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DEVELOPING AND ANALYZING FLEXIBLE CELL SYSTEMS USING SIMULATION

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ABSTRACT

The purpose of this study was to develop and evaluate flexible cell alternatives to support an agile production environment at a mid-sized manufacturer of industrial equipment. Three work cell alternatives were developed based on traditional flow analysis studies, past experience, and common sense. To support the analysis of each option, a simulation model was developed and validated for the current manufacturing environment. The simulation model allowed the analyst to evaluate each cell alternative under current conditions as well as anticipated future conditions that included changes to product demand, product mix, and process technology. This paper will emphasize the modeling aspects of this study and briefly discuss the results and future directives.

1 INTRODUCTION

The manufacturing facility reported in this study is an MRP-driven, job shop that generally processes parts in batch mode. High value and low value parts, production and after-market parts, all flow through the same machine tools and are controlled by the same MRP system. The facility is physically divided into two plants, Plant A and Plant B. Plant A is split into three functional areas: machine shop, sheet metal, and welding. The machine shop and sheet metal areas both contain over 40 workcenters ranging from manual control to computer controlled. The weld area is essentially a manual assembly area where the majority of subassemblys are made. Plant B performs all final assembly as well as any paint operations required. Although product generally flows from Plant A to Plant B, throusands of unique part routings are defined.

This facility anticipates that its volume will double over the course of the next 7 years. In addition, two new product introductions are planned for each year. In order to poise themselves for growth, and in light of various inefficiencies that currently exist (excess inventory, long manufacturing lead times, and little flexibility), Plant A has specific time phased goals:

1. 95% schedule satisfaction
2. 50% reduction in finished goods inventory
3. 50% reduction in cycle time
4. 30% reduction in piece part inventory
5. 30% reduction in work-in-process
6. Reductions in floor and warehouse space.

This paper reports on the progress made in developing and evaluating the flexible work cell option that was expected to result in reduced lead times and increased flexibility. Although the facility discussed in this paper is not identified, the information and data is fully representative of the real system. The authors would like to thank the project team members from Plant A who wish to remain anonymous but whose contributions during cell development, model formulation, model validation, and cell analysis were exceptional.

2 BACKGROUND

The Plant A project team consists of senior leaders from management, engineering, and shop supervision. Over the past 10 years, significant efforts were spent developing work cells based on product flow analysis techniques developed by Burbridge (1991). Most of these ideas were never implemented because of the inability of the analyst to provide a proof of concept. That is, although the creation of machine cells and the identification of part families were based on sound principles, the analyst did not have a tool to quantify the potential gains that could be achieved from work cell concepts.

Historically, the advantages associated with cell manufacturing are (Nyman 1992, Black 1991): reduced inventory, reduced flow time, increased flexibility, and improved quality. There are often other advantages unique to certain systems: reduced control problems, reduced material handling, increased visibility, increased employee synergism, and increased group tooling and group scheduling opportunities. These advantages are often predicated on the adherence to a set of constraining assumptions about how cells are designed and executed. Failure to properly design, analyze, and carefully plan the cell configurations often leads to unsatisfied goals and poor system performance.

The project team searched for a tool that could address their needs. In the literature, a number of papers on cellular manufacturing have been published. However, most of them primarily address clustering techniques, as dicussed by Heragu (1994). Unfortunately, there is no guarantee that perfect work cells can be designed. To complicate matters, a successful design must be capable of responding to the uncertainties of tomorrow. Future demand increases, shifts in part mix and adding new products to the product line are of considerable concern in cell design. In order to capitalize on the advantages of cells, **it is important to design a system that is robust to change.**

Simulation analysis is the only tool that allows one to accurately assess the impact of a dynamic and uncertain environment on particular production configurations. Simulation can also help the analyst determine how to successfully control the system so that the disadvantages of cell manufacturing can be minimized.

The project team was convinced that the machine cell formation and part family formation problems could best be resolved by using fundamental flow analysis, past experience, and common sense. They subsequently choose simulation to help them develop and evaluate the work cell concepts, and to quantify the potential gains.

3 WORK FLOW OPTIONS

The development of work flow cells requires that the system experts conceptualize practical and common sense work cell designs. The project team engaged in a work flow brainstorming session. The purpose of this session was to bring together key project individuals from Plant A to conceptualize and define common sense work flow options. During this session many cell alternatives were developed based on product type, product volume, independent demand, process flow, and material flow. After the options were laid out, a critical analysis of each option was conducted. Through the process of elimination, the project team identified three feasible candidates:

1. Process flow and material flow cells. Basically, material based cells were formed in the sheet metal area (based on material gage), and process oriented cells were formed in the machine shop.
2. Major weldment cells. The concept is to produce complete major weldment parts independent of any other cell. A cell could contain components from sheet metal, machine shop, and welding.
3. As-Is.

To better understand the magnitude of the problem, Figure 1 illustrates one of the machine shop layout options. Corporate wide, there are over twenty thousand part numbers. Over four thousand of these parts appear at the master schedule level, as either end-item demand or after-market demand. The bill of material structure could accomodate up to twenty five levels, but it was typical to see less than ten levels on an end-item.

Figure 2 summarizes the activities required to evaluate each cell option. Four data files are provided as input: Master Production Schedule (MPS), part routings, Bill-of-Material (BOM), and Master Parts File (MPF). Each data file is manipulated to reflect the requirements of a specific cell option and the requirements of the desired type of analysis. A pre-processing routine creates the SIMAN V (Pegden, et al., 1990) Experiment file for each cell option considered. Two SIMAN V models are used to represent the system logic and the MRP order release logic. Finally, each cell option model is exercised by the SIMAN V Simulation System and performance reports are generated. In reality, each option is exercised multiple times and refinements are made to the design until a satisfactory design is established. Insights gained through this iterative process make this process a valuable lesson in itself.

Materials Requirements Planning (MRP) logic is implemented to realistically capture the order release logic that exists in the current system. The MPS end-item demand is exploded each week through the BOM to determine an order release plan for the week. This capability is important for three reasons. First, the analyst can realistically assume forecast uncertainty. Since the forecast will be changing on a weekly basis, the order release plan must change accordingly. Second, the analyst can evaluate the affects of increasing or decreasing, over time, end-item demand. Finally, the analyst will have the option of specifying any run length required, as long as the MPS exists to support it.

This section summarizes the key activities required to develop the cell models and to conduct the comparative analysis.

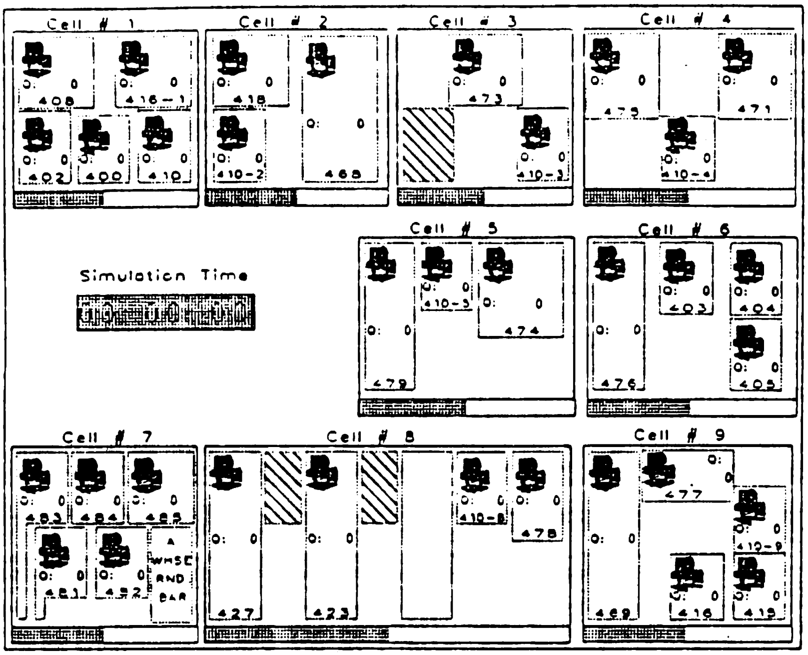

Figure 1: Option 2 Machine Shop Layout

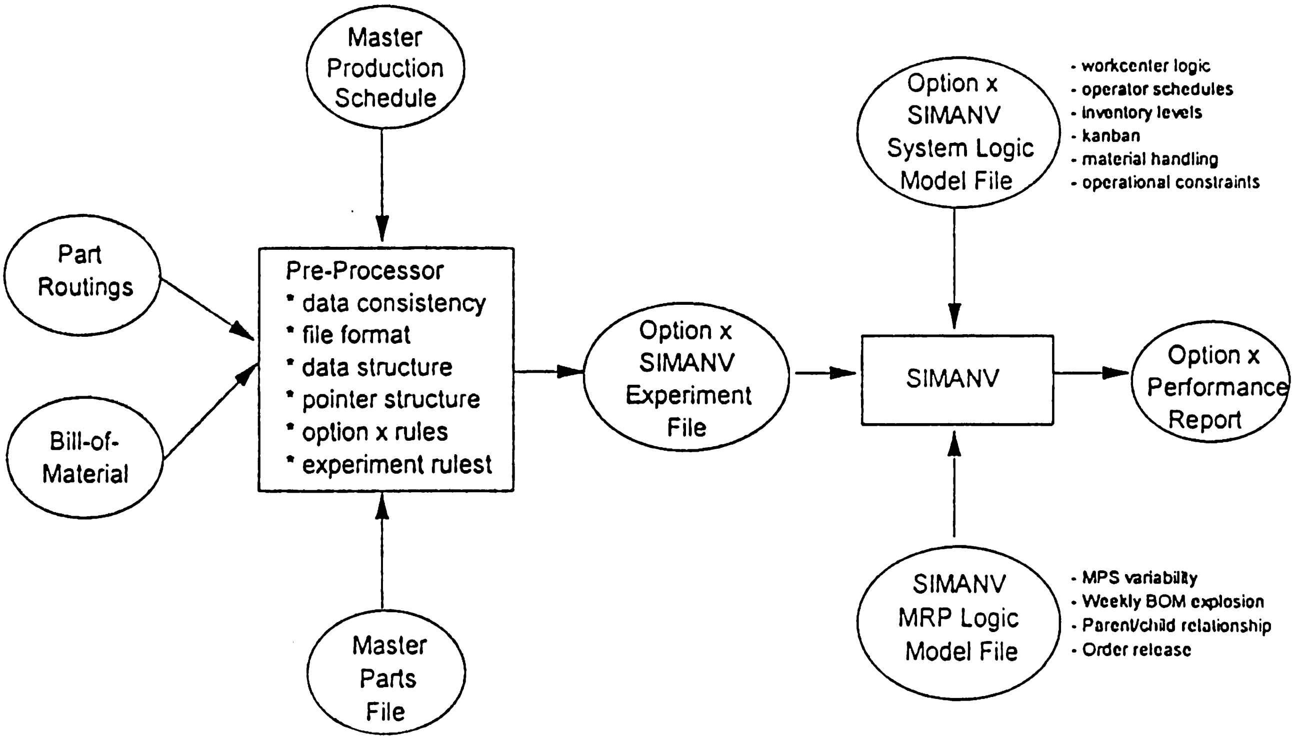

Figure 2: Cell Evaluation Activities

3.1 Data Requirements

The input data required to run the cell model consisted of four large data files. The Master Parts file contained over 27,000 records, one for each part. The Parts Routing file contained over 80,000 records, one for each operation. The BOM contained over 39,000 records, one for each parent/child relationship. The Master Production Schedule file contained over 191,000 records, one for each unit of demand. The contents of these files are briefly discussed below.

The **MPS** is provided for a one year period. Since a weekly MRP bucketing system is employed, requirements are weekly, with a need day of Monday. The master scheduling activity is generally performed one BOM 'level' below final assembly at the planning bill level. In the master schedule there are five types of planning bills used: parts basic, parts common, parts unique, options, and final assembly. Each planning bill that has a requirement greater than zero will generate dependent demand requirements through the MRP logic. Naturally, forecast accuracy decreases further out in the future. This is captured by an MPS variability routine in the MRP logic as described in Section 3.3.

The **MPF** contains one record for each Plant A part that is actively being manufactured, master scheduled, or serves another function such as a phantom part. This includes parts from independent demand (e.g., domestic, after market and repair) and international demand. The part **routings** file contains one record for each part/operation occurrence. When a part completes its routing, the inventory location indicated in the parts file will be incremented accordingly. During preprocessing, the parts routing file is converted into the SIMAN V SEQUENCES Element format.

The **BOM file** contains parent-component relationships for all Plant A manufactured parts. Parts that are not included are obsolete parts, purchased parts, prototype parts, and other non-production parts. During preprocessing, the BOM file is converted into a linked-list format that is easier to process by SIMAN V.

3.2 Preprocess Requirements

The preprocessing activity serves four purposes: to ensure data integrity, to create the required data structures, to reflect the current cell option being evaluated, and for future considerations. The Data Processing department in Plant A maintains an information system grounded on the COBOL language. The data is provided to the analyst in a structure that is inefficient for processing by the simulation model. The preprocessor essentially creates an efficient data structure and creates a pointer scheme that links all four data files together.

Included in this reformatting was the conversion of the Part Routing file to a SIMAN V format. In this process, any part records that do not have an impact on Plant A manufacturing operations are eliminated. In total this resulted in a significantly smaller data set: 27,406 part records were reduced to 10,247; 80,153 routing records were reduced to 37,635; 39,359 BOM records were reduced to 13,635; 191,511 MPS records were reduced to a 2,597 by 52 (week) array.

Each cell option is uniquely characterized by a number of features: cell structure, parts routing, cell capacity, new equipment/processes required to support the cell structure, and obsolete equipment.

The easiest way to incorporate all of these features in each model is by revising the part routings to reflect the changes required for each option. Also, the model and experiment files must be revised to acknowledge these revisions. Figure 3 illustrates some of the routing rule revisions used for each of the options considered. Note that although option 3 represents As-Is, routing revisions were made to reflect new technologies (e.g., a process that reduced process times, and nearly eliminates setup time).

3.3 Material Requirements Planning

In order to represent realistic market conditions, the SIMAN V model incorporates forecast accuracy factors. Factors are used to characterize each of the following bills: parts basic/common, parts unique, and options. At the start of each week the forecast rolls forward. The demand in the current week is frozen. The demand in week x+1 to x+3 experiences an alteration of db_1 with probability fb_1. This concept is used for each BOM type. Week x+4 to x+7 would also have a unique set of forecast accuracy factors, as illustrated in Figure 4.

The primary function of the MRP logic is to convert the master schedule demand and independent part demand into production orders for dependent part demand. The SIMAN V simulation model then simulates the fabrication activities for each production order and reports the system performance that results over the simulation time horizon.

The MRP logic represents a regenerative MRP system and is executed once a week. The primary components of the MRP logic include the master

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OPTION 1A:  Process Flow, No New Equipment

1. IF WC=136, then route to WC 135
2. IF WC=172 and sequence includes 137,138,139,or 130,
   then route to WC172-1.
5. IF WC=137,138,or 139, at frequency of 50% of the
   orders:
   - ignore all operations in WC104,105&106 that occur
   anywhere within the routing sequence
   - reduce setup time by 50% on operations in WC137,
   138 & 139.
   - for each operation in WC 137, 138, or 139, accrue
   orders in groups of 5 and delay processing by the
   sum of the five parts.
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OPTION 1B:  Process Flow, No New Equipment

7. IF WC=410 and preceding WC equals:
      468, 417, 412, or 418           route to 410-2
      473                             route to 410-3
      471 or 475                      route to 410-4
      474 or 479                      route to 410-5
      427, 423, or 478                route to 410-8
      477, 469, 416, or 415           route to 410-9
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OPTION 2:  Major Weldments

5. IF part is a major weldment (identified in parts
   file), and
     IF WC=172,173,174, or 176          route to 171
     IF WC=100 or 199                   route to 199-2
     IF WC=102                          route to 102-2
     IF WC=117,119,120,130, or 138      route to 131
     IF WC=137                          route to 131
        and if runtime > 0,
            then increase s/u by 58% (std. tool change)
     IF WC=139
        - reduce runtime by 20%
        - add an operation WC199-2, runtime=.2, s/u=6.
```

Figure 3: Reroute Rules for Option Configuration

	week							
<u>bill</u>	<u>x</u>	<u>x+1</u>	<u>x+2</u>	<u>x+3</u>	<u>x+4</u>	<u>x+5</u>	<u>x+6</u>	<u>x+7</u>
basic/common								
frequency of change	-	<---fb_1------->			<---fb_2------------->			
degree of change	-	<---δb_1------->			<---δb_2------------->			
unique								
frequency of change	-	<---fu_1------->			<---fu_2------------->			
degree of change	-	<---δu_1------->			<---δu_2------------->			
options								
frequency of change	-	<---fo_1------->			<---fo_2------------->			
degree of change	-	<---δo_1------->			<---δo_2------------->			

Figure 4: Forecast Accuracy Factors

schedule, the parts inventory records, and the parts bill of materials. A linked list pointer structure is used to monitor parent/child dependencies. When a parent part is supposed to be released, if there is not adequate inventory on-hand for the children components, the parent part released is postponed until adequate inventory exists. Typically, there are over 200 open MRP orders in Plant A.

3.4 Operational Logic

Work center submodels, resource sets and subroutining are all SIMAN V features that were utilized in the modeling effort. Since the basic processing logic is common to all forty sheet metal work centers, the station submodel concept was used to represent this activity. Identical parallel resources are easily represented with a capacity greater than zero. After seizing the work center, the component entity is routed to the operator selection subroutine.

The operation selection logic is common to all work centers in the model. Associated with each work center is an operator set. The operator set defines a rank ordering of operators that are trained at a specific work center. Each operator also has a shift schedule that indicates the working hours. A single operator set can contain multiple operators from all three shifts. When the component entity completes processing at the work center, it is routed to the next work center (or to inventory) via a material handler.

Alternate work centers were considered for the press brakes in the sheet metal shop and the vertical milling center in the machine shop. Plant A developed rules to determine the conditions that alternate work centers would be considered. The rules varied from "use the first available press brake" to "if press brake xyz is busy and press break abc is not, route the part to abc if the primary material is 12 gage steel".

With work cells, batch splitting and internal time can be utilized. Batch splitting refers to the ability to process a particular job on two of its operations, simultaneously. The advantage of doing so is that, assuming that both work centers are available, total flow time may be reduced. Internal time refers to the ability of an operator to start a job on one work center, and while the job is being processed, begin a second job on a different work center.

The simulation model allows either MRP order release or Kanban control for each part. The challenge behind modeling Kanban control is identifying which parts use the pull strategy, and also to supply the required reorder and stocking information. For each Kanban situation modeled, Plant A identified the Kanban parts and their reorder trigger level. The order quantity used is that assumed by the MRP system.

3.5 Performance Measures

The performance measures used to evaluate each option are based on the primary themes of the project objectives: on-time delivery, part flow times, work-in-process, material handling, and processing requirements. On-time delivery and flexibility to respond to diverse market demands is captured by two measures: percent of orders that are tardy, and mean tardiness for late orders. Each end item order maintains a due date specified by the master schedule. Orders are evaluated in terms of when they were scheduled to be completed versus when they actually were completed.

Material handling delays and moves are accumulated during the course of the simulation. These measures are useful when comparing the material handling activity between each option. Likewise, certain measures that indicate processing efficiency for each option are collected: number of jobs completed per work center, number of hours completed per work center, and for each cell, the fraction of "parts complete" parts (number of parts completely processed within the one cell divided by the total number of parts processed in the cell).

4 MODEL VALIDATION

Model validation involved three key areas: master schedule uncertainty and MRP logic, component routings, and system logic. Validation was performed on the current system with the assistance of six key personnel: the model builder, the shop floor supervisor, the senior production engineer, the senior systems analyst, the plant manager, and the division vice-president.

The model builder lead the validation effort and relied on three validation methods: code walk-through, animation, and simulation output review. A code walk-through was performed to review the model formulation and explain the model translation. This was performed primarily with the shop floor supervisor, senior production engineer, and senior systems analyst. The shop floor supervisor was convinced that the model captured enough detail in the real world to address the project objectives. The senior project engineer confirmed this belief, and confirmed that the appropriate engineering standards and manufacturing procedures were appropriately represented. The senior systems analyst confirmed that the MRP logic and master schedule variability logic was implemented properly. An animation of the base case was used to enhance the validation activity. This process was iterative as model flaws were revealed, remedied and reevaluated.

When the model was believed to be representative of the system, multiple system scenarios were executed. The output from these scenarios were reviewed by the whole project team. The objective was to determine if the model was stable and representative. Instead of having to review all of the output that could be generated, the project team selected key validation measures: overall lead time, lead time of key components, operator utilization, work center utilization, due date performance, warehouse cost, and cell utilization statistics. The plant manager and division vice-president were invaluable as outsiders. That is, individuals that were not intimate with the model during model formulation and development. The outsiders were able to step back and look at the big picture. They were not afraid to question the assumptions and to make sure that the model was addressing the objectives.

5 ANALYSIS AND EXPERIMENTATION

Numerous experiments were run following model validation to evaluate the robustness of each design as well as to determine how to improve system performance. The specific factors that were adjusted during experimentation included: forecast uncertainty, setup time, order quantity, master schedule demand, work center capacity, and cell configuration.

The experimentation effort allowed the analyst to determine whether each of the cell options was feasible, how each cell option performed assuming current conditions, and how each cell option performed under future conditions. The analyst also performed sensitivity analysis to fine tune each cell option.

A number of observations were made based on this aggregate analysis. From a simulation perspective, the success of each option stems from the ability to route each part through the facility in such a manner as to avoid work center bottlenecks. This depends on the effectiveness of the reroute rules and on the capacities of key resources. The simulation model quantified the overall work center utilization and the overall operator utilization. It is apparent that work center utilization is fairly low and that operator utilization is currently the constraint on the system.

The selection of the final solution was based on other factors external to the modeling effort (e.g., capital expenditures, training requirements, and the corporate business plan). Other intangibles of work cells that were evaluated included: improved manageability, decreased material handling, reduced setup, quick response, increased visibility, and increased group synergism.

6 CONCLUSION

The development of work cells was based on over 100 combined years of experience and on basic production flow analysis techniques. These designs were further refined with the assistance of a detailed simulation model of the facility. Routing revision rules were key in the development and refinement of the cell configurations.

The validation of the simulation model was performed based on the existing facility. Key performance measures were defined to ensure that the input data, model logic, and MPS variability and MRP logic was representative. The comparative analysis of each option indicated that each cell option was feasible. This was only after the reroute rules were refined so that the load was balanced between cells. The advantages and disadvantages of each option in terms of lead time, inventory, and schedule performance were evaluated.

The simulation model played a crucial role in the refinement of the work cells. Reroute rules were repeatedly revised for each cell option until a feasible solution was obtained. The analysts determined where additional capacity was needed to support each cell option. The simulation analysis effort revealed that the work cell gains were not as great as originally anticipated. Material handling was only marginally reduced and setup reductions were minimal. Management is currently evaluating tradeoffs. Additional analysis is expected.

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