University of Northern Iowa
UNI ScholarWorks

Graduate Research Papers | Student Work

1993

An Assessment of Cellular Manufacturing

Bruce A. Thurm
University of Northern Iowa

Let us know how access to this document benefits you

Copyright ©1993 Bruce A. Thurm

Follow this and additional works at: https://scholarworks.uni.edu/grp

Recommended Citation

Thurm, Bruce A., "An Assessment of Cellular Manufacturing" (1993). *Graduate Research Papers*. 3785.
https://scholarworks.uni.edu/grp/3785

This Open Access Graduate Research Paper is brought to you for free and open access by the Student Work at UNI ScholarWorks. It has been accepted for inclusion in Graduate Research Papers by an authorized administrator of UNI ScholarWorks. For more information, please contact scholarworks@uni.edu.

Offensive Materials Statement: Materials located in UNI ScholarWorks come from a broad range of sources and time periods. Some of these materials may contain offensive stereotypes, ideas, visuals, or language.

An Assessment of Cellular Manufacturing

Abstract

The problem of this study was to explain the process of cellular manufacturing and identify the key elements to help manufacturers improve the efficiency and productivity of their operations and improve the quality of their products. The study focused on the key issues of cellular manufacturing, and the design, implementation, and control of cellular manufacturing work cells. The study included the potential benefits of cellular manufacturing, as explained by Overbeeke (1988) including reduced lot sizes, reduced throughput time, greater flexibility, reduced inventory, improved quality, improved scheduling, and reduced material handling. Job enrichment, a less quantifiable potential benefit of cellular manufacturing, is also included in the study.

This open access graduate research paper is available at UNI ScholarWorks: https://scholarworks.uni.edu/grp/3785

An Assessment of Cellular Manufacturing

A Research Paper

Submitted

In Partial Fulfillment

of the Requirements for the

Master of Arts Degree

by

Bruce A. Thurm

March, 1993

Approved by:

Dr. John Fecik, Advisor — Date: May 5, 1993

Dr. Rex Pershing, Graduate Falculty Member — Date: 8-4-93

An Assessment of Cellular Manufacturing

A Research Paper
Submitted
In Partial Fulfillment
of the Requirements for the
Master of Arts Degree

by

Bruce A. Thurm

Spring, 1993

TABLE OF CONTENTS

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The manufacturing process of converting raw material to finished parts or sub-assemblies is undergoing change. According to Martel (1989), "The majority of today's manufacturing plants have manufacturing work centers consisting of grouped similar manufacturing resources, capable of performing exact duplicate operations and accepting interchangeable tooling" (p. 26). An example of this would be a plant with separate departments including press and forming departments, machining departments, welding departments, inspection departments, and assembly departments. Each of these departments perform a specific operation and the parts or sub-assemblies travel between them until completed. This process results in increased lead times, excessive material handling, increased error potential, and increased inventory cost, all of which hamper the company's ability to compete. (Koelsch, 1990).

An alternative to the current manufacturing process is cellular manufacturing. Martin (1989) explains cellular manufacturing as the grouping of people, processes, and dissimilar types of machinery into a- specific area dedicated to the production of a family of parts. A simple example of this concept would be a work center consisting of a lathe, a welder, and a press. The part would enter the cell as raw material and move between the three different operations within the work center, and would be a completed part when it left the work center. The benefits of this process include reduced lot sizes, reduced throughput time, greater flexibility, reduced inventory, improved quality, improved scheduling, reduced material handling, and increased job enrichment. (Overbeeke, 1988).

Background of the Problem

Todays manufacturers are under increasing competitive pressure to increase their productivity and quality. One possible technique to help increase productivity and quality is cellular manufacturing. According to Martin (1989), "US industry, in its drive to increase productivity, has adopted cell technology as the strategy for improving its production operations on the plant floor" (p. 49).

Problem Statement

The problem of this study was to explain the process of cellular manufacturing and identify the key elements to help manufacturers improve the efficiency and productivity of their operations and improve the quality of their products. The study focused on the key issues of cellular manufacturing, and the design, implementation, and control of cellular manufacturing work cells. The study included the potential benefits of cellular manufacturing, as explained by Overbeeke (1988) including reduced lot sizes, reduced throughput time, greater flexibility, reduced inventory, improved quality, improved scheduling, and reduced material handling. Job enrichment, a less quantifiable potential benefit of cellular manufacturing, is also included in the study.

Purpose Statement

The purpose of this study was to provide a reference that explains the concept, and key issues of cellular manufacturing and how it can be used to increase productivity, the efficiency of an operation, and product quality. When the concept of cellular manufacturing was first introduced at the the Tractor Assembly Division of John Deere approximately a year ago very few people in the division understood the concept. The Tractor Assembly Division currently has one manufacturing cell in operation and other may be considered in the future. As other departments within the division consider the use of cellular manufacturing this reference could be used by business unit managers, process engineers, supervisors and wage employees to gain a basic understanding of cellular manufacturing.

Statement of Need

A reference was required that explains the concept of cellular manufacturing, its potential benefits, and the effect it can have on traditional job roles. Though there are several reference books published on large Flexible Manufacturing Systems there is only a limited amount of information published on the concept of Cellular Manufacturing specifically. This reference may be used by business unit managers, process engineers, supervisors and wage employees to provide an opportunity to gain a basic understanding of cellular manufacturing before considering its use.

Research Questions

The following questions were asked as a result of this study:

1. What is cellular manufacturing?
2. What are the key issues to be considered beforeimplementing cellular manufacturing?
3. What are the steps used to implement cellular manufacturing?
4. What are the potential benefits or advantages of implementing cellular manufacturing?
5. How does cellular manufacturing affect the traditional job roles of wage and salary employes.
6. What are the basic steps of designing a manufacturing cell?
7. What are the control techniques used in cellular manufacturing.

Statement of Assumptions

The following assumptions were made in pursuit of this study:

1. The cell operators have the skills or can be trained to perform multiple tasks.

2. The labor force and their representative unions are supportive and willing to participate in cellular manufacturing.
3. That upper management will provide adequate support and commitment to cellular manufacturing.
4. That management is committed to improving the level of job satisfaction of its employees.

Limitations

The study was conducted in view of the following limitations:

1. This study will be limited in that it will not investigate specific machinery or tooling used in cellular manufacturing.
2. This study will be limited to the use of cellular manufacturing in medium to large size manufacturing industries.
3. This study will be limited to investigating cellular manufacturing in context to single cells.

Definition of Terms

The following terms are defined to clarify their use in the context of the study:

Cell Control: The integration of management information systems and manufacturing systems (Friscia, 1989).

Cellular Manufacturing: The grouping of people, processes, and dissimilar types of machinery into a specific area dedicated to the production of a family of parts (Martin, 1989).

Cluster Analysis: A technique used to form part families by specifying a mathematical expression for the "distance" between two part types in terms of similarity (Kinney, October, 1987).

Computer Simulation: The process of designing a mathematical model of a system and performing experiments with this model on a computer (Akbay, 1989).

Continuous Improvement: Constant adjustments to the product quality by a process of tracking, measuring, analyzing, recording, and controlling the process (Fisher, 1990).

Flexible Manufacturing Systems: A flexible manufacturing system, through the careful combinations of computer control, communications, manufacturing processes and related equipment enables a section of the production-oriented aspects of an organization to respond rapidly and economically, in an integrated manner to significant changes in its operating environment (Greenwood, 1988).

Group Technology Classification: A technique used to form part families by identifying similar parts by assigning an alphanumeric code to each part based of the part attributes, which may include factors such as the handling requirements, the size and demand rate, in addition to fixturing and tooling (Kinney, October, 1987).

Job Enrichment: The process of redesigning work to provide employees with more than meaningless, repetitive, monotonous operations (Juran, 1979).

Logical Cells: The same basic elements of a physical cell plus the addition of speciality process that can not be physically included in the cell. These specialty processes are considered to be part of the cell because they are connected to the cell by automated material handling systems (Kinney, August, 1987).

Physical Cell: The physical group of processes, equipment, and people dedicated to producing a family of parts in a defined area (Kinney, August, 1987).

Production Flow Analysis: A technique for forming part families based on existing process plans (Kinney, October, 1987).

CHAPTER 2

REVIEW OF LITERATURE

The development of the concept of cellular manufacturing can be viewed as the latest development in the evolution of manufacturing processes. The most recent manufacturing processes to proceeded cellular manufacturing were process oriented manufacturing systems first and flexible manufacturing systems second. The cause for the evolution in manufacturing processes was the need to meet customers needs and the need to improve efficiency. This does not mean that any of the three manufacturing processes is superior to the other in every cause. Each of these systems have their strengths and weakness and must be matched to the proper manufacturing and customer environment.

Process Oriented Manufacturing

The exact date that process oriented or mass production manufacturing was introduced is difficult to determine. Greenwood (1988) explained that Henry Ford and the introduction of the Model T in 1907 are commonly cited as one of the first examples of process oriented manufacturing. The Model T marked one of the first times a large number of accurately machined mechanical components were combined to form a finished product. This manufacturing process was based on the principle of manufacturing products economically in mass quantities with limited or no variety.

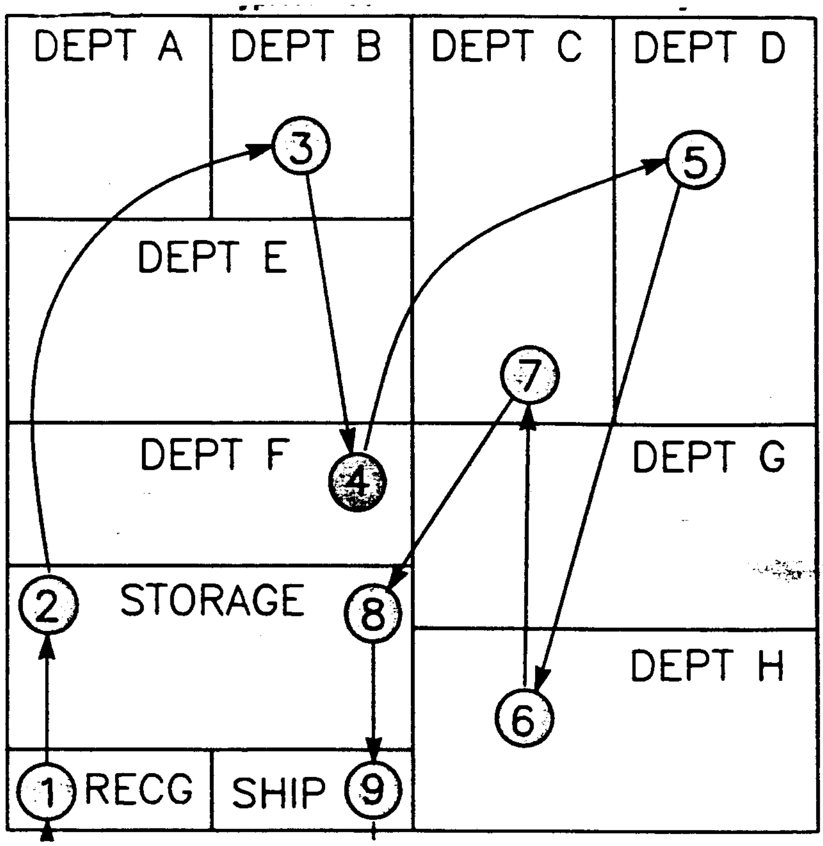
The traditional way to organize a process oriented manufacturing system as explained by Hays (1988) was by departmental specialty where each department specializes in a type of equipment, process, or technology. As briefly described in the introduction, a typical factory layout using a process oriented manufacturing system may include a weld department, a press and forming department, a machining department, and an assembly department.

When factories are laid out or arranged by functional specialized departments, parts are commonly run in large batches (Kinney, August, 1987). These batches of parts are passed between the various departments where each department performs a specific operation (See figure 1). As these parts progress through the manufacturing system they may also be placed in temporary storage if the next department in the process is not ready to perform the next operation. This type of layout results in high work in process inventory levels and unnecessary material handling.

As the incomplete product passes between departments it is usually the departmental supervisor's or foreman's responsibility to ensure the work is completed within their department. However, according to Kinney (August, 1987) these people were rarely held accountable for ensuring the finished product was completed on schedule. Unfortunately, the responsibility of getting the product completed on time commonly fell on the last department in the manufacturing process even though they had little control of the

FIGURE 1

Sample Process Oriented Process Flow



Note. From "Manufacturing cells solve material handling problems." by Kinney, H. D. & McGinnis, L. F., (August, 1987), Industrial Engineering, p. 56

departments before them. This lack of accountability resulted in schedule slippage and high overtime cost to get back on schedule.

In addition to the problems of high work in process levels, lack of accountability, and high material handling cost Kinney (August, 1987) explains process oriented manufacturing systems were very inflexible. Customers demanded more variety and product life cycles became shorter. Process oriented manufacturing systems were unable to react quickly to these changes. While the products made using this process oriented manufacturing systems were affordable, customers were given little or no variety to choose from. Process oriented manufacturing systems were only practical if products had long life cycles and were produced in mass quantities.

Flexible Manufacturing Systems

The original concept of flexible manufacturing systems, according to Patankar (1991) was developed in the late 1960's and early 1970's. The first operational flexible manufacturing system was developed by D. T. N. Williamson while working for Molins Machine Tool Company in England during 1968 (Greenwood, 1988). The system was designed to produce light flat alloy components. The basic goals of the system were the ability to manufacture a large variety of components economically, the ability to load and unload tooling and work pieces automatically, and the capability of running virtually unattended for long periods of time.

Unfortunately, Greenwood (1988) explained, the system was unsuccessful due to a lack of market for the product and the lack of refined machine control technology. Even though this first attempt at developing a flexible manufacturing system was considered a failure it was closely studied by representatives from around the world. These representatives learned a great deal from the first attempt at developing flexible manufacturing systems, and as technology advanced, they started building primitive systems in their own countries. This was the start of flexible manufacturing systems.

Origins of Flexible Manufacturing Systems

According to Martin (1989) the use of flexible manufacturing systems became popular in the late 1970's and early 1980's. The primary attractive features of these systems were their ability to bring the economics of scale of mass production to small batch production. This was accomplished by reducing lot sizes, reducing material handling cost, lowering work in process inventory levels, and increasing the flexibility.

Due to the fast paced changes in customer demand, manufactures were being forced to produce a larger variety of products in smaller quantities. Steinhilper (1985) explained that this demand for variety was not suited to the more conventional mass production methods of producing products in large quantities and limited variety. To meet the customers need for variety flexible manufacturing systems were developed that were highly automated and flexible enough to produce high quality, mid-volume and mid-variety products economically.

What are Flexible Manufacturing Systems?

There are a variety of reference books available that describe the technique of flexible manufacturing systems, but a concise definition is difficult to obtain. One definition given by Greenwood (1988) defines flexible manufacturing systems as:

> "A flexible manufacturing system, through the careful combinations of computer control, communications, manufacturing processes and related equipment enables

> a section of the production-oriented aspects of an organization to respond rapidly and economically, in an integrated manner to significant changes in its operating environment' (pp. 3).

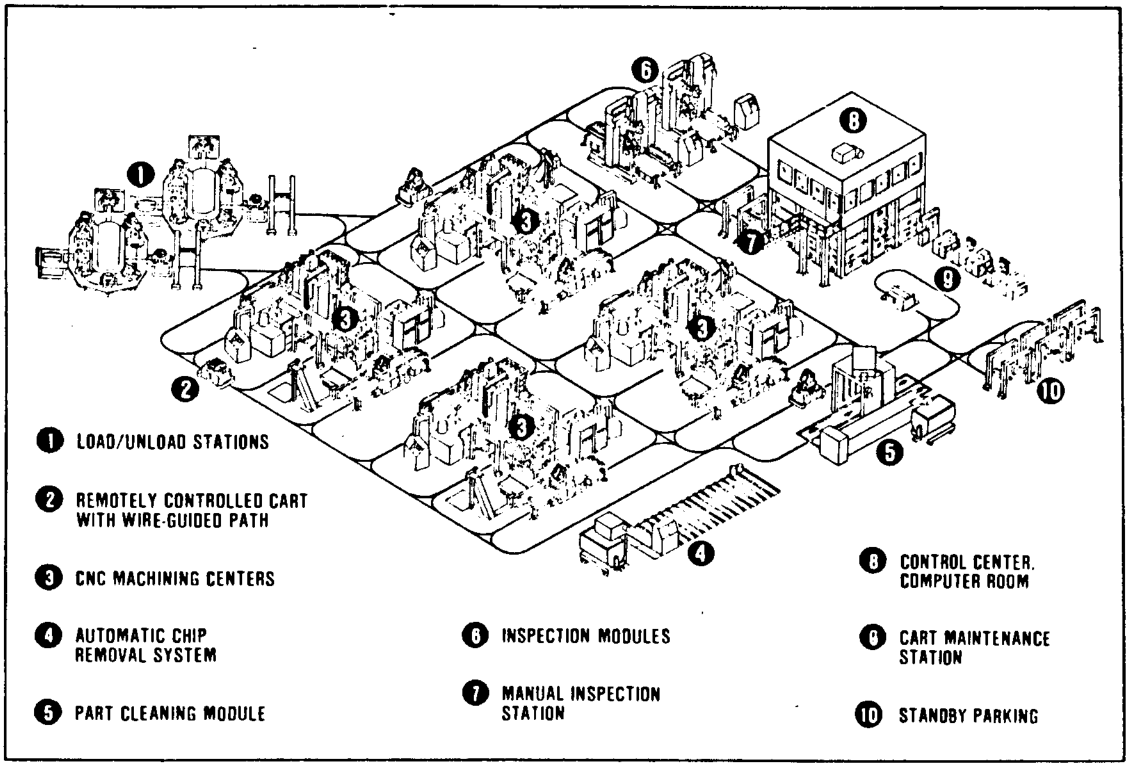
A more basic and understandable explanation given by Maleki (1991) defines flexible manufacturing systems as "... a computer controlled manufacturing system using semi-independent numerically controlled machines linked together by a means of a material handling network" (pp. 8). While this definition emphasizes the use of computer control, numerical control, and material handling system Maleki goes on to explain that robots, automated guide vehicles, automated storage, and automated inspection may also be part of a manufacturing system. Flexible manufacturing systems are also not restricted to machine operations. For example, they may also include a variety of other manufacturing processes including welding, washing, fabrication, and assembly (See figure 2).

Parts to be manufactured in this cell enter as raw material and are loaded onto remote control vehicles. The remote control vehicles transport the material between the various operation within the cell based on the process requirements until completed. The entire system is controlled by a central computer and includes computer numerically controlled machining centers, automated load and unload devices, and a automatic inspection station.

Regardless of the definition used Maliki (1991) explained the basic characteristics of a flexible manufacturing system include:

1. High degree of computer control and communication.
2. Highly automated material handling systems.
3. Automated numerical controlled processing.
4. Limited operator involvement.
5. The flexibility to produce mid-volume, mid-variety products economically

FIGURE 2
Sample Flexible Manufacturing System



Note. From Flexible manufacturing systems. (p. 29) by Maleki, R. A. 1991, New Jersy:, Prentice-Hall Inc. Copyright 1991 by Prentice-Hall.

Technology used in Flexible Manufacturing Systems

The basic technologies used in flexible manufacturing systems included automated manufacturing processes, material handling systems, computer control, and numerical control. While all of these technologies were important in the development of flexible manufacturing systems the one most important building block in developing these systems was numerical control, which was later to become computer numerical control (Greenwood, 1988).

Numerical control as explained by Maleki (1991) came into existence in 1952, and provided a more efficient and economical method to produce high quality products. Numerical control was a form of automation that enabled machines to perform with extreme accuracy automatically. A program of instructions was punched into a special tape producing holes in various patterns. The holes were read and interpreted by the controller unit of the machine and converted to electrical signals which activated the servomotors and other controls of the machine. When changes in the instruction program were needed a new tape could be made quickly and easily.

With advancements in computer technology and the development of integrated circuits, true computer numerical control was developed. Greenwood (1988) stated that "these controllers, being centered around a small minicomputer, were far more versatile and reliable, and often less expensive than their numerical control predecessors" (pp. 9). Computer numerical control eliminated the need for punch tapes and also incorporated additional features including computer aided programming and sophisticated editing capabilities. The ability to make changes to operation instructions and the ability to change over from running one part to another quickly and easily, is what gave flexible manufacturing systems their flexibility.

To take the development of numerical control one step farther Maleki (1991) explains numerical controlled machines were linked together to form Direct Numerical Systems. Direct numerical control systems allowed production information to be collected from each of the numerical control machines in the system. Direct numerical control also allowed program instructions to be down loaded directly to each numerical control machine using a larger main computer.

Flexible manufacturing systems and direct numerical control systems both involve the use of computer control. The major difference is that flexible manufacturing systems provided the potential for unmanned operation including the automatic loading and unloading of tooling and work pieces. Direct numerical control only performed the task of data exchange between the the numerical control machine and the direct numerical control controller (Maleki, 1991).

Advantages and Disadvantages

The benefits of a successfully implemented flexible manufacturing system in the correct manufacturing conditions were substantial. The drawback to these potential benefits were that they were all not easily quantified. Greenwood (1988) explained that the lack of accountability made the cost justification process of flexible manufacturing systems difficult.

Some of the potential benefits of flexible manufacturing as stated by Greenwood (1988, pp. 22) included:

1. Improved capital/equipment utilization.
2. Reduced work in-process and set-up.
3. Substantially reduced throughput times/lead times.
4. Reduced inventory and smaller batches.
5. Reduced manpower.
6. Ability to accommodate design changes easily.
7. Consistent quality.

Some of the potential disadvantageous included:

1. Still a relatively new technology.
2. Good design/implementation expertise was difficult to find.
3. Systems were complex, necessitating lengthy operator and maintenance training.
4. Systems were expensive.
5. Systems took several years to implement.
6. Systems required the the writing of a significant amount of once-off software for the central computer.
7. Difficult to integrate devices from different manufacturers.

Cellular Manufacturing Systems

The concept of cellular manufacturing became popular in the mid 1980's and was similar to flexible manufacturing systems, but less complex (Martin, 1989). The similarities between cellular manufacturing and flexible manufacturing systems were that they both involved the use of a variety of equipment, computer control, and automated manufacturing processes. The primary objectives of cellular manufacturing and flexible manufacturing systems were also similar. Both were designed to improve the flexibility and efficiency of producing mid-variety, mid-volume products. Both manufacturing systems were also similar in the potential benefits of reduced lot size, reduced throughput and lead times, reduced work in process, and increased flexibility.

The Differences Between The Two Systems

Because of their similarities there were no hard fast rules for differentiating between flexible manufacturing systems and cellular manufacturing. Martin (1989) explains that one possible method to differentiate between the two was by size. As the number of machines or processes involved increased, the more likely the manufacturing process was considered a flexible manufacturing system.

The level of computer control and operator involvement were also used to differentiate between the two manufacturing methods (Martin, 1989). When the operation of the work area is dependent on operator involvement and not strictly computer controlled it is more likely to be classified as cellular manufacturing. When the operation of the work area is dependent on extensive computer control requiring little operator involvement, and several work areas are inter-connected by computer, the manufacturing process was likely to be classified as a flexible manufacturing system.

According to Maleki (1991) another difference between the two manufacturing systems is the variety and volume of parts each is designed to produce. While both systems are designed to produce a wide variety of mid volume parts flexible manufacturing systems are designed to produce a slightly lower variety and higher volume of parts than cellular manufacturing systems.

Development of Cellular Manufacturing Concept

The design of cellular manufacturing was basically a simplification of flexible manufacturing systems. Tooling and Production (1986) explained the goals of cellular manufacturing were to maintain the many advantages of flexible manufacturing systems while avoiding the disadvantages of complexity, cost, specialized software, and unreliable vendors.

When flexible manufacturing systems were first put into production the benefits promised by vendors in the design stages were not all realized. Tooling and Production (1986) explained that one possible reason flexible manufacturing systems did not live up to their expectations was that they were oversold by the vendors. The vendors, sometimes unknowingly, promised more than they could deliver. Flexible manufacturing systems were a new and complex concept with many aspects being specialized or made custom. Many inexperienced vendors simply did not realize what was needed to make the system work.

Another drawback to flexible manufacturing systems was the complexity of the software needed to operate the system (Martin, 1989). Flexible manufacturing systems relied heavily on computers to operate and control the entire manufacturing process. The computer systems used include the mini-computers used in each work area, and a central computer which controlled the operation of the entire system. Flexible manufacturing systems were custom built to each customer's specifications, and each required specialized computer software. The need for customized software caused delays in implementing the system, drove the cost up, and often resulted in production interruptions due to program errors.

Kinney (August, 1987), explained the capital investment and operating cost of flexible manufacturing systems made their use impractical in most applications. Flexible manufacturing systems required the purchase of new highly automated and expensive manufacturing and computer equipment. Because of the high investment cost flexible manufacturing systems needed to operate near capacity to be cost effective. During the economic slow down of the 1980's flexible manufacturing systems that were in use were only operating at a fraction of capacity. At the lower production levels the cost of operating and supporting a flexible manufacturing system could not be justified.

Simplification and Down Sizing

Martin (1989) explained that cellular manufacturing took the concepts of flexible manufacturing systems including automated machining, material handling, and computer control and down sized and simplified them. Cellular manufacturing used computer control but it was limited to independent computer numerical controlled manufacturing cells. These cells were not linked together by a central or main computer. This eliminated the need for a main computer, specialized software and the associated problems.

Cellular manufacturing also grouped manufacturing operations into dedicated work areas, but on a much smaller scale. This helped to eliminate the complexity making large system work as one unit and made the work areas more manageable (Martin, 1989). Each work area could operate more independently of each other giving the manufacturing process increased flexibility.

Cellular manufacturing also used the concepts of automated machining and material handling systems, but used simpler versions that already existed and were tried and proven. Kinney (October, 1987) explained existing machines and material handling systems could be used in cellular manufacturing, keeping the price of the initial investment in the system down. More operator involvement in the operation of the work area also limited the need for specialized automatic material handling system to load and unload work pieces. These specialized systems were usually custom built, expensive, and sometimes unreliable.

CHAPTER 3

GENERAL INFORMATION

What is Cellular Manufacturing?

Cellular manufacturing as explained by Martin (1989) is a manufacturing technique where people, processes, and dissimilar equipment are grouped together in an area and dedicated to the production of a family of parts. Kinney (August, 1987) defines cellular manufacturing in further detail by explaining it as:

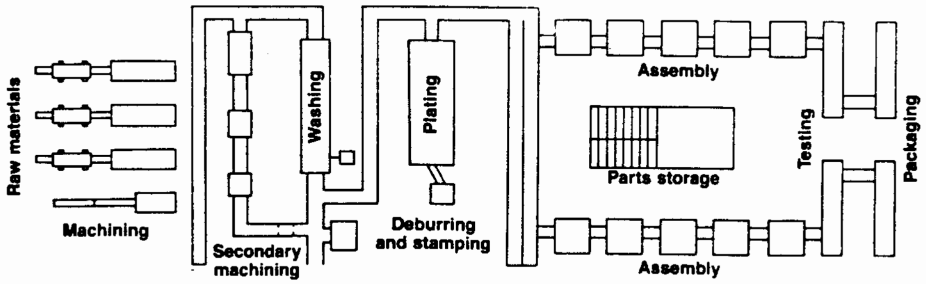
> "... a technique for manufacturing small to medium lot size batches of parts of similar process, of somewhat dissimilar materials, geometry, and size, which are produced in a committed small cell of machines which have been grouped together physically, specifically tooled, and scheduled as a unit." (pp. 54).

Parts produced in manufacturing cells enter the cell as raw material. As the part passes through the cell each station performs a different operation depending on the requirements of the part (See figure 3). Kinney (October, 1988) explains that one of the objectives of cellular manufacturing is that after the part has passed through the entire cell it will be complete and will require no or limited additional processing.

Benefits of Cellular Manufacturing

The benefits of cellular manufacturing can best be seen in its ability to help manufactures to improve their competitiveness by producing small to medium size batches of parts economically. Baran (1991) explains that todays manufactures are facing increased

FIGURE 3
Sample Manufacturing Cell



Note. From "Manufacturing cells trim throughput time 80%". 1986, Modern Material Handling, p. 109..

competition from overseas and customers that demand better quality, shorter delivery times and greater variety. Cellular manufacturing can help meet these demands by reducing lot sizes, reducing throughput time, providing greater flexibility, reducing inventory, improving quality, improving scheduling, reducing material handling, and increased job enrichment. Overbeeke (1988) described these benefits in detail.

Reduced Work In Process - Parts are made in smaller batches and passed directly between operations within the cell eliminating the need for in process storage and stock piling.

Improved Quality. - Since parts are move directly between operations defects caused by material handling are reduced. Defects that do occur for various reasons are found earlier and the cause correct before excess scrape is produced. Operators also develop a since of pride and work harder to eliminate causes for defects.

Reduced Material Handling Cost. - By passing the parts directly between the operations either manually or with material handling systems until completed the distance the parts travel and handling cost are reduced dramatically.

Greater Flexibility. - Parts with similar characteristics are produced on numerical control equipment using common fixturing and tooling making the process of change over between different parts quick and easy.

Reduced Throughput Time. - By passing the parts between the parts directly between the operations within the cell until completed the throughput time is reduced dramatically.

Reduced Lot Sizes - Parts are produced in smaller lot sizes to economically meet the production demands of lower volume and greater variety.

Increased Job Enrichment - Cell operators are given the opportunity to perform several operations instead of just one over and over, and are encouraged to work as a team. Operators are also given greater responsibility including scheduling and set-ups.

Improved Scheduling - Because the machines in the cell can easily change from running one part to another with limited set up cost they can be scheduled more efficiently. Also, because the material does not leave the cell until it's completed it is easier to track, maintain accurate inventory control, and less scheduling is required.

Manufacturing Strategy

The decision to use cellular manufacturing relies on a well defined manufacturing strategy. A long term plan should be developed including future products and potential production volumes. Specific goals including reduced cycle times, improved quality, or reduced product cost should also be identified and consistent with the corporate strategy. The corporate strategy should include an analysis of the industry, sources of competitive advantage, existing and future competitors, and the firms competitive position (Baran, 1991).

To help define the manufacturing strategy, Barran (1991) explains manufacturers should answer questions concerning product strategies, quality demands, technology assessment, and business goals. To answer these question manufactures should:

1. Identify present and future products and their expected volumes.

2. Determine the firm's quality and reliability expectations based on customer's needs.
3. Identify the new products, materials, processes, and equipment necessary to be competitive.
4. Define business goals and performance expectations including quality, productivity, lead times, inventory levels, and return on investment.

When considering the use of cellular manufacturing, manufacturers are forced to develop a good understanding of their manufacturing strategy and future expectations.

Critical Issues

When considering the use of cellular manufacturing, Kinney (August, 1987) explains that every manufacturing cell is different. The cause for these differences are variations in part mix, production rates, equipment availability, labor availability and flexibility, and budget. In spite of the variations there are key issues that are common to all cellular manufacturing operations. These key issue include batch size, part mix, cost of capacity, labor flexibility, setup times, process planning, and the choice between physical and logical cells.

Batch Size

One of the primary advantages of cellular manufacturing is its ability to reduce batch lead times and reduce the amount of work in process (Kinney, August, 1987). The size of the batch being processed has a direct impact on the choice of methods to move the material between the operation within the work cell. The method used to move the material between the operation in turn has a direct impact on the lead times and the amount of work in process.

When the size of the batches being processed are large, Kinney (August, 1987) explains that the movement of parts between operations is "pipelined". Pipelining involves the passing of parts directly from one operation to another without accumulating the entire batch between the two operation before starting the next operation. The pipelining of parts results in lower lead time and work in process inventory levels. Manufacturing cell that are intended to be used for processing large batches should be designed to support pipeline processing.

The opposite of large batch processing is small batch processing. With small batch processing pipelining may not be required. Kinney (August, 1987) explains that as long sufficient room is available, and the number of parts does not become too large, small batches may be allowed to accumulate without having a drastic impact on lead times and the amount of work in process. The increase in lead times and the amount of work in process may be relatively large, but small enough to be acceptable.

Part Mix

As explained earlier one of the main characteristics of cellular manufacturing is the grouping of machinery, people, and processes to manufacture parts with similar attributes. However, Kinney (August,

1987) explains that process rates and setup times can vary significantly in parts with only marginal differences. As the part commonality decreases the need for redundant capacity and labor flexibility increases. To ensure the efficiency of a manufacturing cell it is important to group with as high of process commonality level as possible.

Cost of Capacity

Individual parts within a family of parts may have long cycle times on an individual process or require two operations on the same machine requiring a setup change. When this occurs, Kinney (August, 1987) explains additional machines can be added to the cell to increase throughput. If the cost of increasing capacity is inexpensive additional capacity should be considered even if some of the parts do not utilize the capacity. While the though of under utilized capacity may seem strange it may be justified to increase the capacity of the cell if the cost is inexpensive.

Labor Flexibility

Overbeeke (1988) explains that in a cellular manufacturing environment operators may be required to be more skillful and take on a greater level of responsibility. Operators must know how to perform each operation, and the required setup for all operations within the cell. They need to be trained and expected to perform all the jobs within the cell on a rotating basis. Operators should also be encouraged to help one another when problems or unexpected interruptions occur. For cellular manufacturing to operate at peak efficiency the operators need to view the operation of the cell as a whole and not as individual operations.

Setup Times

An important factor affecting the efficiency of cellular manufacturing is setup times. The flexibility and capacity of a manufacturing cell can be increased significantly by reducing the amount of time spent on setups (Kinney, August, 1987). Reductions in setup times can also allow for reductions in batch sizes and lead times. Cell operators and process engineers need to work together to find ways to reduce setup times and ensure maximum efficiency is reached.

Process Planning

Process planning for cellular manufacturing is completely different than it is for conventional stand alone or for process oriented manufacturing systems. In the past process engineers concentrated on maximizing the output of each individual machine by increasing their feeds and speeds. With cellular manufacturing, Kinney (August, 1987) explains process engineers must concentrate on optimizing the operation of the manufacturing cell as a whole. Matching the feeds and speeds of the machines to the required production rate and using the labor for other operations within the cell is more important than running each machine as fast as possible.

Physical Versus Logical Cells

The traditional definition of cellular manufacturing includes the physical grouping of machines and processes. Exceptions to this rule are processes that are not practical to include in the cell like heat treat or chemical finishing. Kinney (August, 1987) explains that as new specialized manufacturing processes are developed the number of exceptions may increase. The increasingly short product life cycles could also require manufacturing cell to be redefined and rearranged more frequently than is practical.

Logical manufacturing cells are an alternative to physical manufacturing cells. With logical cells, Kinney (August, 1987) explains the operations that are not practical to include in the cell are linked to the cell using automated material handling systems. The automated material handling systems bridge the distance between the work stations allowing them to be included as part of the cell.

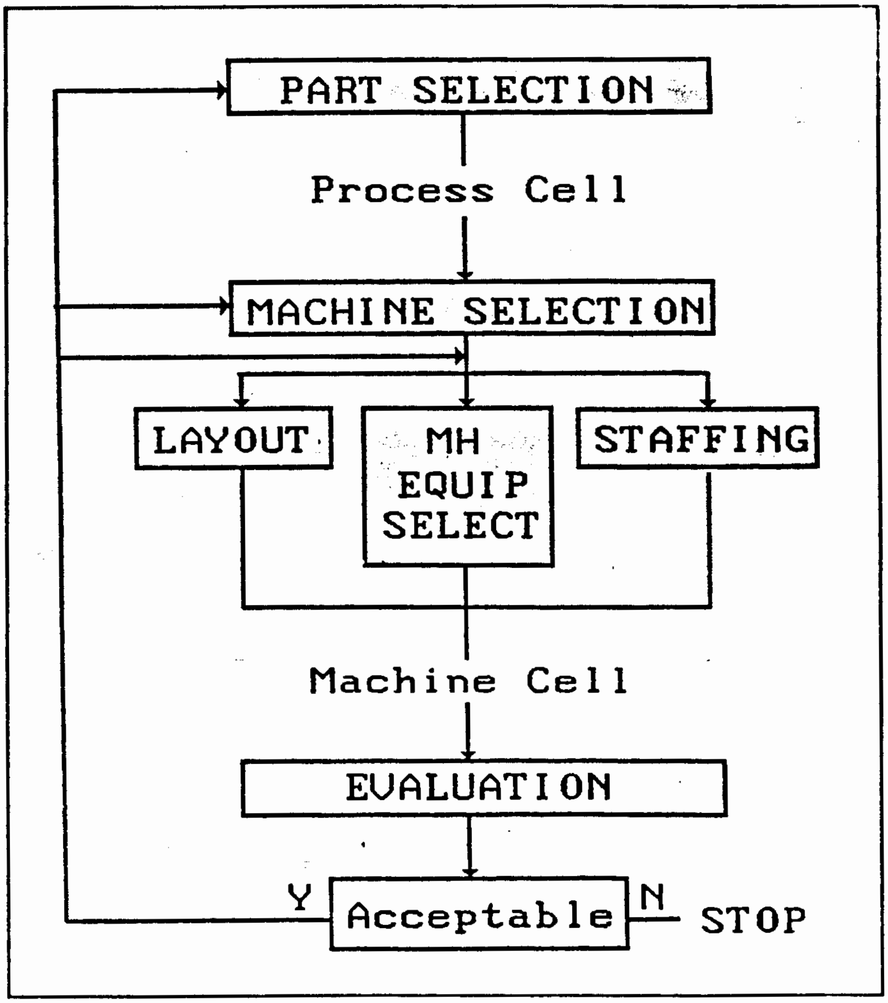
Designing Manufacturing Cells

Once the manufacturing strategy has been developed, and the key issues of cellular manufacturing have been considered, the next step is to design the manufacturing cell. Kinney (October, 1987), explains that designing a manufacturing cell involves virtually every aspect of manufacturing. These aspects include part design, process selection, process planning, staffing, production planning, and scheduling.

Kinney (October, 1987), explains that one approach to designing a manufacturing cell involves a five step decision process. The decisions in this approach concern part selection, machine selection, layout, equipment, and staffing (See figure 4). Another important decision to be considered in manufacturing cell is the method of controlling the manufacturing cell. While each of these decisions are discussed separately, it should be made clear that they can not be made independent of each other and must be reviewed continually as the design is developed. The next step in the design process is to evaluated the manufacturing cell design to ensure it meets the manufacturing strategy.

FIGURE 4

Cell Design Methodology



Note. From "Manufacturing cells solve material handling problems." by Kinney, H. D. & McGinnis, L. F., (October, 1987), Industrial Engineering, p. 29.

Part Selection

Part selection is the process of identifying similar parts or components to be grouped together which are then put into families. These part families are then used as a basis for developing the manufacturing cell design.(Kinney, October, 1987). The parts selected to be grouped should be similar in terms of processing, tooling, and fixturing.

A number of different techniques are available for identifying families of parts including: group technology classification, production flow analysis, and cluster analysis (Kinney, October, 1987). These techniques rely on a relatively complete data base of information containing process routes, part attributes, fixturing, and tooling requirements. If this information is not available a more pragmatic method called "eyeballing" can be used.

Group Technology Classification Group technology classification is a process of forming families of parts with similar attributes based on a code system (Kinney, October, 1987). Each part is assigned a code based on the attributes of material handling requirements, size, demand rates, fixturing, and tooling. Parts with similar codes may then be reviewed and grouped into families. These part codes can also entered into the computer and used for other applications including standardization of design and process planning.

Production Flow Analysis Kinney (October, 1987) stated, "Production flow analysis is a technique for forming part families based on existing process plans." (pp. 29). Each part is assigned machine codes based on the manufacturing operations required. Parts with identical machine codes are grouped into packs. The packs are then represented in a matrix in which an entry of one in a row indicates that pack of parts requires the corresponding machining code. The columns and rows of the matrix are manipulated to find groups of machine codes and packs that make up a cell (See table 1). After manipulating table 1, two families of parts can be identified. (A,C,E) and (B,D,F) (see table 2). There is no set procedure for manipulating these tables, and it is done in a hap hazard fashion.

TABLE 1
Sample Process Flow Analysis Matrix

MACH CODE	PACK: A	B	C	D	E	F
01	1		1		1	
02		1		1		[illegible]
03	1		1			
04				1		1
05	1	1			1	1
06		1		1		

TABLE 2
Manipulate Process Flow Analysis Matrix

MACH CODE	PACK: A	C	E	B	D	F
01	1	1	1			
03	1	1				
05	1		1	1		1
06				1	1	
04					1	1
02				1	1	1

Note. From "Manufacturing cells solve material handling problems." by Kinney, H. D. & McGinnis, L. F., (October, 1987), Industrial Engineering, p. 30.

Cluster Analysis Cluster analysis uses the same process of grouping parts by production processes as the production flow analysis technique. Kinney (October, 1987) explained the difference between the two techniques is the way the matrixes are manipulated. The goal of the two techniques is the same, but cluster analysis uses a logical approach to identify groups of parts that should be processed together. Cluster analysis, however, uses a mathematical technique to replace the hap hazard method used in the production flow analysis technique. The distance between parts in similarity is expressed in mathematical terms.

Eyeball Technique The least analytical method of grouping parts into families is the eyeball technique. The eyeball technique involves visually inspecting parts to find obvious groupings. The drawback to this technique is that while parts may appear similar, the manufacturing processes used to make them may be quite different. Also, as the number of parts increases, the potential for error when using the eyeball technique increases.

Machine Selection

The machine selection process involves identifying exactly which production machines need to be in the cell and how many of each will be needed to meet the production requirements. Kinney (October, 1987) explains when selecting the machinery to be used, the natural temptation would be to want the latest and greatest equipment available. Quite often only one or two operations in the cell will cause a bottleneck and require machines that can provide optimum capacity. Martin (1989) explains that the beauty of cell design is that in most cases manufacturing cells can be set up without new equipment simply by rearranging older equipment. This can be a big advantage for older production facilities, or when capital to buy new equipment is not available.

The process of selecting the machinery to be used in a cell can be time consuming. Kinney (October, 1987) explained that there is no truly useful analytical method for selecting the machinery to be used. Process engineers need to detail the process requirements and functional specifications for each part in the family of parts to be processed in the manufacturing cell. The specifications are then compared to the capabilities of the available equipment to determine the new equipment required.

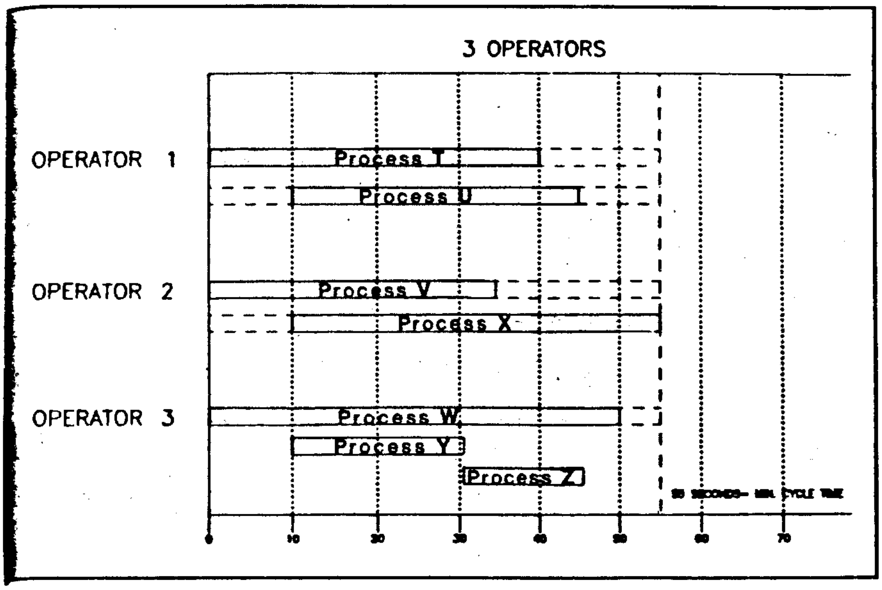
The process of detailing each part in a family of parts requires a lot of time and information. To speed up the process Kinney (October, 1987) suggested using the 80/20 rule when developing the initial cell design. This rule states that 20% of the parts in the family will represent 80% of the work load in the cell. Machinery should be selected to accommodate these high volume parts. Parts in the family that require additional machinery not covered by the initial design can be accommodated by adding redundant capacity to the cell.

Staffing

Regardless of the type of cell design, (physical or logical), Kinney (October, 1987), explains the ideal cell should be staffed by multifunctional operators. The operators assignments may change with each different part type, and operators may need to tend two or more processes simultaneously. While the ability to operate more than one operation at a time may be restricted by the cell layout, the best operator assignment combinations can be found using Gantt charts (see fig. 5). The work loads should also be balanced as much as possible, and operators should be encouraged to help one another when needed.

FIGURE 5

Operator Assignment Gantt Chart



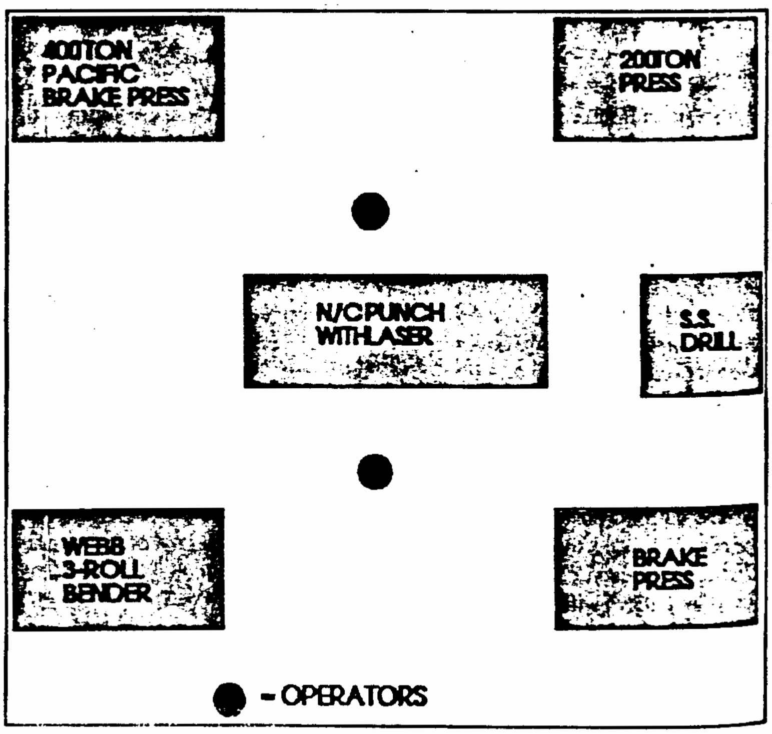
Note. From "Manufacturing cells solve material handling problems." by Kinney, H. D. & McGinnis, L. F., (October, 1987), Industrial Engineering, p. 37.

Layout and Material Handling Equipment

When determining the layout of a manufacturing cell two important factors to be considered are material handling flexibility and work place ergonomics (Kinney, October, 1987). The process routing requirements must be reviewed to ensure the material handling equipment allows the parts to travel to all potential paths through the cell. The machines should also be aligned for easy access by the operators, robots, and material handling equipment.

The two key performance considerations when laying out a manufacturing cell as explained by Kinney (October, 1987) are the opportunities to assign operators to more than one operations while meeting all the required part routings (See figure 6). To meet these two performance considerations process engineers commonly use templates and manipulate them to find the best solution. This manipulation can also be done using computer graphics.

FIGURE 6
Sample Manufacturing Cell Layout



Note. From "Cellular manufacturing: A good technique for implementing just-in-time and total quality control" by Overbeeke, J. & Welke, H. A., 1988, Industrial Engineering, p. 40.

Cell Control

A wide variety of methods are currently available to control modern manufacturing cells. These methods of control range from relatively simple programmable logic controllers (PLC) to the more complex large main frame computer-based cell controllers (Friscia,1989). Between these two extremes there are a variety of control techniques with various levels of complexity. To gain a better understanding of the process of cell control it may be helpful to explain the low and high end of the possible control techniques.

Low End Control A common method of control used at the low end of the control scale are Programmable Logic Controllers. PLCs can be used in conjunction with devices that can store and execute only one instructional program at a time. Mellish (1986) states that the PLCs are used to store a number of instructional programs and the operator must select the program to be used. After being selected the PLC down loads the program to the numerical control device. When the operation is complete, the operator then selects the next program from the PLC and down loads it to the numerical control device, replacing the previous program.

While this method is effective it does not allow for program changes to be made quickly and easily. PLC control also requires all process monitoring, scheduling, inventory tracking, and communication to be done manually. This type of control is considered to be operator dependent because the operator is required to select the program to be used and load and unload the parts being processed.

High End Control At the other end of the control spectrum are large main frame computer based cell controllers. These controllers receive information from a host computer which breaks the master production schedule into specific manufacturing tasks (Mellesh,1986). The tasks are then queued within the cell controller to form a mini schedule. The specific programs to perform these tasks can be stored within the cell controller or down loaded from the host computer.

As the operations are completed, the cell controller communicates the information back to the host computer and to other cells that supply or receive material from the cell. In contrast to PLC controllers, main frame computer based controllers are intended to reduce the level of operator dependency by operating unattended for several hours. Material is delivered between the operations by automated material handling systems and loaded and unloaded from the machines automatically.

The cell controller also monitors the entire manufacturing process being performed. Mellesh (1986) explains that the controller checks to ensure the raw materials, tooling, and fixtures are available. The controller also collects information concerning lot number, start time, and quality measurements. It also collects information on the equipment condition including downtime and causes of idle time.

The possible draw backs to main frame computer based control is its complexity. The more complex the control system, the greater the need for customized software and hardware (Larin, 1989). This need for customization may prove to be expensive and impractical. The high level of complexity may also be viewed as over kill by floor personnel. Friscia (1989), states "There is a back lash going on against advanced technology (including computer based cell controllers) in the manufacturing area." (pp. 80). After the frustrations experienced with Flexible Manufacturing Systems shop floor personnel are inclined to stay with simpler, proven control techniques.

Selecting the Proper Control Technique The selection of the proper control technique is primarily dependent on the level of control desired by the user. Friscia (1989) describes the levels of control in cellular manufacturing as device, cell, area, and plant. At the device level the use of PLCs or the controllers on computer numerical control devices may be adequate. As the levels of control progress, possible control devices may include mini computers, personal computers, main frame computers, or a combination of all three. As the level of computer control increases, it becomes increasingly difficult to distinguish between cellular manufacturing systems and flexible manufacturing systems.

Design Evaluation

According to Kinney (October, 1987) the completed design must be evaluated to ensure it meets the process and capacity requirements Depending on the size and capacity of the cell, this evaluation process can be done using simple Gantt charts, or more complex computer simulation. When evaluating a cell the user should also include the impact equipment failures could have on the manufacturing cell.

To take the evaluation process one step further, Kinney (October, 1987) recommends not only considering the current production rates, but also the possible future production rates and new part types. The evaluation should include what if questions concerning process routing changes, new technology, and increased part family sizes.

Computer Simulation Computer simulation has become an increasingly popular method of evaluating manufacturing cell designs (Overbeeke, 1988). This increased popularity has been kindled by the availability of powerful hardware, and off the shelf software packages made for PC's and work stations. The simulation is used to answer questions concerning que-sizes, lot sizes, and material handling systems.

To further supplement the simulation process Overbeeke (1988) explains that animation packages are available that provide a method to visualize the proposed manufacturing cell in operation. The animation gives the planning group an opportunity to understand the interactions between the machines, or the impact various changes can have on the cell.

Implementing Cellular Manufacturing

With the manufacturing strategy well defined, and the manufacturing cell designed and evaluated, the next step is implementation. While this may seem to be the easiest of the steps to this point, the implementation process can have the largest impact on a manufacturing cell's success or failure. Droy (1987) stated that one of the key factors to ensure success is to "... involve the shop floor from planning through implementation." (pp. 67).

Martin (1989) explains that in addition to the shop floor people, it is important to include people from the various functions of the production process including manufacturing engineering, quality, information services, etc.... These various functional groups need to understand the process of cellular manufacturing, their job roles, and the impact it might have on their area, before the manufacturing cell can be implemented. Cellular manufacturing can be thought of as a "... grouping strategy that requires a group effort" (Martin, 1989).

Another suggestion given by Droy (1987) to ensure a successful implementation of cellular manufacturing is to give the cells identity. This can be done in a variety of ways including:

1. Giving each cell a specific name that distinguishes it from the rest of the manufacturing operations.
2. Painting the equipment a different color to distinguish it from the other manufacturing areas. The different color can also signify the process of change and improvement at a glance.

3. Placing a bulletin board or showcase in the cell that shows the improvements in quality, inventory, lead times, and part travel compared to before cellular manufacturing was introduced.
4. Providing the operators with shirts or jackets that identify them with the cell.
5. When scheduling the cell provide the operators short horizon schedules, and let them decide the order to make components to meet the production requirements and minimize setup costs.

Each of these suggestions is intended to gain the endorsement of the shop floor personnel by giving them a sense of ownership and responsibility for the manufacturing cell. Droy (1987) states that, "if the shop floor is behind the idea: it will likely be successful; if not, the planning and execution will probably fail." (pp. 68).

By following the suggested guidelines the process of implementing cellular manufacturing can be improved, but Koelsch (1990) explains to be prepared for "a lot of confusion, resistance to change, lack of understanding, delays, hard work, and frustration" (pp. 77). During the implementation process the focus should be on the original cell design and purpose, communication, training, and working together will make it worth the effort.

Traditional Job Roles

The concept of cellular manufacturing and its effect on traditional job roles can at first be both frightening and frustrating (Koelsch, 1990). It requires changes to be made in the traditional job roles of almost all aspects of the manufacturing process, wage and salaried employees alike. At first employees may be resistant to this need for change, but with training and communication the process of change can be performed smoothly.

Wage Employees

Traditional process oriented manufacturing systems required wage employees to perform monotonous, repetitive task classified by restricted job descriptions. Pay systems were primarily based on each individuals output on a specific operation. Employees had little control over the duties they perform or their work environment. These conditions resulted in lower quality levels, loss of productivity, boredom, and in general low job satisfaction (Overbeeke, 1988).

Cellular manufacturing, however, according to Overbeeke (1987), requires flexible people who are capable of performing several different task, under broad job classifications. Employees are not only responsible for performing the operations and required setups, but may also be involved in scheduling, problem solving, and operations improvements. Operators are given greater control over their work environment and encouraged to think of the manufacturing cell as their work place.

The methods to determine an employees pay are also different when using cellular manufacturing. Cell operators are encouraged to work as a team by basing each persons pay on a group incentive standard. The standard is based on the output of the manufacturing cell as a whole and not on each individuals output. These conditions result in improved quality, productivity, and job satisfaction (Overbeeke, 1987).

Departmental Supervisor

Cellular manufacturing can have a dramatic impact on traditional job role of a departmental supervisor. The traditional method of large batch manufacturing required the departmental supervisor to spend a large portion of their time chasing after parts coming to their department from other departments or storage facilities (Overbeeke, 1988).

In contrast cellular manufacturing would reduce the amount of chasing by reducing the dependency on other departments or storage areas. According to Modern Material Handling (1986), the ideal cell would start with relatively raw material and end with a completed part or subassembly. (p. 109). This would allow the supervisor to become more involved in other projects such as orchestrating continuous improvement programs within the cell and in the product design. (Overbeeke, 1988).

Design Engineers

In the past Design Engineers traditionally developed a new product design and then passed it along to the Process Engineers to determine the processes and equipment needed to produce it. Kinney (October, 1987) explains that with cellular manufacturing Design Engineers must work closely with Process Engineers during the design stage to ensure new product designs are compatible with existing manufacturing cells. This prevents the cost of reorganizing existing manufacturing cells, or designing new ones.

Process Planners

As explained earlier, process planning for cellular manufacturing systems is completely different than it is for other manufacturing systems. In the past process planners would optimize the output of each individual operation by running the equipment as fast as possible. Kinney (August, 1987) explains that rather than optimizing the output of each operation in the manufacturing cell process planners must optimize the output of the manufacturing cell as a whole.

Production Schedulers

The process of production scheduling is also completely different when using cellular manufacturing. When using traditional manufacturing system the production scheduler would receive detailed requirements for parts processed in their area based on the master production schedule. The scheduler would then make assignments to the individual machines based on the calculated amount of time required on each machine to manufacture the parts. When the parts where complected they would be sent to the next department to receive additional processing and the scheduling process would start all over.

With cellular manufacturing the production scheduler would also receive detailed requirements for the operations in their area based on the master production schedule. But, instead of making work assignments based on individual machine capacities, assignments would be made based on the capacity of the cell as a whole. In ideal cells the parts are considered finished when they leave so the scheduling process does not need to be repeated. The parts are shipped as completed or sent to a final assembly operation. Chernik (1987) explains this method of scheduling is much faster and more efficient than traditional scheduling methods.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Summary

Cellular manufacturing can be a powerful tool in meeting todays customers need for high variety and short product life cycles. Cellular manufacturing enables manufactures to produce mid-volume mid-variety products economically while increasing productivity, efficiency, and quality. These improvements are accomplished by reducing lead time, batch sizes, and material handling cost while increasing job satisfaction, product quality, and flexibility.

When considering the use of cellular manufacturing potential users must first develop a detailed manufacturing strategy and review critical issue that impact the design of of a manufacturing cell. These two factors are used to form the foundation of cellular manufacturing. If these two areas are not well defined the concept of cellular manufacturing will likely fail.

The design process of cellular manufacturing can be viewed as a five step decision process. Each of these steps must be constantly reviewed as the design is developed to ensure it is consistent with the manufacturing strategy. The design must also be evaluated to ensure it meets both the process and capacity requirements for the products being made. Manufacturing cells design should be evaluated using computer simulation and animation. This allow the designers to ask what if questions and visualize the interaction between the areas within the cell.

The method of implementing cellular manufacturing can have the strongest impact on determining its success or failure. To ensure its success functional groups through the entire organization will need to be feeling to make changes in their traditional job roles. Manage must show true commitment to the concept of cellular manufacturing and be willing to give the wage employes greater responsibility. Wage employes must be willing to perform a variety of tasks, except added responsibility, and work as a team. The implementation cellular manufacturing may prove to be difficult but with commitment, communication, and cooperation it can prove to be well worth the effort..

Conclusions

Based on the current trends in manufacturing the following conclusion can be made.

1. Customers are going to continue to want more variety forcing product life cycles to become short and requiring manufactures to produce produces in smaller quantities and greater variety.
2. Cellular manufacturing will become an even more popular tool to meet these needs economically.
3. As advancements are made in technology and the process of cellular manufacturing is refined, there may be an increased interest in flexible manufacturing systems to meet the customers need for variety and low volumes.

References

Akbay, K. S. & Musil, D. C. (1989, November). Improve efficiency of a FMS cell through use of a computer simulation model. Industrial Engineering, pp. 28-34.

Baran, J. J. (1991, February). Tips on tackling GT-based cells. Manufacturing Engineering, pp. 46-49.

Chernik, R. C. (1987, August). One company's experience with automated flexible cells. Tooling & Production, pp. 24-27.

Droy, J. (1987, March). Tips on developing cells. Production Engineering, pp. 67-68.

Facilitating Juran on quality improvement. (1990, June). (Available from [Juran Institute, Inc., 11 River Road, Wilton, CT 06897]).

Fisher, G. M. (1990). Measuring the unmeasurable. World, 2, 4-5.

FMS, cells, and machining centers. (1986, August). Tooling & production, pp. 20-26.

Friscia, A. J. (1989, January). Cell controls. Automation, pp. 80.

Greenwood, N. R. (1988). Implementing flexible manufacturing systems. New York: Halsted Press.

Hays, E. (1988) The just in time breakthrough New York: John Wily & Sons

Juran, J. M. "Ed." (1979). Quality Control Handbook . New York: McGraw-Hill.

Koelsch, J. R. (1990, September). Flexible cells take control. Manufacturing Engineering, pp. 75-77.

Kinney, H. D. & McGinnis, L. F. (1987, August). Manufacturing cells solve material handling problems. Industrial Engineering, pp. 54-60.

Kinney, H. D. & McGinnis, L. F. (1987, October). Design and control of manufacturing cells. Industrial Engineering, pp. 36-41.

Larin, D. J. (1989, January). Cell control: What we have, what we'll need.

Maleki, R. A. (1991). Flexible manufacturing systems. New Jersy: Prentice-Hall Inc.

Martel, R. (1989, October). Reduction in lead time does make the difference in profitable operations. Industrial Engineering, pp. 25-28.

Martin, J. M. (1989, January). Cells drive manufacturing strategy. Manufacturing Engineering, pp. 49-54.

Manufacturing cells trim throughput time 80%. (1986, August). Modern Material Handling, pp. 107-109.

Mellish, M. (1986, April). Gaining control of work cells. Mechanical Engineering, pp. 30-32.

Overbeeke, J. & Welke, H. A. (1988, November). Cellular manufacturing: A good technique for implementing just-in-time and total quality control. Industrial Engineering, pp. 36-41.

Patankar, A. K. (1991). Flexible manufacturing systems: A survey of U.S. applications. In N. K. Jha (Ed.). Handbook of flexible manufacturing systems. (pp. 275-292). New York: Academic Press.

Steinhilper, R. (1985). Recommendations for FMS planning realization. In H. J. Warnecke & R. Steinhilper (Eds.). Flexible manufacturing systems. (pp. 87-98). New York: IFS Publications.

Bibliography

Cells boost engine-part output. (1986, August). American Machinist & Automated Manufacturing, pp. 65-68.

Evans, J. R., & Lindsay, W. M. (1988). The management and control of quality. St. Paul: West.

Flexible manufacturing cell enters next phase. (1992, January). Wood & Wood Products, pp. 62.

Herbert, S. (1992, June). When the old ways work best (cell manufacturing). Engineer, pp. 16-17.

Knight, D. O., & Wall, M. L. (1989, January). Using group technology for improving communication and coordination among teams of workers in manufacturing cells. Industrial Engineering, pp. 28-34.

Manson, F. (1985, October). Planning a machine cell. American Machinist, pp. 103-105.

Miller, P. C. (1991, February). Automation swings to cells. Tooling & Production, pp. 51-55.

Owen, J. V. (1990, August). Flexible cells and machining centers. Manufacturing Engineering, pp. 24-28.

Owen, J. V. (1990, September). Flexible justification for flexible cells. Manufacturing Engineering, pp. 39-45.

Quinlan, J. C. (1987, August). Flexible cells for small companies: a dilemma. Tooling & Production, pp. 28-30.

Wolfe, I. & Wallin, R. K. (1984, October). Customizing a machining cell. American Machinist, pp. 86-89.