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CELLS AND FLEXIBLE AUTOMATION: HISTORY AND SYNERGISTIC APPLICATION

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1. INTRODUCTION

Flexible manufacturing equipment is the technological union of computer integration and machine tools. Flexible manufacturing is commonly understood as offering certain types of 'flexibility' for manufacturers to mitigate or manage the significant uncertainty they may encounter. For example, with this investment they are better able to respond to customers' needs and desires in product design, product availability, and adaptation for successive part-type designs. Such promises have resulted in widespread investment in these technologies in industry and significant investment in research in academia. The competitive pressures in global manufacturing markets, primarily during the 1980s, drove companies to improve product quality and 'flexibility' without sacrificing operational cost reductions already achieved in many industries. The use of flexible automation was suggested as one way to answer these pressures, even though these new technologies were more expensive. However, it soon became clear than mere capital investment was insufficient to satisfy these challenges: significant technical and managerial issues needed to be resolved before the full benefits of these technologies could be attained.

There is a continuum of what is considered flexible automation. Although there has been great progress in the area of flexible assembly, the majority of installations and research has focused on flexible machining. The basic building block of such flexible automation is the machine tool which could be a lathe, drill press, milling machine, or other material (usually metal) removal device.

A description of the technologies and their historical development is discussed in §2. The capabilities inherent to these technologies are also included. This discussion leads to an outline of the various research streams associated with flexible automation in §3. The literature suggests that these technologies must necessarily be managed differently compared with conventional technologies in order to reap the promised benefits. In order to understand these differences, the 'flexibility' exhibited by flexible automation needs to be understood. The various flexibilities are examined in §4. §5 contains a discussion of the relationship of flexible automation to group technology and cellular manufacturing. Issues for future research are highlighted in §6. Concluding remarks are in §7.

2. FLEXIBLE AUTOMATION: DESCRIPTION AND HISTORY

Flexible automation has many accepted definitions and meanings. For example, a small example of flexible automation is a stand-alone CNC machine tool, whereas a totally automated system contains multiple CNC machine tools, possibly with robotic arms loading and unloading parts, automated guided vehicles transporting parts between machines, inventories sometimes accessed by automated storage and retrieval systems, and a coordinating computer overseeing the scheduling and production planning of the system. Installations of flexible automation can be found throughout the world that lie on the automation continuum anywhere between the above examples. The level of human intervention varies inversely with the level of automation, with the appropriate mix determined by the particular application.

Flexible automation may be found in both fabrication and assembly and the various types of manufacturing included in these categories. However, the focus in this paper is on flexible automation in fabrication and machining. This is because of both historical circumstances and the particular focus here on cellular manufacturing. That said, it would be remiss to not highlight the rapid advances of flexible automation in assembly operations. Automated assembly is extremely complex because of the necessary planning for all contingencies that can occur during operation. There is also the complicated nature of the process itself: the combination of multiple physical parts brought together into an assembly. This aspect can require an enormous number of monitoring devices to ensure a successful operation, an expensive proposition. Since automated assembly is currently used mostly in simple tasks, and flexible assembly automation, where multiple part types may be assembled at a single station, is still in the development phase, we do not discuss it further. Interested readers should consult Boothroyd (1992).

Various texts provide extended histories of process automation technologies (Cohen and Apte, 1997; Buzacott and Shanthikumar, 1993) including the evolution of flexible automation. A shorter description is now provided. Flexible automation has its source in fixed automation which began to appear in the early 20th century, particularly in the Ford Motor Company in the United States. Fixed automation is a group of special purpose technologies and was developed to attend to a regimen of relatively simple tasks repeated many times. The automation fit perfectly with Henry Ford's philosophy of automobiles with few variants or options but at high volumes to spread the fixed costs over many units. This type of automation evolved during the first half of the 20th century and was used in conjunction with human operators.

In the wake of the second World War, development on machining centers (usually for prismatic rather than rotational workpieces) took place with the arrival of the first numerical control machine tools. These technologies delivered commands to the machine tool, controlling the spindle speed, axes location and movements, and tool movements and speeds. Initially these commands were hardwired into the machine tools, typically milling machines and drill presses. The next development was to have instructions delivered via punched paper tape, allowing some greater flexibility in the variety of programs that could be executed on a machine.

The rapid advances in computer technology subsequently permitted direct numerical control (DNC) of machine tools, where a centralized computer issued commands to numerous numerical control machine tools. This was appropriate when computer technologies were still somewhat expensive and physically bulky. However, the advent of microprocessors allowed the computer control of the machine tools to become localized, with one computer dedicated to a single machine tool. This computer numerical control (CNC) lessened the impact of computer downtime, a mishap which disabled all the machine tools under DNC but affected only the local machine tool under CNC. As with all computer technologies, the reliability of numerical control of CNC machine tools today is not questioned; the cause of unplanned downtime on CNC machines today is more likely to be a broken tool or another unexpected contingency.

The CNC machine tool is the basic building block of flexible automation in machining. This is because it is easy to download part programs consisting of code describing machine operations using a reasonably high-level language for a variety of part types. These part programs can be easily adapted for engineering design changes or generational changes in the part design. Consequently, access to a library of 'standard' program routines, which may be executed from larger programs, enables far greater versatility than equivalent paper-tape machine tools. Interface with a variety of ancillary machine tool equipment such as robot arms, tool exchangers, tool magazines, automated pallet changers, inspection equipment, part conveyors, CAD/CAM, and automated guided vehicles provide greater flexibility capability.

The typical operation of a flexible machine is as follows. A part is delivered to the machine either by a human operator, an automated guided vehicle, a gravity feed system, or a conveyor. Parts are attached to fixtures designed to hold the parts during machining. The fixtures are attached to pallets which are held on a table inside the CNC machine. The part may be put onto a fixture by operators at the machine or it may be manually put on the same fixture and pallet at a load/unload station and then travels through the system. Sometimes the table inside the machine can rotate so that the spindle holding the tool may cut multiple sides of a part, or multiple parts may be attached to different sides of a fixture. The pallet itself is sometimes fixed semi-permanently to the machine table or sometimes it is automatically exchanged with another pallet containing a new part. The part program is downloaded into current memory and the sequence of operations described by the code commences, controlling the axial movement, spindle speed, tool exchanges, table rotations, coolant delivery, and many other tasks. Once the task sequence has finished, the part/fixture/pallet is changed for another part either automatically (pallet exchanger, robotic arm) or by an operator. The new part may be the same type or different from the newly completed part. The entire sequence occurs again without delay because a different part program may be downloaded almost instantaneously and a different task sequence can commence, requesting different tools and tasks. Due to a finite tool magazine capacity, care must be given to the decisions concerning which tools are loaded. This is one production planning problem (the loading problem) that must be planned for in order to successfully operate a flexible manufacturing system. This and other production planning problems are discussed in §3.

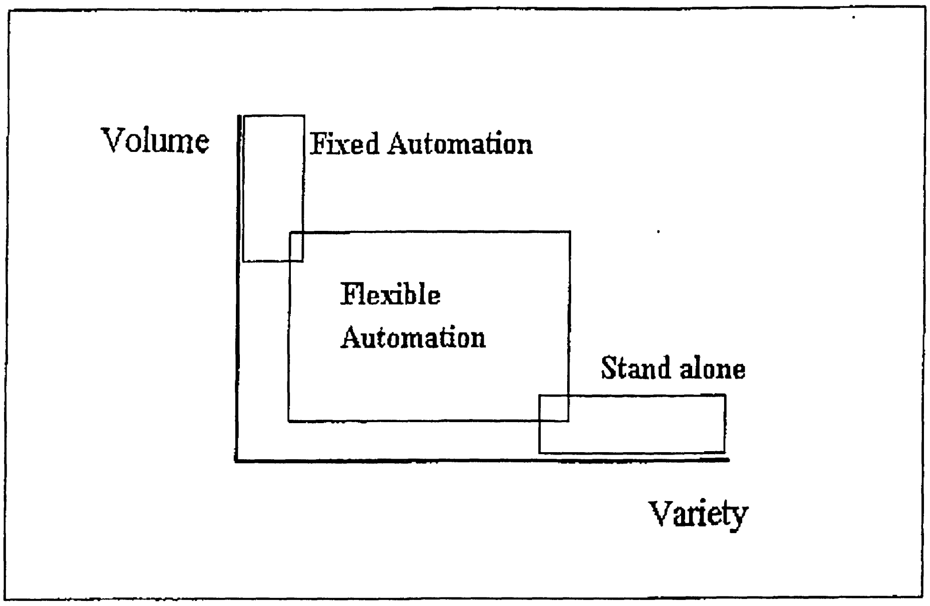

Figure 1. Location of flexible automation on volume and variety scales

It may seem that a system having all of the ancillary hardware listed above may be the most flexible of flexible automation. However, it is generally considered that the hierarchy of flexibility follows that in Figure 1. The placement of flexible manufacturing systems, a common form of flexible automation, is positioned to make a medium variety of part types and a medium volume of parts of each type. A dedicated manufacturing technology makes a very limited variety of parts (typically one) but at high volumes. A stand-alone machine tool, perhaps operated by a skilled worker, is considered more flexible in that many more part types can be made but with a correspondingly smaller volume. It is commonly said that flexible automation attempts to gain the efficiencies of large batch processing while retaining the flexibility of a job shop. Flexibility here means an ease of changing between the manufacture of different part types. Many other aspects of flexibility are presented in §4.

3. FLEXIBLE AUTOMATION: LITERATURE AND RESEARCH

The research described as flexible automation research using management science and operations research techniques began to appear regularly in academic journals in the early 1980s. Here, we highlight the various research topics, survey articles, and pieces which contributed significantly to the field. Survey articles include Gunasekaran et al. (1993), which surveys many articles related to flexible manufacturing, Buzacott and Yao (1986), which reviews analytical models, and Sethi and Sethi (1990), which reviews various aspects of manufacturing flexibility.

In a study of early flexible manufacturing practice, Jaikumar (1986) described differences in FMS usage in Japan and the United States. The study found that the more of the capabilities of FMSs were being utilized in Japan, where greater numbers of part types were being made concurrently, and more part designs were being introduced on the machines every year. The American counterparts were using the systems to make high volumes of a few part types, turning over the designs of parts infrequently. These observations should be regarded with caution when considering the situation since then. In a more recent study, Mansfield (1993) ascertained that the rate of acquiring flexible manufacturing systems was no slower in the United States than in Japan but that the first installations in particular industries occured later in the U.S., and the expected rate of return in the U.S. was lower than in Japan. While not exploring the differences in usage as seen in Jaikumar (1986), Mansfield suggests that there could simply be a lag in experience in the usage of such systems between companies in the two countries. This would imply that this difference in usages of system potential could merely be a symptom of this lag, and anecdotal evidence and factory visits strongly suggest this. The difference in usage might also be explained merely by different needs from the system.

As Gunasekaran et al. (1993) notes, management decisions regarding flexible manufacturing systems can be divided into pre-release and post-release decisions. The former deal with decisions that pertain to the planning of parts, machines, and tools before production begins, whereas the latter deals with the decisions once production has begun. Stecke (1983) provides a framework for the production planning (i.e., pre-release) decisions relating to FMSs. This framework suggests the following five problems, with some representative articles:

(a) Part type selection problem: From a set of part types that have production requirements, determine a subset for immediate and simultaneous processing (Stecke and Kim, 1988; Hwang and Shogan, 1989).

(b) Machine grouping problem: Partition the machines into machine groups in such a way that each machine in a particular group is able to perform the same set of operations (Purcheck, 1985; Kumar et al., 1990).

(c) Production ratio problem: Determine the relative ratios at which the part types selected in problem (a) are to be produced (Stecke, 1992).

(d) Resource allocation problem: Allocate the limited number of pallets and fixtures of each fixture type among the selected part types (Montazeri et al., 1988; Widmer et al., 1990)

(e) Loading problem: Allocate the operations and required tools of the selected part types among the machine groups subject to technological and capacity constraints of the FMS (Kumar et al., 1987; Sarin et al., 1987).

This framework has formed the basis for much research in FMS production planning. These five problems are interrelated and ideally should be solved simultaneously. Indeed many researchers have solved two or more of these problems simultaneously, although it is more common to observe single problem models. Most of these problems are solved subject to the constraints of the other problems, resulting in feasible solutions. Although not all these problems are unique to FMSs, some are very specific, such as the loading problem. The loading problem arises since a machine in an FMS has automated tool exchanging from a tool magazine which typically hold 60 tools, although some have up to 160. Determining which tools should be allocated to a magazine is a challenging management problem that can affect various other functional areas (Gray et al., 1993). FMS planning problems are seen as more complicated than the comparable dedicated system decisions because the system needs to adapt to a variety of contingencies that may arise during automated production. Examples are the completion of the operations for a given part type which must be followed by a different setup, or a tool breaking on one machine and a reallocation of work to the remaining similarly equipped machines in the group. An FMS is typically known for its multiple and frequent setups whereas a more conventional technology has few and infrequent setups. Other pre-release decisions would be the machine and equipment selection (Whitney and Suri, 1985; Monahan and Smunt, 1989; Fine and Li, 1988), design of the FMS layout (Kouvelis and

Kiran, 1989; Afentakis et al., 1990; Heragu and Kusiak, 1988), and economic justification of the investment (Fine and Freund, 1990; Wallace and Thuesen, 1987; Meredith and Suresh, 1986; Son, 1992; Rajagopalan, 1992).

The post-release decisions are scheduling problems. Some representative articles are Doulgeri et al. (1987), Garetti et al. (1990), Montazeri and Van Wassenhove (1990), Sawik (1990), and Shalev-Oren et al. (1985).

4. MANAGING FLEXIBILITY: HOW IT CAN BE DONE

There are many meanings of flexibility in manufacturing. As a result of the recent developments in manufacturing technologies, there has been much work on defining workable definitions. Browne et al. (1984) were the first to formally present a taxonomy of eight manufacturing flexibility types, with Sethi and Sethi (1990) reviewing the large literature on the field that grew in the intervening years. Sethi and Sethi (1990) identified about fifty terms relating to eleven flexibility types. Recent activity has focused on developing valid measures for these flexibility types. To a lesser extent, there has been empirical work attempting to determine the 'true' nature of manufacturing flexibility. Some work in this area is Dixon (1992) in the textile industry, Upton (1994, 1995) in the paper industry, and Maffei and Meredith (1995) in various industries. Gupta and Somers (1992) and Slack (1987) gathered the opinions of executives to investigate manufacturing flexibility. They found that managers' knowledge of flexibility is not consistent, providing impetus for further study of the topic.

Flexibility has been examined before under the auspices of economics (e.g. Kreps, 1979) and mathematics but we focus on manufacturing applications. The commonly accepted flexibility types (Browne et al., 1984; Sethi and Sethi, 1990) are:

Machine flexibility (of a machine) refers to the various types of operations that the machine can perform without requiring a prohibitive effort in switching from one operation to another.

Material handling flexibility is the ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves.

Operation flexibility of a part refers to its ability to be produced in different ways, commonly by changing the sequence of operations.

Process flexibility of a manufacturing system relates to the set of part types that the system can produce without major setups.

Product flexibility is the ease with which new part types can be added or substituted for existing part types.

Routing flexibility of a manufacturing system is the ability to produce a part by alternate routes through the system.

Volume flexibility of a manufacturing system is its ability to be operated profitably at different overall output levels.

Expansion flexibility of a manufacturing system is the ease with which its capacity and capability can be increased when needed.

Program flexibility is the ability of the system to run virtually untended for a long period.

Production flexibility is the universe of part types that the manufacturing system can produce without adding major capital equipment.

Market flexibility is the ease with which the manufacturing system can adapt to a changing market environment.

This piecewise segmenting approach to manufacturing flexibility implicitly assumes that there are various types of flexibility which are more effectively captured by individually considering them. Indeed, much work has focused on developing measures for individual flexibility types (for example, Brill and Mandelbaum, 1990). Other researchers (Chung and Chen 1989) took a more 'holistic' approach. The variety of approaches is a strength in this challenging field and is not considered contradictory.

While acknowledging the multiple types of flexibility, further aspects of the flexibilities are highlighted. For example, Slack (1983) considers flexibility to be a measure of *potential* rather than performance, whereas Browne et al. (1984) see both *potential* and *actual* aspects of flexibility. This distinction between the potential and actual dimensions of flexibility is discussed by Dixon (1992) also. Further, other 'dimensions' of flexibility have been used to develop measures. These include:

Action vs *State* (Mandelbaum, 1978). Action flexibility is considered present when active decisions are needed to counter new circumstances after some change. State flexibility is considered present when the system can cope with changes without intervention.

System vs *Machine* level (Buzacott, 1982) refers to the source of the capability for the flexibility type. For example, machine flexibility is a machine level flexibility since it is self contained, and independent of the other system elements. Routing flexibility on the other hand is a system level flexibility since it requires system resources (machines tools, materials handling system, coordinating software) to be used.

Range vs *Response* (Slack, 1987) refers to the distinction between the extent to which a system can adapt to a change, and how quickly it adapts to the change. Slack and Upton (1994) observed that managers thought about flexibility more constructively when aligning their thoughts along these dimensions.

Static vs *Dynamic* (Carlsson, 1992) refers to the scope of uncertainty surrounding the changes to the system. If a system is static flexible, it is capable of handling foreseeable changes such as fluctuations in demand. Dynamic flexibility refers to the system's ability to cope with changes that were largely unpredictable such as sudden regulatory or environmental changes.

Potential vs *Actual* (Browne et al., 1984) draws the distinction between possessing a flexibility to use when a circumstance arises, and utilizing a flexibility consistently in operations regardless of contingencies. For example, a potential use of routing flexibility would be having the AGV routes programmed and laid out between various machine tools and load/unload stations but using only a fixed route until a machine breakdown or some other event occurs. The active use of routing flexibility would be sending parts through the system independent of changes.

Short vs *Medium* vs *Long term* (Carter, 1986) refers to the time horizon over which the flexibility type influences the system or the system's environment.

Range vs *Mobility* vs *Uniformity* (Upton, 1994) refers to three aspects of length of measure, ease of movement, and similar performance at different operating positions.

Now, how can manufacturing flexibility be managed? As can be seen from the above taxonomies, flexibility is a complicated concept. However, it may be more beneficial for managing flexibility by thinking along these dimensions and types rather than attempting to manage the rather nebulous 'manufacturing flexibility' as a whole. Upton (1995) suggests that flexibility can be managed but that it is folly to assume that automation alone will provide this flexibility; the involvement of human operators is more important for effective utilization of manufacturing flexibility than computer integration. Upton (1995) found that inexperienced workers may provide more operational mobility flexibility than experienced workers; this was attributed to not being as conscious of equipment limits. Maffei and Meredith (1995) investigated the importance of the operational infrastructure to achieving the benefits of flexible manufacturing technologies. The three aspects of operational integration considered were: operator's role, the production planning systems, and the integration of technology. Specific relationships between these infrastructures and system benefits were proposed.

5. FLEXIBLE AUTOMATION, CELLULAR MANUFACTURING, AND GROUP TECHNOLOGY

Flexible automation, group technology, and cellular manufacturing are three distinct concepts. However, when they are applied concurrently, a powerful mixture may result. The three can be used separately with positive results, but as we observe, the synergy of using all three can sometimes result in a formidable combination.

We firstly establish some common definitions for sake of clarity. Group technology (GT) is a technique which groups part types into families based on some common factor or factors, such as manufacturing process or functionality. Cellular manufacturing is a layout strategy based on grouping manufacturing equipment into cells to produce a family of part types. These terms are sometimes used interchangably in the literature. As discussed earlier, flexible automation is a technology which permits the concurrent manufacture of multiple part types. For the sake of exposition, these are simplified definitions.

Group technology has various techniques and criteria for achieving the grouping of the part types. The primary criteria for categorizing part types are some form of commonality in part geometry or processing requirements. The operating objective of classifying the part types in this way is to subsequently manufacture more efficiently, in some sense, than could otherwise be done with all of the part types in one large family, by exploiting some aspect of commonality in the manufacture while still maintaining a portfolio of heterogeneous part types. For example, if all of the cylindrical part types requiring a specific customized tool were grouped into the same family, they could be manufactured on a single lathe machine, in a cell with other machines for the remaining operations. However, the criteria by which parts are grouped into families can vary markedly, depending on objective, which is a primary challenge for GT researchers.

Cellular manufacturing (CM) is often regarded as directly related to group technology because the techniques can naturally be applied together. It is, however, a separate concept that may be applied independently. Simply stated, CM is the grouping of several machines into a configuration that specializes in the production of a part type family. The suggested benefits of cellular manufacturing are reduced material handling, less work in process inventory, fewer quality problems through more direct feedback, greater operator commitment, reduced production leadtimes, and fewer machine setups. Manually operated cells are often U-shaped for ease of movement for the operator, flexibility and balance for operators, more immediate rework of mistakes, team-oriented, and easier linking with other U-shaped lines. More automated cells can be any shape.

Radharamanan (1994) suggests that flexible automation should be considered differently when analyzed in group technology. He suggests that machine tools can be grouped logically rather than physically since they have automated material handling available. He then suggests methods for grouping part types that are particularly suited for flexible manufacturing systems, which overcomes limitations of usual methods, and a group scheduling heuristic for batch production processes.

More pertinent than the automated material handling equipment is the availability of automated tool handling and tool magazines, which enable a variety of operations to be performed on a single machine tool. For an FMS, the set of similar part types produced simultaneously can easily and quickly change over time, just by changing cutting tools. A logical machine tool can be changed continuously by exchanging cutting tools resident in the automated tool magazine. The distinction between physical and logical machines is an interesting one and potentially very useful; it should be explored further in future research.

Burbidge (1992) states that GT is a useful precursor to flexible automation. He suggests that GT permits suitable tooling families to be found for automation investment in the future. Specifically, he details how a group technology technique, Production Flow Analysis (PFA), can be used as a tool to plan for flexible automation. PFA is a technique used to plan a change from a process-focused plant to a product-focused plant. PFA divides part types into "families" and machines into associated "groups" to define the part type families. This simultaneous finding of families and groups highlights the difference of PFA from the usual classification and coding (C&C) systems such as OPITZ, KC-1, KK-

I, MICLASS, TELKA, CODE-MDSI, DCLASS, and BRISH-BIRN. These C&C schemes are used to decompose part types into descriptions of geometric shape, material, dimensional accuracy, function, and so forth. PFA incorporates C&C but goes the additional step of examining the flow of material at the company, factory, department, and machine group level.

PFA is divided into five progressive techniques: company flow analysis, factory flow analysis, group analysis, line analysis, and tool analysis. Burbidge suggests that the sequential solution of these PFA phases up to and including line analysis results in a useful plan for the design of FMSs. Line analysis is based on examining the flow of material between machines in a group. Given a large proportion of "simple" part types (i.e., part types that could be made on a combination of lathes, drills, and mills) in a family, the selection of flexible automation could greatly simplify the flow. The final PFA phase is tool analysis, which considers each machine in a group and determines the list of tooling required, tooling families of part types made with the same tools, and information needed to reduce tooling variety and standardize the tooling used in a group.

The successive nature of PFA suggests that the decisions taken at one stage are fixed for subsequent stages. However, the nature of flexible automation suggests that PFA is an inappropriate tool for planning either the design of FMSs, the part type assignments to FMSs, or the tool loading of FMSs. Since many tools can be allocated to a single tool magazine on a flexible machine, it seems inappropriate to allocate machines, part types, and tools at different stages. Also, tools are changed over time, to allow the production of different part types on different days, for example.

The concept that GT can form a basis to design FMSs contrasts with the experiences of Slomp et al. (1993). They studied seven Dutch manufacturers who found that acquiring flexible automation first, served as a useful precursor to the development of cellular manufacturing in their firms. Several of the companies that were studied, had acquired flexible machine tools first, which then acted as a catalyst for the transition from a functional layout to a CM product layout.

A good use of flexible automation requires an examination of how the part types are allocated to the equipment, so the installation of the FMSs prompted the companies to undergo a GT analysis and to eventually implement a CM structure. The transitions took from 3 months to 2 years. For these companies, the CM structure was not fixed. The companies fully expected, and experienced, that any current CM structure (people and machines) needed to be reallocated within 1 to 3 years because of changes in the part type mix and/or new technology. These expectations suggest that there are benefits to incorporating flexible automation with cellular manufacturing to accommodate such changes in the future. Gunasekaran et al. (1993) suggests that for the FMS grouping problem, "the GT approach needs to code the characteristics of the parts and their associated components such as tools, pallets, and fixtures" and consider the "limits on the number of part types and associated components in each group". That is, the concepts are not always incompatible but need to be adapted for successful implementation.

Slomp (1997) relates another industrial experience. SVEDEX, a manufacturer of doors, found that the installation of two CNC machines greatly simplified the material flow on their shop floor clearing the way for production expansion. The CNC equipment integrated three different existing manufacturing processes, and the company expects further manufacturing lines to be added. Indeed, a couple of assembly processes will immediately follow the CNC operations, incorporating teams. In essence, the company believes that flexible automation was a prerequisite for CM.

Further, Slomp (1997) suggests that there is an inherent contradiction between CM and flexible automation. With CM there is a tendency to decentralize several tasks, such as maintenance, quality control, planning and control, etc. In flexible automation there is a tendency to centralize more: maintenance is complex and usually dedicated to an FMS; also, parts of the planning and control are more complex. These opposing tendencies create an interesting problem for those intending to implement a blend of CM and flexible automation. The experiences of Slomp et al. (1995) demonstrate that the introduction of flexible manufacturing is often a catalyst for a firm to reorganize its production using GT and CM.

Some researchers claim that GT and/or CM can be used to help design FMSs. See, i.e., Mitchell (1991) and Luggen (1991). It is easy to see why. GT and CM group like part types and form small cells of the few machines necessary to produce families of similar part types. However, we believe that using only GT and CM are insufficient to design FMSs for many reasons.

One reason is because of the flexibility and the automation. Because of the versatility of the machine tools to perform many (sometimes all) types of operations required and the cutting tool magazine quick interchange capability, often a part type only requires one machine visit for its entire processing. Also, for the same FMS, a wide variety of part types can sometimes be produced, with different mixes of different part types produced over time.

Then using only GT and CM to design an FMS appears to be too limiting. GT/CM selects only a minimum number of machines of each type that are necessary to produce a family of similar part types. Such GT/CM techniques are incapable of designing an FMS consisting of a number of identical CNCs that are to be used to produce changing mixes of part types over time.

Another reason is that the modes of operation are very different for GT cells and FMSs. A GT cell tends to be a fixed route, unbalanced flow system, often with workers helping one another, producing the same family of part types. An FMS tends to have variable routing, continuously changing part types over time, and the capability of balancing the workloads for various mixes of part types. Indeed, the mode of operation can change from day to day. As an example, consider an FMS consisting of eight identical CNCs. If the FMS is "sufficiently" flexible and reliable, it can operate in many ways. For example, if there is a rush for an order (and there are sufficient cutting tools and all machines are equally capable), it is possible to tool all machines to produce only that rush part type. Over time, these same machines can be tooled in many ways. Sometimes a large number of part types need to be processed and each operation is assigned to only one machine. At other times, fewer part types can be selected and two or more machines can be tooled for each operation. There could be a wide variety of ways to operate an FMS.

Indeed, Askin and Standridge (1993) treat these two topics independently in two separate chapters. Often, more capacity-oriented methods are more appropriate to use to design FMSs. GT/CM techniques are too limited.

An interesting question is how flexible automation can operate harmoniously and profitably with group technology and cellular manufacturing. An answer may lie in which of the flexibility types listed in §4 are used to advantage. Cohen and Apte (1997) describe an interesting application of the three concepts at Cummins Engine Company, a manufacturer of diesel engines, who has incorporated an innovative mixture of cellular manufacturing and flexible automation. After enjoying a stable, profitable market during the 1970s, Cummins experienced competitive and regulatory pressures during the 1980s forcing them to increase product variety, reduce costs, and decrease delivery leadtimes. The company adopted cellular manufacturing to replace their existing process focused production.

But as the variety of part types proliferated, their cells became congested with the changeovers needed. The answer lay with innovatively investing in flexible and dedicated equipment arranged in cellular layouts. They chose to allocate their high volume part types to traditional layouts and cells with dedicated technologies, and the large number of remaining part types with smaller volumes to the cells with flexible automation. Part types with unstable designs were also allocated to the flexible systems, which could handle the design changes. The company experienced substantial improvements. This is an example of Burbidge's hypothesis that cellular manufacturing can establish the foundation for flexible technologies.

With conflicting theories and experiences regarding the relationship between GT/CM and flexible automation, we suggest that investigating how these concepts and technologies can operate harmoniously is a fruitful research topic. It should also prove to be useful for firms intending to implement cellular manufacturing with flexible automation but are apprehensive about the risks inherent in investing in expensive technologies; guidelines resulting from academic research as to how to best invest could be invaluable for such companies.

6. ISSUES FOR FUTURE RESEARCH

There are a variety of future directions for combined group technology, cellular manufacturing, and flexible automation. Firstly, there is the question of whether it is appropriate to invest in flexible automation before or after reorganizing for cellular manufacturing. The current evidence from practice for determining this is contradictory and further rigorous empirical studies could suggest appropriate implementation strategies. Resolution of this sequencing issue would be of tremendous interest to practitioners. It is highly likely, as in other fields of study, that the solutions to answer this problem may lie in industrial practice. As with any empirical study, however, caution must be exercised so that field observations do not mislead the development of theory. Care should be taken to ensure that observations are common enough to be generalized, not aberrant exceptions resulting from inefficient industry practice. The next step is to find theoretical foundations for these decisions. The most appropriate domain for this research is academia, building mathematical models of cellular manufacturing organization and the investment of flexible automation.

The integration of group technology with CAD/CAM activities is another issue. It is apparent that the incorporation of aspects of GT with CAD/CAM will produce superadditive benefits. For example, using a CAD/CAM system, firms can determine quantitative methods to find similarities in part types in both manufacturing process and physical configuration (size, material, etc.). Consequently, a more effective grouping of machines can be found. In addition, the design of various part types could be adapted to accommodate some better grouping of part types.

7. SUMMARY

Technological developments in manufacturing present challenges and opportunities for both practitioners and observers (academics, consultants, etc.). Flexible manufacturing is one of these developments. It has presented challenges to overcome in integrating it into existing concepts, practices, and theory. The opportunities it presents focus on integrating the technology in a way to produce a greater effect, that is a synergistic effect, than the current practices or the new technology could by themselves.

In this paper we introduce and describe the technologies collectively known as flexible automation. We summarize a history of its development which draws primarily from the combination of standard machine tool technology and the advent of the computer integrated circuit, which permitted the automation of various tasks. These tasks involve programmed operation commands such as the transit of the spindle, authorizing spindle speed, using lubricant and coolant, exchanging tools from a magazine, input and output of a part using automated material handling equipment and pallet exchangers, and rotating the table inside the workspace to gain access to various sides of a part.

Then, various research streams involving flexible automation are described, with relevant articles cited. Five production planning problems are reviewed and other problems involving acquisition, design, layout, and scheduling are listed. Section 4 contains a discussion of the various flexibilities that have been observed in practice and studied in theory. Several conceptual dimensions are listed to highlight the conceptually difficult problems posed by attempting to measure and capture these flexibilities in models, as a step towards attempting to manage them effectively.

Following this is a discussion of how flexible automation may mesh with group technology and cellular manufacturing. There is not much theoretical grounding for recommending a particular acquisition sequence of these technologies and the evidence from practice is somewhat conflicting, thus suggesting an important future research topic. We suggest this, with others, as potentially fruitful research directions in the final section.

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