A SYSTEMATIC TRANSITION TO FLEXIBLE MANUFACTURING

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ABSTRACT

The transition from basic automation to flexible manufacturing is an expensive and tedious procedure. It requires meticulous planning and almost clairvoyant forecasting to insure that the initial flexibility obtained is sufficient to allow growth and expansion in the future. This paper will suggest a systematic and methodological approach to achieve optimal flexibility and describe the present results of its application to an ongoing system transformation.

Conclusions based on existing levels of completion are presented along with identification of critical and non critical flexibility requirements. The considerations and steps taken are summarized in a procedural format which may then be applied to a wide variety of system transformations.

INTRODUCTION

It is estimated that there are currently over 350,000 manufacturing companies in the United States. Of these companies approximately 50,000 are expected to automate either part or all of their facilities in the next two years [1]. The majority of these companies will implement automation under conditions of uncertainty and incomplete knowledge and in doing so jeopardize their own financial security.

A major obstacle to the successful integration of any flexible manufacturing system is the difficulty of accurately foreseeing the future needs associated with product design and system capability. This paper will present an account of such a system transformation and the ongoing process attempting to reunite system performance with system goals.

Experience, synthesis and a compilation of existing and on going research will be applied to the current transition, establishing a methodology that will assist other similar system transformations.

Section 1 will introduce the facility and developments which resulted in a redefinition of system goals. Section 2 will introduce the

methodology and the various components from which it is derived. Section 3 describes the original automated system. Section 4 applies the methodology to the specific system and describes the present status of the ongoing transformation.

SECTION 1

The manufacturing system, around which this paper is centered, is located in the Engineering Management Department of the University of Missouri - Rolla. The primary goal of the facility is to provide opportunities and experience in all aspects of computer integrated manufacturing for both class and individual student projects and research.

Just as in industrial applications, system flexibility is a vital concern in an educational manufacturing environment. However, unlike industry where several systems may exist, each dedicated to a particular part family, the university facility contains a single cell which must produce a wide variety of part designs. To achieve this flexibility the system must be able to quickly and efficiently alter its production process, including major reprogramming of some or all of the cell components. In addition, each machine in the unit must possess the ability to perform multiple functions and accept several tooling configurations without requiring major set-up time.

When the original decision was made to obtain an educational manufacturing system, "flexible manufacturing" potential was one of the basic criteria. In order to avoid the problems associated with integration of differing brands of equipment, a systems vendor was selected and all equipment was supplied as integrated components. It wasn't until after the system was installed and individual research began that it became apparent that system flexibility was limited with the existing hardware configurations.

As familiarity with the system grew, so did expectations finally resulting in a redefinition of system goals which required an enhanced level of flexibility. Not surpri-

singly these could be introduced for an additional investment in equipment and components. The question then became, as for anyone contemplating the transition from basic automation, "What is the optimal procedure to effect this change given present goals and resource limitations?"

These decisions required a clear understanding of the expanded facility goals and familiarity with the capabilities of proposed equipment to insure sufficient flexibility in the future.

Without any previous experience to draw upon it became readily apparent that some form of systematic approach assisting the transition to flexible manufacturing was needed.

SECTION 2

Flexibility in manufacturing is a concept which has been defined differently on numerous occasions dependent on the system or situation under analysis. While each facility and process is indeed a distinct entity, the goals to achieve optimal production with high quality at minimal cost are all similar. It would therefore seem reasonable to assume that a similar definition of flexibility, and an approach to achieve such, could also be shared among manufacturing applications.

The success of any approach is dependent on obtaining a succinct definition of flexibility that is neither restrictive nor overly broad in focus. Such a definition has been proposed by Buzacott [2] when he defines flexibility as the ability of a system or decision process to cope with changing circumstances.

In a manufacturing environment these changes can take various forms, each of which may impact differently on the individual elements of a manufacturing cell. It therefore becomes necessary to isolate the various components of change and identify their effect upon the system using criterion of the overall flexibility definition.

The following flexibility criteria, some of which are borrowed from Browne, [3] and Gerwin [4], represent the major categories of emphasis which are addressed in this paper:

1. **Expansion flexibility** - an ability to add capacity easily and modularly as needed.
2. **Machine flexibility** - the ability to change tools and fixtures to process a given set of part types.
3. **Mix flexibility** - the capability to absorb changes in product mix.
4. **Mix-Change flexibility** - an ability to alter manufacturing processes to accommodate new part types.
5. **Operation flexibility** - the ability to interchange the ordering of operations for a given part type.
6. **Routing flexibility** - an ability to process a given part set on alternative machines.

These measures are more than adequate when flexibility goals are concise and well defined. Unfortunately, as we discovered, even the slightest alteration to original requirements can introduce factors which are

not directly addressed by any of the currently accepted flexibility measures.

Published research to date has overlooked the importance of two critical measures of flexibility related to goal sensitivity. In essence what has been lacking is the ability to deal with forecasting uncertainty which is an unavoidable reality.

The two measures of flexibility which reflect the system forecast sensitivity can be defined as follows.

7. **Programming flexibility** - an ability to alter basic operating parameters via control instructions.
8. **Communications flexibility** - an ability to transmit and receive information or instructions freely between system components.

An application of these two criteria, and their importance in analysis will be presented in section 4.

While all these measures are applicable to overall system analysis their real strength appears when they are applied to each of the individual components which make up the manufacturing work cell.

In agreement with the basic assumption that all transitions share a set of similar goals, a general methodology was sought which could be applied in a wide variety of situations. The approach would provide a systematic procedure to identify potential flexibility problem areas and assist the analyst in obtaining a complete and accurate estimation of system capability under forecast flexibility requirements.

An overview of the resultant methodology is presented in the figure below.

Figure 1. - Model of the proposed methodology

The process begins with the overall definition of flexibility goals. Individual details reflecting company policy and objectives are identified using traditional methods appropriate for each situation. If the definitions require major changes in product mix, application may be made of the modernization matrix introduced by Moore [5].

Once decisions have been reached on the individual equipment list it is important to apply the flexibility criteria to each of the components in turn.

As each cell element is evaluated lists are constructed of noted deficiencies. After all criterion have been examined, solutions to the problems are grouped into three categories, those requiring replacement of existing equipment, those requiring only equipment upgrade, and finally those which require a supplementary equipment purchase.

A proposed decision is made based on the compiled solutions. This decision is then compared against the original goals and additional financial, space, and related considerations. If the result is satisfactory the process begins again with the next cell component, if not, reconsideration is given to that element in the equipment list, an alternative selection is made, and the process analysis is repeated.

SECTION 3

The system to be transformed is a single flexible manufacturing cell consisting of an automated storage and retrieval system (AS/RS), loop conveyor with 2 work stations, pneumatic pick and place robot mounted on a translating axis, CNC mill, two programmable electronic controllers (PEC), and cell control microcomputer. The facility is located at the University of Missouri - Rolla in the Engineering Management Department and is shown below in figure #2.

Figure 2. - UMR flexible manufacturing cell

Descriptions of the original system equipment are given below.

2.1 AS/RS

The Automated Storage and Retrieval System, shown in figure #3, contains a storage capacity of seventy (70) bins. Material and in-process inventory retrieval is based on palletized units with single pallet storage per bin. The control language used is proprietary to the manufacturer, however a user friendly, menu driven system does permit specialized programming. Raw materials and in-process inventory accounting are controlled and

Figure 3. - AS/RS

monitored internally. An AS/RS terminal is used to update the inventory status as additional raw materials are stocked. This information is accessed by the cell computer during the manufacturing cycle.

Individual programs may be transferred between the cell computer and the AS/RS using a dedicated LAN network. The communications protocol is also a proprietary system developed by the manufacturer.

2.2 Loop conveyor and workstations

The loop conveyor provides the materials handling link between the inventory and production areas in the cell. The conveyor width and enclosing guide rails have been designed to match the dimensions of the pallets used for inventory and parts storage. There are three work stations locations allowed on the conveyor of which two are currently defined. Station #1 is occupied by the AS/RS and station #2 by the pick and place robot. Their respective locations may be found by referring to figure 2.

Belt movement during operation is constant in both direction and speed. All programming involving the individual workstations is controlled by a Gould Modicon P370 programmable electronic controller. Individual programs may be loaded from and stored on individual "program packs" or modules. The PEC is equipped with an additional RS-232 module allowing communication over the LAN network.

2.3 Pick and place robot

The pick and place robot is a four axis pneumatic robot illustrated in figure 4. The entire robot is mounted on a pneumatic track. Range of joint movement is defined by physical stops positioned by the user depending on the requirements of the particular task. Programming is achieved using a Gould modicon PEC similar to that used by the loop conveyor. Individual programs are stored in program

Figure 4. - Mercury pneumatic robot

packs or modules for later retrieval. The original accessories include three end effector and finger toolings.

2.4 - CNC mill

The computer numeric controlled mill supplied with the system is a small, full featured three axis machine capable of machining accuracy to within tolerances of .0005 inches. There are two methods that can be used to program the mill. The first method involves step by step programming using the attached controller. The second method provides an ability to utilize "off-line" programming packages and techniques which are then downloaded to the mill from the cell computer via the LAN network. Mounted to the mill table is a pneumatic vice in which the robot places the material or part to be machined.

2.5 - Cell computer

The computer control of the manufacturing cell is provided by a micro computer. The computer is equipped with enhanced graphics capabilities, 20 megabyte hard disk storage, serial and parallel communication ports, 640 Kb RAM memory, dot matrix printer and color CRT display.

2.6 - Software & system control

The existing computer integrated manufacturing software is an integrated package which consists of manufacturing, production and communication control modules. All production processes are monitored and controlled, from raw material retrieval through finished part storage. The program modules are completely menu driven and are capable of generating in-process reports at any time during the manufacturing cycle covering assembly, inventory, station and process status.

SECTION 4

Application of the methodology begins by defining the level of system flexibility required to meet the new expectations. The primary requirement is an increase in the number of part types that can be manufactured. A secondary goal is also specified involving computer integrated inspection.

The new part family consists of rectangular name plates, to be inscribed with individual names supplied immediately prior to the production run. Lot sizes in all cases will be one. This scenario requires an ability to quickly design and prepare new part programs, downloading them directly into the CNC mill. An inspection operation is needed to compare the part design with the carved name plate.

Applying the modernization matrix, two additional elements were identified, an intelligent robotics cell and a the need for zero defects. As a result the equipment list was updated to include a second robot and a vision system.

Next the revised goals were identified for each component of the equipment list and each element was analyzed independently. The following sections will document the results of this procedure. Acceptable solutions are identified following each analysis.

4.1 AS/RS analysis

Revised goal requirements - The AS/RS should possess the following requirements for system flexibility:

1. **Mix flexibility** - the ability to handle a wide variety of part configurations, sizes and designs.
2. **Expansion flexibility** - The physical design should allow the introduction of additional system components and upgrades (i.e. automated material loading in the form of AGVS or related technology in the future).
3. **Programming flexibility** - The system should allow the user to alter major operational functions. In addition the inventory strategies should include various techniques such as LIFO, FIFO, JIT, etc.

The AS/RS of the existing system meets several of the specified needs, but falls far short of satisfying all the requirements for primary goal fulfillment.

Component deficiencies -

Many operational parameters established by the manufacturer are stored on EPROM chips of the AS/RS control board. These may not be changed by the user and ultimately constitute the majority of impediments to our particular flexibility goals as follows:

- a. - The particular orientation of AS/RS to conveyor desired in our cell has rendered 57% of the storage area inaccessible, and therefore unusable. This could be reduced to between 6% and 11% if modifications to the programming in the EPROM chips were possible.
- b. - The materials and inventory tracking procedure has been based on pallet instead of part or inventory number. Because of the current overall system configuration it is presently impossible to direct a finished or new inventory item to any bin other than where it originated.
- c. - The distance the carriage may "index

down", once inside the storage bin in order to grasp the pallet, may not be adjusted by the user. This in turn restricts the overall entrance height of the carriage which imposes severe limitations on part assembly dimensions. Currently the maximum allowable height is six inches.

- d. - The communications protocol between the AS/RS and the external system is classified as proprietary by the manufacturer and does not conform to the emerging standards of MAP II.

Probable solution - Equipment upgrade

4.2 Conveyor analysis

The present configuration satisfies all requirements including that of expansion flexibility. The quality control operation will be located at unused workstation 3.

4.3 Robot analysis

Revised goal requirements - The robot should possess the following abilities to provide ultimate flexibility to the system.

1. **Machine flexibility** - Available design and tooling should allow the robot to grasp a variety of part configurations and perform assembly operations in addition to simple materials handling.
2. **Mix-Change flexibility** - Rotation and translation of the various joints should be under complete user control and interactively variable to accommodate various part designs.
3. **Programming flexibility** - The robot control unit should provide an easy and reliable method of programming, editing, storing and retrieving various assembly, part handling procedures and task descriptions.
4. **Communication flexibility** - The robot controller should possess the ability to communicate with other components of the system and respond appropriately to various sensory feedback devices.

Component deficiencies -

- a. - The existing PEC possess no ability to communicate with other system components and is limited in memory to programs consisting of no more than 72 rungs.
- b. - There are no provisions for feedback of any kind either to the system or the robot itself to assist in part orientation or positioning.

Probable solution - Purchase of additional robot which would provide the degree of control and programmability needed for an inspection operation

4.4 CNC mill analysis

Revised goal requirements - The following

abilities should be available to insure a high degree of system flexibility.

1. **Programming flexibility** - Individual NC programs and program segments should be easily stored and retrieved from the unit. Provisions should also allow the manual operation of the mill by direct controller interaction.
2. **Machine flexibility** - The fixtures provided to mount and secure the material being machined should possess a flexibility similar to that of the robot end effector. In the case of the existing systems pneumatic vice, the jaws should be quickly and easily interchangeable.
3. **Communication flexibility** - A method should be provided to allow not only basic communication over a LAN network with external systems components, but additionally to permit full access to all mill functions from a remote location such as the cell computer. This last option would permit the loading, initialization and activation of NC part programs without need of operator intervention.

Component deficiencies -

- a. - Memory limitations of the controller limit part programs to no more than nine hundred (900) individual commands. While this may be sufficient for basic operations, it is entirely inadequate for surface and contour milling of any semi-complex object.
- b. - The program upload and download process as well as run activation require the physical interaction of a human operator. A system allowing remote electronic emulation of these operations is necessary for optimal flexibility.

Probable solution - Equipment upgrade

4.5 Control software analysis

The importance of software flexibility to overall system performance cannot be over-rated. Unless the software and hardware both are of an equivalent level of flexibility the system will remain somewhat less than optimal for any given situation.

This paper will not address the issue of software compatibility. Topics and concerns in this area are too numerous to be included in a paper of this length.

4.6 Analysis of remaining cell elements

An in-depth analysis of the remaining cell components will be omitted in the interest of brevity. The preceding examples provide ample illustration of the appropriate method of application.

CONCLUSIONS

As a result of the methodology developed in this paper, and the introduction of the additional measures of flexibility associated with

forecast sensitivity, a list of proposed system changes was obtained. The status of these changes and system transformation follows.

A decision was made to pursue a software update for the AS/RS. To this date the replacement EPROMS have not been received from the vendor, however alternate pallet tooling has been designed and tested to circumvent the problems resulting from gripper clearance on the carriage. This has allowed materials retrieval to function as required.

The pneumatic robot proved too inflexible to function in a dual role which included quality control and inspection. A decision was made to obtain an additional servo robot allowing the pneumatic robot to continue its primary function of mill loading.

A secondary robot which includes a vision system was obtained by donation. It is currently being installed in the facilities laboratory. Research and experimentation is under way to determine the effectiveness of the vision system supplied. The results as yet are inconclusive.

A CAD/CAM link has been established between the cell computer and the CNC mill. Sample name plates have been constructed which were designed in AutoCad, processed into NC code and downloaded over the LAN network into the mill.

A CNC equipment upgrade which will circumvent the 900 line memory limitation and allow remote control of all controller functions is pending completion of final testing by the manufacturer.

Portions of this transition are still ongoing. Fortunately we are not subject to rigid deadlines for the completion of the project.

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