Time. Initially, 35 parts were selected to be produced in the Smart-Cell^{TM} and three vertical machining centers and one CNC lathe would comprise the cell. Operation of the cell would be conducted by moving parts from machine to machine, as dictated by the cell's Takt Time. However, the final design and operation of fixtures and sub-plates that were implemented would make production under single piece flow very difficult. The combination of heavy, awkward sub-plates, multiple fixture locations per machine, and large distances between the machines will further encourage batch production.

5.2.2 Theory of Offsets and Error Sources

Typically, when a part is programmed, tool paths are generated relative to an arbitrary datum on the part. This reference point, which is referred to as the programmed part zero, is one that is convenient for the programmer. To machine the part, the CNC machine must relate the programmed part zero to the corresponding machine zero by knowing the x,y, and z offsets of the part. These offsets will change every time the same part is placed on the machine if its location on the machine changes. The location of the part on any machine is determined by the fixture in which it is placed. Similarly, the fixture also has position offsets relative to the machine's zero that can change depending on whether the fixture is permanently attached to the machine, which is rare in job-shops, or if the fixture is accidentally shifted or bumped. Thus, the work offsets of the part relative to the machine is the vector sum of the offsets of the fixture relative to the machine and the offsets of the part relative to the fixture:

$$dX_{mach-part} = dX_{mach-fix} + dX_{fix-part}$$
$$dY_{mach-part} = dY_{mach-fix} + dY_{fix-part}$$
$$dZ_{mach-part} = dZ_{mach-fix} + dZ_{fix-part}$$

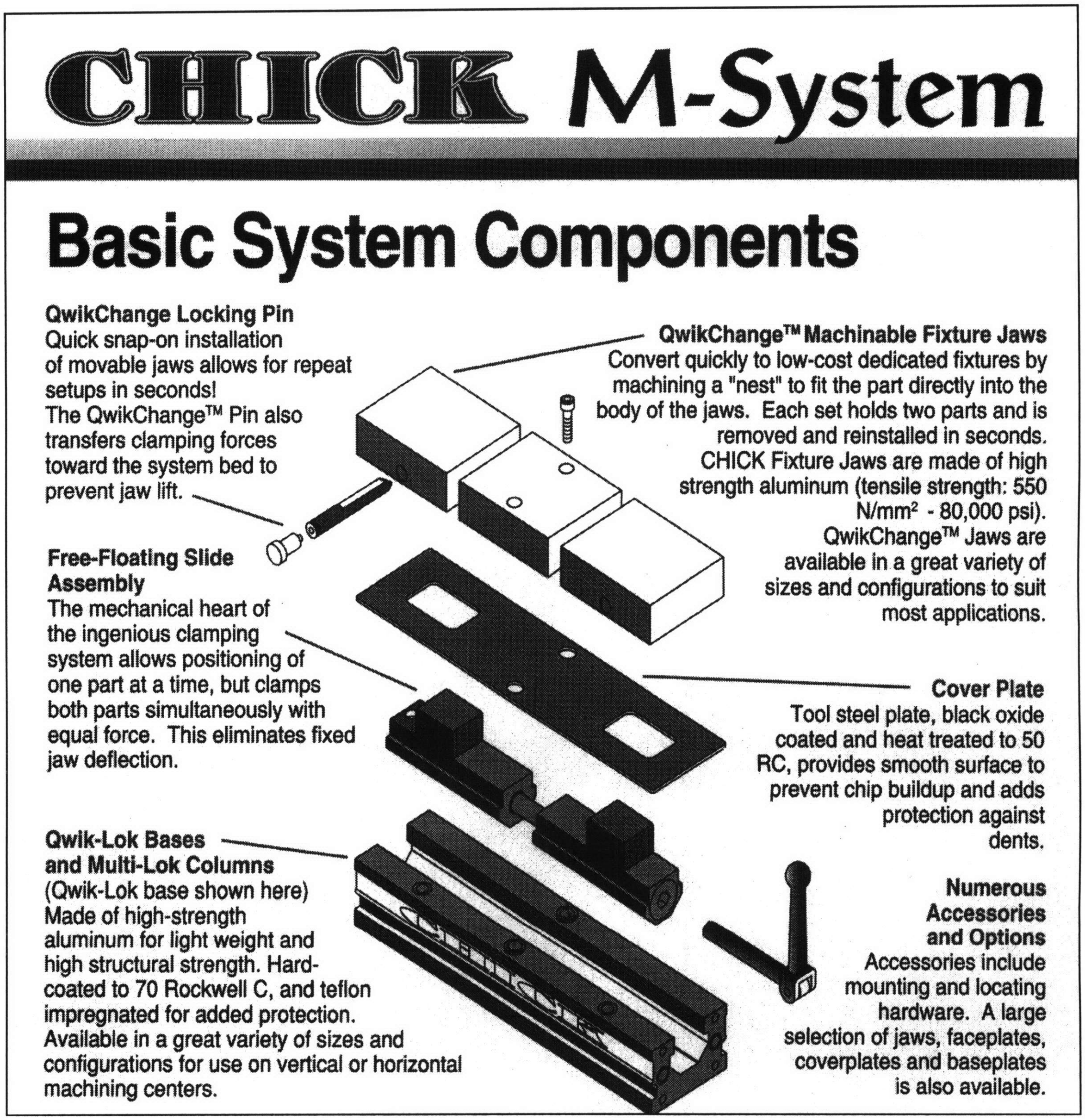
It is these offsets that need to be measured and accounted for prior to machining. This task is sometimes called "touching off" and is one that constitutes to a large setup time.

5.2.3 Fixture & Sub-Plate Implementation

A study of the 35 parts that were planned to be produced in the Smart-Cell^{TM} revealed that the majority implemented simple vises for location on the machines. At least 10 of the parts however were using fixtures in the form of machineable jaws, held in a Chick M-System. This quick-change system, shown in figure 5-8, essentially allows quick and easy setup of fixtures and placing the parts in these fixtures, figure 5-9. The advantage that this system provided over the ordinary vise jaws is that they prevent variations in the offsets of the part relative to the fixture. The positions of parts are highly repeatable in the fixture and thus eliminated the need to adjust offsets on a part. The quick-change system also has the benefit of being quick and easy to operate, thereby minimizing set-up time. The problem that still remains, however, is that the offsets of the part relative to the machine zero may change if the Chick system were to move on the machine, either by accident or otherwise. The offsets of the part may be stated as follows:

$$dX_{mach-part} = dX_{mach-fix} + X_{fix-part}$$
$$dY_{mach-part} = dY_{mach-fix} + Y_{fix-part}$$
$$dZ_{mach-part} = dZ_{mach-fix} + Z_{fix-part}$$

Note, the offsets of the part from the machine zero are still variables due to the potential movement of the fixture. If the position of the fixture on the machine never changed, the offsets of the part would be constant.



CHICK M-System

Basic System Components

QwikChange Locking Pin
Quick snap-on installation of movable jaws allows for repeat setups in seconds! The QwikChange™ Pin also transfers clamping forces toward the system bed to prevent jaw lift.

QwikChange™ Machinable Fixture Jaws
Convert quickly to low-cost dedicated fixtures by machining a "nest" to fit the part directly into the body of the jaws. Each set holds two parts and is removed and reinstalled in seconds. CHICK Fixture Jaws are made of high strength aluminum (tensile strength: 550 N/mm^2 - 80,000 psi). QwikChange™ Jaws are available in a great variety of sizes and configurations to suit most applications.

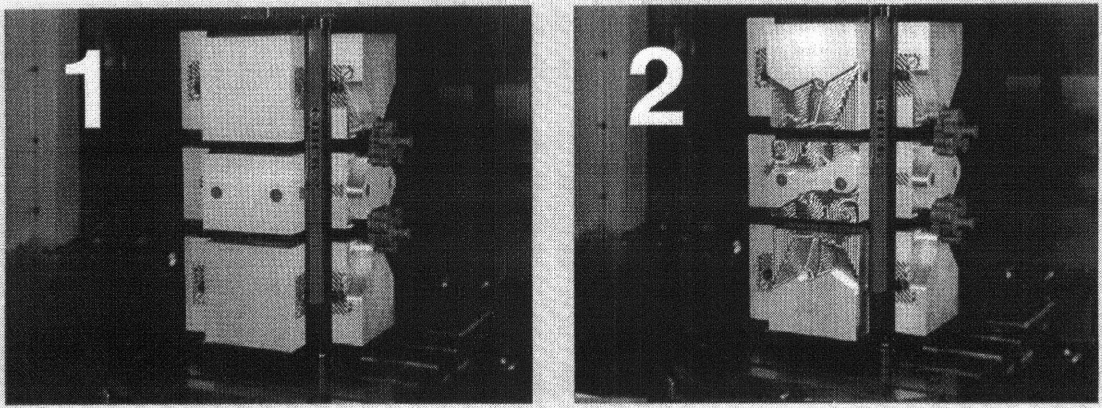
Free-Floating Slide Assembly
The mechanical heart of the ingenious clamping system allows positioning of one part at a time, but clamps both parts simultaneously with equal force. This eliminates fixed jaw deflection.

Cover Plate
Tool steel plate, black oxide coated and heat treated to 50 RC, provides smooth surface to prevent chip buildup and adds protection against dents.

Qwik-Lok Bases and Multi-Lok Columns
(Qwik-Lok base shown here) Made of high-strength aluminum for light weight and high structural strength. Hard-coated to 70 Rockwell C, and teflon impregnated for added protection. Available in a great variety of sizes and configurations for use on vertical or horizontal machining centers.

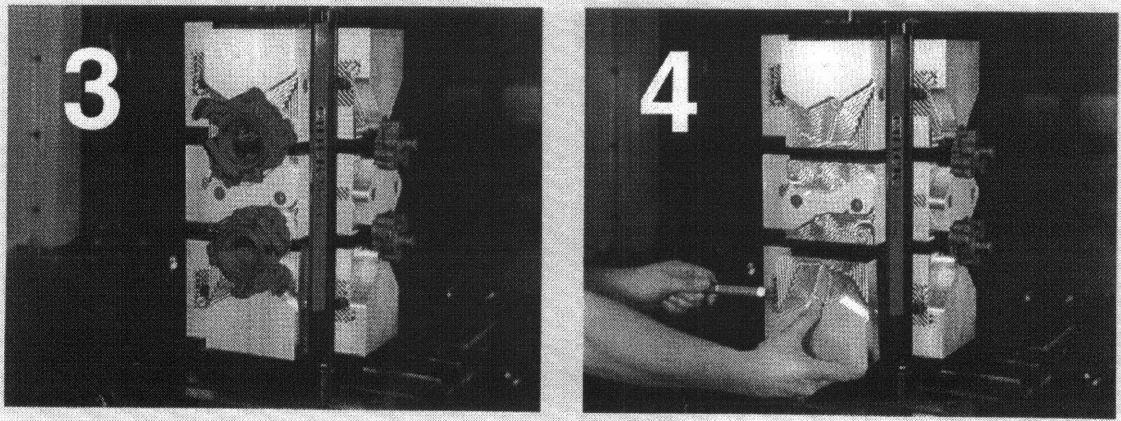
Numerous Accessories and Options
Accessories include mounting and locating hardware. A large selection of jaws, faceplates, coverplates and baseplates is also available.

Figure 5-8 Basic Components of The Chick M-System



Fastest setup ever! Snap-on a set of CHICK QwikChange™ Machinable Fixture Jaws.

Convert QwikChange™ jaws into dedicated fixtures by machining them to locate and hold the parts.

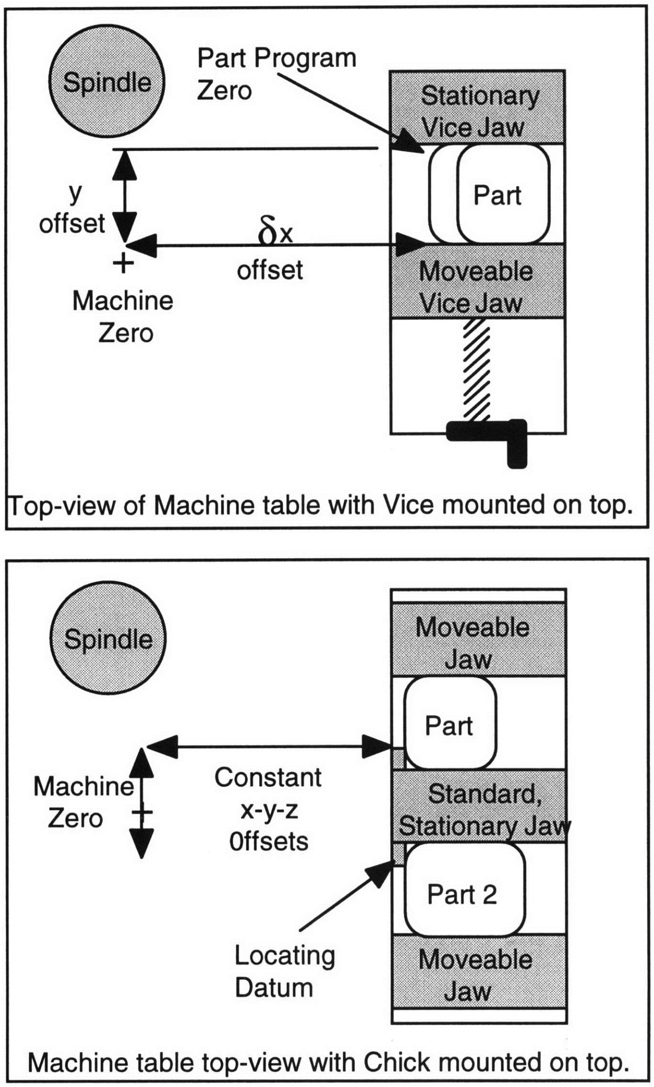


Load parts - ready! Easy to load and unload - easy to clean chips away!

For repeat setups, simply snap on your machined jaws in less than 1 minute per part!

Figure 5-9 Using the Chick M-System

Using vise jaws, which did not have any locating datum, required that every time a part was placed in the jaws, work location offsets would have to be inputted. In addition, if the vise is not permanently attached to the machine, its location relative to the machine zero would also be inconsistent. However, as mentioned earlier, many of the parts were currently being machined in traditional vise jaws. Making dedicated fixtures for each part would be costly, timely and even unnecessary. To eliminate the need to "touch off," standard vise jaws were designed. These standard jaws would work on the Chick M-System and be applicable to a variety of parts where possible, similar to traditional vises. The standard jaws would simply incorporate locating reference points on them which would always maintain constant x-y-z offsets from the machine's zero to the part's program zero, see figure 5-10



Traditional use of Vices required touching off on the part to enable the machine to know exactly where it was. Parts never sat in the same position in the vice, as shown by the δ x offset. In addition, there would be a y-offset determined by the stationary jaw on the vice. If the vice was moved, either intentionally or by accident, this y-offset would have to be re-entered as well. The same rules also apply for the z-offset.

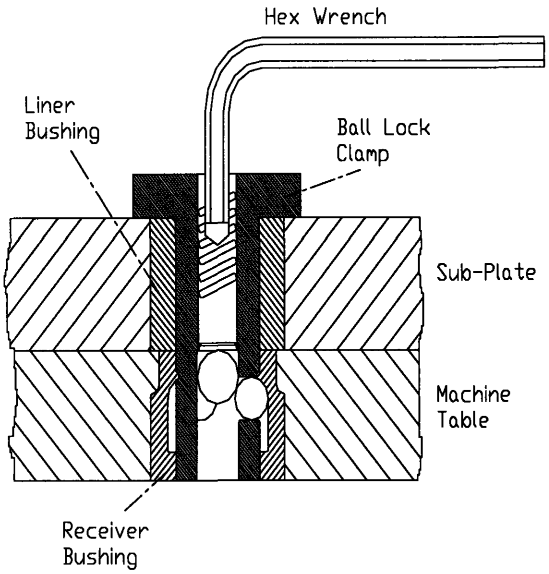
The Chick M-System Qwik-Change jaws with the use of a standardized, stationary jaw allows parts to be dropped in and machined readily and repeatably without having to touch off on the parts. Parts are programmed using the locating datums on the standard jaw as a reference point.

Figure 5-10 A Standardized Chick Jaw Versus the Traditional Vise Jaws

There would undoubtedly be certain parts that require specific nests and features in their fixtures and thus dedicated fixtures would need to be utilized. The dedicated fixtures are effectively the machineable jaws that easily and quickly snap into the Chick M-System. However, for the most part, much of the effort was to not create a large inventory of fixtures for each of the 35 parts and thus where possible, use the standard jaws.

Interestingly enough, there were some parts that were potentially too large to be held in the 4" Chick vise system that was selected for the cell. This 4" size, corresponding to the dimensions of the square jaws, was already quite popular throughout the shop, however the 6" jaws also existed and were required for a few of the 35 parts. The implications of this meant that there was no standard size of Chick vises that could have been used in an economic way. One may argue that perhaps the 6" system may be the one to use throughout, but then that would have meant purchasing more of these systems, which are more costly than the 4" systems, and re-creating fixtures for the parts that are already fixtured in 4" jaws. The reader may recall that preliminary analysis of the 35 parts had indicated however that only 10 parts currently implemented the Chick jaws, thus the application of 6" jaws throughout may have been more feasible. Regardless, not having a standard vise system meant having to include both sizes on each of the three CNC machines. This then further supported the development of sub-plates that would allow the vises to be interchangeable from machine to machine.

Sub-plates were initially introduced by an independent consultant. The main idea behind using sub-plates was to eliminate "touching off" in downstream machining operations. The sub-plates would function similar to the repeatable jaws of the Chick M-System so that they would always be placed in the same position, supposedly to within .0005", on the tables of the machines. Locating and clamping of the sub-plates onto the machines' tables were achieved with ball lock mounting clamps, illustrated in figure 5-11.



Turning the clamping screw with a hex wrench advances the large center ball, pushing the three clamping balls outward. These balls engage the angled ID of the Receiver Bushing, pulling the entire unit firmly downward.

Figure 5-11 Ball Lock Mounting System

The part's work offsets are then given by:

$$X_{mach-part} = X_{mach-fix} + X_{fix-part}$$
$$Y_{mach-part} = Y_{mach-fix} + Y_{fix-part}$$
$$Z_{mach-part} = Z_{mach-fix} + Z_{fix-part}$$

The benefit is immediately apparent; the part's work offsets are constant provided the fixture's position on the machine is repeatable and the part's position in the fixture is repeatable. Once these offsets are measured, the "touching off task" becomes redundant. Through vector calculus, the repeatability obtained with this system can be calculated as the vector sum of the repeatabilities of the sub-plates and the Chick M-System respectively:

$$\Delta X_{mach-part} = \Delta X_{mach-fix} + \Delta X_{fix-part}$$
$$\Delta Y_{mach-part} = \Delta Y_{mach-fix} + \Delta Y_{fix-part}$$
$$\Delta Z_{mach-part} = \Delta Z_{mach-fix} + \Delta Z_{fix-part}$$
$$\text{Repeatability} = \sqrt{(\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2}$$

Assuming the plates are repeatable to 0.0005", due to the ball locks, and the Qwik-Change Jaws are repeatable to 0.0002", the effective repeatability of the system is 0.0012". Of the 35 parts that will be machined in the Smart-Cell^{TM}, any with tolerances less than 0.001" can have potential quality problems. For the majority however, the tolerances are 0.005".

The actual intended operation of the sub-plate system will pose a problem. Parts will be loaded in the traditional manner in the vises and sub-plate of the first machine, requiring the operator to "touch off" and enter the work offsets on that machine. As the part, vise, and sub-plate are all moved to downstream machines, the same work offsets from the initial machining operation would have to be entered in the later machines, provided that the part is never removed from the vise. The only benefit lies in the fact that the actual measurement or "touching off" operation is avoided in the downstream operations. This benefit is slim in comparison to the time that is still consumed in typing in the offsets on the machine, and the potential human errors intrinsic to that manual operation. The important distinction to make is that the entire practicality of this procedure is rendered useless if the part is removed from its initial fixture. The problem is that the current method of production requires that 29 out of the 35 parts be re-positioned or machined in several different orientations, thereby rendering this "touch free" application via the sub-plates of no benefit!

Another problem that will arise from the sub-plate-fixture design lies in the operation of single-piece-flow within the cell. As mentioned earlier, the sub-plates have been designed such that several may be placed simultaneously on each of the three machines. Figure 5-12 shows the second machine, called the "Large Comet", with four sub-plates mounted on top, while the two other machines have two and three sub-plates, respectively. As a result, the Large Comet has the potential of fixturing a batch of eight parts, two per sub-plate-fixture. Operators will prefer and will be inclined to fixture a batch of eight at a time instead of placing one part and leaving the remaining seven locations open.

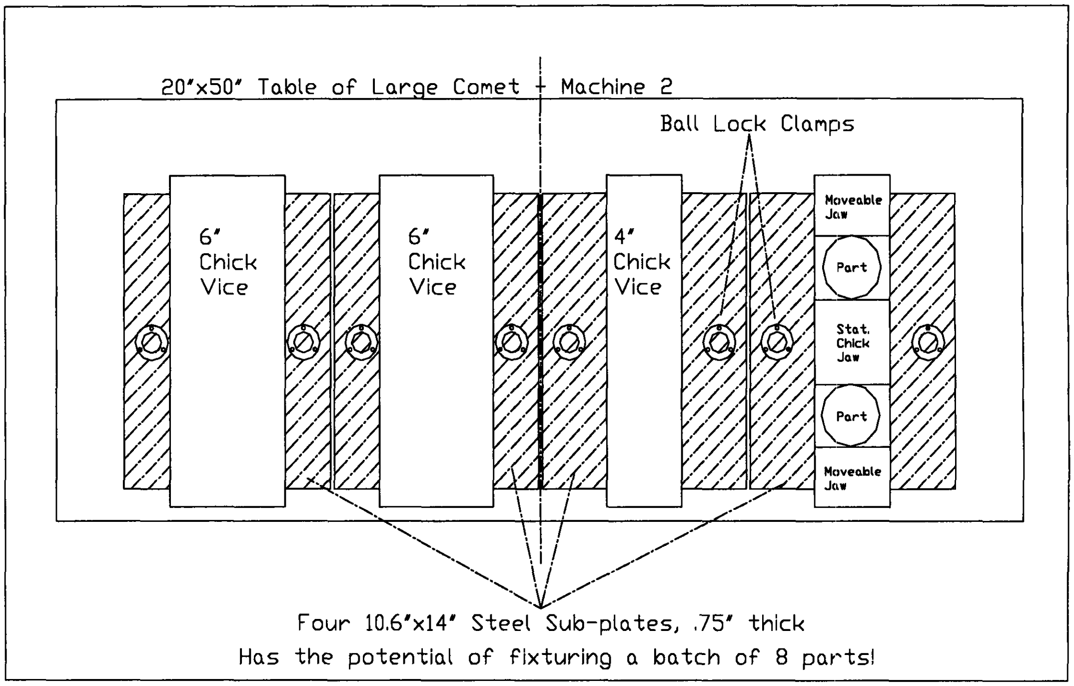
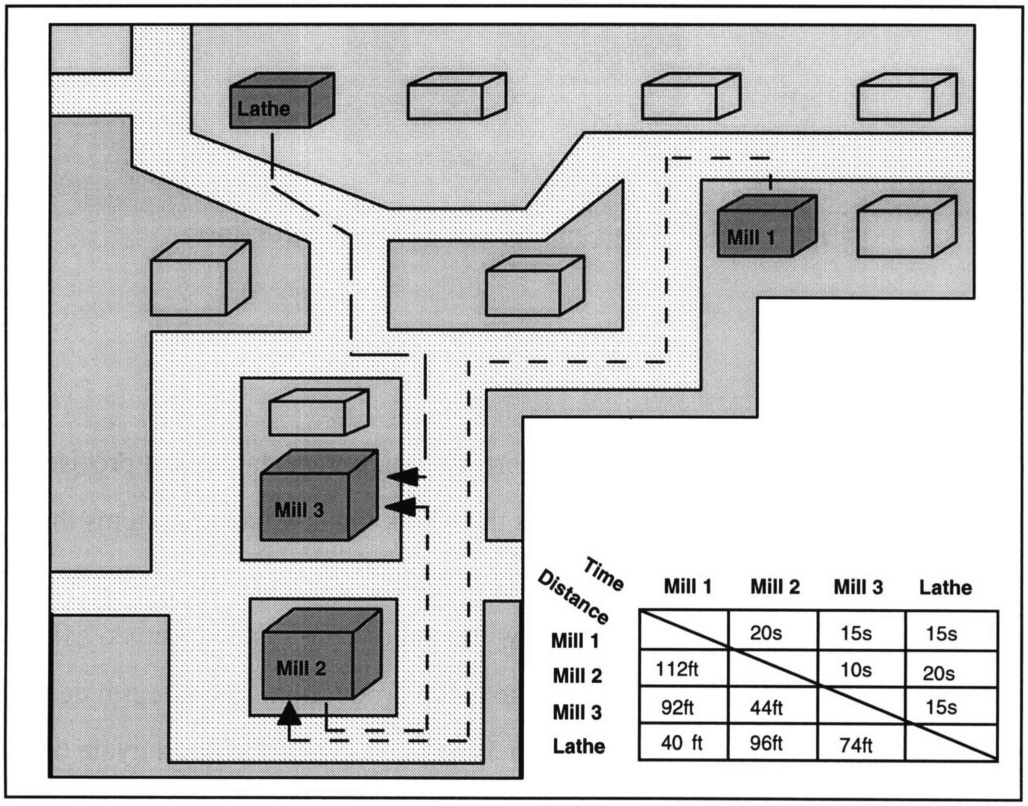


Figure 5-12 Layout of Vises and Sub-Plates on the Table of a CNC Machine

As designed, the sub-plates are also very close to one another, approximately 0.2 inches apart. There would be little room for adjustment and handling, which may be beneficial for rough alignment. However, the two blind holes underneath the sub-plate, in which the ball lock clamps connect, may not allow easy access. Perhaps one clamp would need to be fitted first, the plate then pivoted about it, and then the other clamp inserted. Incidentally, the 10"x14"x0.75" steel plate, weighing approximately 30lbs, the 6"Chick vise system at 48lbs, and a 5lb part, totaling over 80lbs, would certainly be difficult to handle. Furthermore, the company has the initial reservation of not wanting to move the machines closer together. The current layout is such that the three machines are between 40 feet to over 100 feet apart, see figure 5-13. All the above factors: heavy, awkward sub-plate, multiple sub-plates per machine, and the large distances between machines would make the operation of the cell virtually impossible under the single piece flow paradigm.

Workers will definitely object and revert to the traditional batch production.



Time / Distance	Mill 1	Mill 2	Mill 3	Lathe
Mill 1		20s	15s	15s
Mill 2	112ft		10s	20s
Mill 3	92ft	44ft		15s
Lathe	40 ft	96ft	74ft	

Figure 5-13 Layout of Machines Showing Walking Distances and Times Between Machines

Chick provides a wide assortment of quick-change vises, shown in figure 5-14. These systems enable production in huge batches. Here, the gains of amortizing setups and tool changes over a number of parts are perceived to be greater than the problems of long lead times, due to lot delay, and large inventory. Today, that perception is changing, and one must be careful in selecting work-holding devices such as these that encourage batch production instead of production in a single-piece-flow manner.

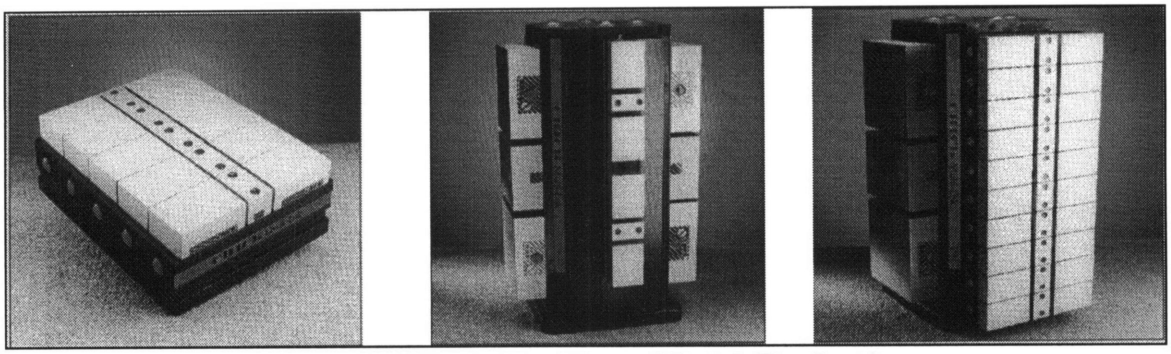


Figure 5-14 The Enablers of Batch Production

5.2.4 Conclusions

To conclude, the technology exists today to perform quick, repeatable, and precise machining operations. There are tools such as the Chick Qwik-Change systems that reduce set-up times from several minutes to mere seconds. However, it has been shown that in attempting to design a single-piece-flow manufacturing system, Lemco Miller has selected inappropriate tools that will encourage batch production. The integral design of a system that includes other characteristics such as reduced inventory, short cycle times, and quick changeover between product types via single-piece-flow, involves a much broader, more comprehensive consideration of how the components will gel. To accomplish these features in any production system the designer must beware of the flashy, striking tools that often deviate from what is required.

5.3 Concluding Rules in the Design of Jigs & Fixtures

In conclusion, this chapter presented some fundamental issues involved in the design of jigs and fixtures. A detailed study on the design of a fixture to facilitate a machining operation was presented. That evaluation implemented the Axiomatic Design methodology as a tool to facilitate the design process. The approach provided a step-by-step procedure for developing, documenting, and evaluating the design. The design of fixtures and sub-plates and their impact on one-piece-flow operations were then discussed. This study, conducted at a job-shop, also illustrated the importance of selecting appropriate designs for successful operation of a manufacturing system. At this point, the chapter will conclude with some basic rules on the design of jigs and fixtures.

5.3.1 Jig and Fixture Fundamentals

1. State what are the functional requirements of the jig or fixture design. This exercise should be answered at least five times to ensure a complete understanding of the need(s).
2. Study previous tools designed for a similar operation. A lot can be learnt on how to do and not to do things by studying existing tools.
3. Stress simplicity. It is very easy, almost natural, to allow a fixture to become complicated. The real challenge is to design something simple.
4. Use standard, off-the-shelf components wherever possible.
5. Design around stock sizes.
6. Mistake-proofing (Poka-Yokes) is necessary for any fixture design. It is defined as the incorporation of certain design features that do not interfere with the loading and locating of the workpiece yet make it impossible to place the part in an improper positon.
7. Don't demand unnecessary tolerances on noncritical dimensions. For example, baseplates can often be +/- 1/8 inch.

8. Loading and unloading of small parts should not exceed two seconds for each operation. Unloading, in most cases, should be automatic.
9. If a fixture has removable parts, such as a drill bushing and a ream bushing for one hole, provide a hole and setscrew to retain the bushing not being used. This prevents loss in the tool crib.
10. If locating points are covered, provide sight or peep holes for the operator's benefit.
11. Tools that weigh over 30 pounds must have lifting hooks.
12. If springs are subject to chip accumulation, shield them or position them on raised bosses. Don't ask the operator to continually pick or blow chips out of a spring.
13. Safety is a prime responsibility of the tool designer. Design the jig or fixture so that the operator's hands will not be to close to cutting tools and so that clamps and levers can be operated without danger of injury.

CHAPTER 6

CONCLUSIONS

6.0 Conclusions and Future Work

It is the intent of this thesis to highlight necessary phases in the design and control of production systems. Though much attention has been given to the design of these systems, in practice most efforts still remain ad-hoc. Two tools have been identified to facilitate the evaluation and design of manufacturing systems: Axiomatic Design and the Three Pillars of Manufacturing. The Axiomatic Design methodology follows a logical process of matching goals with design parameters, and is more structured than a consensus-based method of decision-making. The framework of Three Pillars of Manufacturing System Design and Manufacturing System Control implements the principles of Axiomatic Design. This framework was motivated by the need for a structured design process for manufacturing systems The power and utility of these two tools in the evaluation and design of manufacturing systems is demonstrated in their application at several manufacturing companies.

Chapter two provided a system's level analysis of a job-shop manufacturer. The two primary markets were revealed along with the inefficiencies with which the shop responded to them. The purpose of this was to provide a structured approach to evaluating and designing a new system that would more effectively respond to these markets. Recommendations were proposed at the end of this chapter, which then led to a detailed design and analysis of one of its manufacturing sub-systems in chapter three.

Chapter three presented three examples of manufacturing sub-systems at a cellular level. The first represented a brief description of a cell that is involved in the manufacture of steering gears. Following this, the machining cell at Merlin Metalwork's Inc. was evaluated using two tools: Axiomatic Design and Time Based Management. The principles of Axiomatic Design indicated coupling and non-fulfillment of certain cell requirements. Time Based Management proposed metrics that may be used to quantify inefficiencies in the cell, however there was no distinct solution to the problems. However, further studies must be conducted to maximize the feedback from these two approaches, and then implement them in the design and control of manufacturing systems such as this. Finally, the third evaluation was conducted on an attempt to apply cellular manufacturing in Lemco-Miller's job-shop. This attempt demonstrated how industry's constraints and mis-interpretation of manufacturing system design principles often inhibit successful cell design. Principles and guidelines were proposed to aid the process of designing and evaluating the new manufacturing system. Sufficient time, critical analysis, and a thorough understanding of the principles for manufacturing system design are recommended for success.

Chapter four represented a description of a custom machine design that was conducted for Merlin Metalworks Inc. The case study demonstrated issues that companies must address in deciding on making or buying any machinery that will be used in their manufacturing process. The importance of determining the critical system requirements with regard to the machine design was stressed.

Chapter five presented fundamental issues concerning the design of jigs and fixtures. A detailed study on the design of a fixture to facilitate a machining operation was presented. That evaluation demonstrated the ability of Axiomatic Design as a tool to facilitate the design process. The approach provided a step-by-step procedure for developing, documenting, and evaluating the design. The design of fixtures and sub-plates and their impact on one-piece-flow operations were then discussed. This study, conducted at a job-shop, also illustrated the importance of selecting appropriate designs for successful operation of a manufacturing system.

Much work must still be done to reach the goal of developing the principles governing design and control of production systems. The basic premise is that there are principles that guide decision making in manufacturing system design. Each manufacturing system must be critically evaluated using tools that highlight the root problems. A framework must then be used to propose a strategy for system-redesign. The journey towards developing these principles has begun. This thesis is but a path in the quest for answers.

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