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A MACRO/MICRO MODELING APPROACH TO THE SIMULATION OF CELLULAR MANUFACTURING SYSTEMS

Suraj M. Alexander
William E. Biles
Gerald W. Evans
Ismail M. Zahran

Department of Industrial Engineering
University of Louisville
Louisville, Kentucky 40292

ABSTRACT

This paper describes a bi-level modeling approach to the simulation of cellular manufacturing systems. At the plant level, a "macromodel" simulates the overall production system, modeling the production inventory control system as well as the manufacture of batches of parts and their assembly into product end items. At the manufacturing cell level, a "micromodel" simulates the processing of batches of parts one-at-a-time, over the individual machines in the cell. The micromodel can be animated to graphically depict the behavior of the cell.

1. INTRODUCTION

The trends taking place in manufacturing are dictating a planned evolution from production job shops, with their functional or process-oriented plant layouts, to cellular manufacturing systems, which bring many of the advantages of the production flow line to batch manufacturing. The proliferation of the number and variety of products is continuing, resulting in a decrease in production lot sizes. The increased variety of materials, including composites, is causing a proliferation of manufacturing processes. Customers are demanding higher quality products, which leads to a requirement for closer tolerances. Customers are also demanding lower costs and on-time delivery of orders, which calls for better management and operational control of the manufacturing system.

The solution for responding to these trends is cellular manufacturing. With this approach, manufactured parts are organized into part families based on Group Technology concepts. The members of the part family exhibit strong similarities with respect to a set of design attributes, including part geometry and size, and a set of manufacturing attributes, which include the processing steps for making the part. The manufacturing cell is a group of machines needed to process all the parts in the part family, together with any associated tooling (tools, jigs, fixtures and gages). A cell may be manned or robotized. In a manned cell, such as that shown in Figure 1, an operator walks a part around a U-shaped layout of machines. The longest machine cycle dictates the operator's trip time around the cell.

The development of cellular manufacturing systems requires either the complete re-layout of an existing plant or the construction of a new one. The production machines that have heretofore been laid out in functional or process layout arrangements, such as shown in Figure 2(a), must be repositioned in a group of machine cells as depicted in Figure 2(b). This re-layout requires a great deal of forethought and evaluation by plant engineers. Computer simulation becomes a vital tool in evaluating proposed cellular systems before they are built to determine if the postulated effects of faster production throughput, higher machine utilization, and reduced work-in-process are realizable.

The application of computer simulation to complex manufacturing systems inevitably seems to require the development of new modeling tools, or to necessitate the interfacing of simulation models with other software systems such as database systems, optimization programs, or graphical packages. That is most certainly the case here, as will be discussed later.

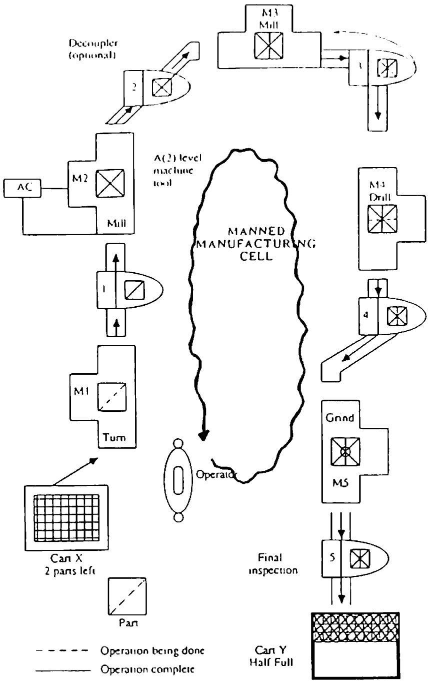
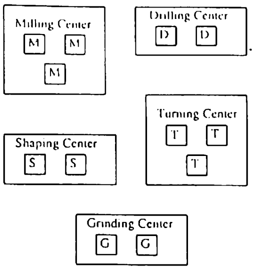
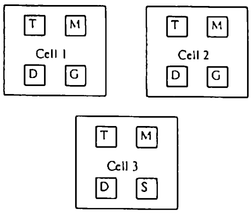


Figure 1. A Manned Manufacturing Cell



a) Functional Layout



b) Cellular Layout

Figure 2. Functional vs. Cellular Plant Layout

This paper describes the development of dual-level computer simulation models to evaluate cellular manufacturing plant layouts. The two levels are called "macromodeling" and "micromodeling", with the macromodel simulating factory-level planning and control operations, and the micromodels simulating the behavior of individual manufacturing cells. Whereas the macromodel simulates the production inventory control system and the flow of batches of parts through the manufacturing plant, a micromodel simulates the flow of individual workparts over a manned manufacturing cell. There is a specific micromodel for each cell in the system.

2. ILLUSTRATIVE MANUFACTURING SYSTEM

The simulation concepts described in this paper were developed as part of a project aimed at evaluating several alternative plant layouts for a company contemplating the construction of a new, single-floor manufacturing plant to replace an old, seven-floor facility. This company manufactures pipe valves and fittings, and markets 1842 different products. The aggregate bill of materials for its manufacturing operations includes more than 4500 manufactured parts and 2000 purchased parts. The 1842 products are classified according to annual sales volume as either A, B, C or D items. Although some parts are used on two or more different classes of products, a specific part is assigned the class of the highest-level product into which it is assembled.

The plant layout alternatives under consideration were (a) a functional or process layout which groups similar machines into process areas, (b) a cellular layout which features a number of manufacturing cells through which Group Technology-based part families are processed, and (c) a combination of these configurations. Actually, the 75 Class A parts are processed either on transfer machines or loosely-linked production flow lines, so that the eventual plant layout would very likely consist of a combination of transfer lines (machines), production flow lines, process-oriented machining areas, and manufacturing cells featuring a variety of flow patterns from highly sequential to very flexible routings. There are 252 production machines in this system, as well as such batch processing equipment as heat treatment ovens, surface treatment enclosures, and manual workstations for such tasks as deburring and inspection.

3. DATA ANALYSIS

The data files acquired to support this simulation modeling effort included the following:

- Monthly demand for each of 1842 products for a 33-month period from January, 1987 through September, 1989.
- Bill of materials for each of these same 1842 products, which yielded a catalog of more than 4500 manufactured parts and 2000 purchased parts.
- Process sequences for the 4500 manufactured parts, listing the machines on which the part was processed, the set up time for each machine, and the processing time for the part on each machine in the sequence.
- Batch sizes for the assembly of each product and for the processing of each part.
- Machine utilization for all 252 machines in the plant.

The first four data files were used as data input to the simulation models, while the last was used to validate the results of the simulations.

The first effort with analyzing the data was to organize it into a coherent database. This database employs the Foxbase system, a relational database language, and consists of the following seven files:

- Product data, including product code, name, annual demand, and production batch size.
- Manufactured parts data, including code, name, and the number of steps in the processing sequence.
- Purchased parts data, including code and name.
- Machine data, including code and name, number of machines, and the location in the existing plant.
- Manufactured parts processing sequences.
- Product structure by manufactured parts.
- Product structure by purchased parts.

The key to operating the database was the development of a database manager, consisting of the following programs:

- Menu programs, which present the various system options to the user.
- Data editing programs, which enable the user to insert new records into a file, delete unnecessary records, and correct erroneous data entries.
- Report programs, which enable the user to transfer data from the database to a text file.
- Simulation data programs, which serve as the link between the manufacturing database and the simulation programs by presenting any data needed for the simulation models in the form of text files organized in the formats needed by the models.

The relationship of the manufacturing database with the other modules in the total simulation system is illustrated in Figure 3.

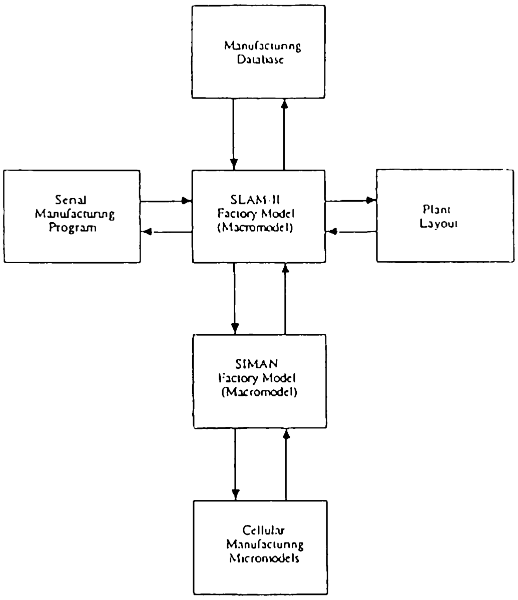


Figure 3. Simulation Model of Company Pipe Valve Manufacturing

4. PLANT LAYOUT DEVELOPMENT

The main objective of the project was the development of layouts for the efficient manufacture of valves and fittings. The alternate layouts generated were then evaluated by the micro and macro simulation models. The alternate layouts considered had to be compatible with the changing manufacturing environment within the company. The company's production system was changing from a made for stock environment (order point system) to a made to order environment (MRP II System, specifically IBM's COPICS). Considering this change in production control mechanisms the lot sizes were expected to reduce considerably. The formation of manufacturing cells was investigated in order to facilitate the production of small lot sizes efficiently. The cell formation procedure is explained in the next section.

4.1 Cell Formation Procedure

The crux of designing a cellular manufacturing system is the identification of the part families and their associated machine cells. A multitude of techniques are now available in the literature for dealing with this process. The major source of information for these techniques are the part processing routes. These techniques can be classified into two categories. The first category involves what are called hierarchical techniques, and the second involves what are called concurrent techniques. Hierarchical techniques consider the identification of part families and machine cells as two separate steps, while the concurrent techniques deal with both steps simultaneously. Some of the techniques recognize the problem of designing a cellular system as the diagonalization of a part-machine matrix whose entries are either ones or zeroes. The rows of this matrix represent the parts while columns represent the machines. A digit of one at any intersection indicates that the row part requires the column machine, and a zero indicates that opposite. Examples of such techniques are Rank Order Clustering Algorithm [King and Nakornchai, 1982], Zero-One Data Ideal Seed Algorithm for Clustering or ZODIAC [Chandrasekharan and Rajagopalan, 1987], and Cluster Identification Algorithm [Kusiak and Chow, 1987]. The other techniques recognize the problem as developing clusters of machines and assigning the parts to these clusters. Such techniques usually employ some similarity measures in the process of machine clustering. Examples of such techniques are the Single Linkage Cluster Analysis [McAuley, 1972], Graph Theoretic Approach [Rajagopalan and Batra, 1975], and Average Linkage Cluster Analysis [Seifoddini, 1988].

The technique used in this research,called the Load-Based Technique, is completely different from both of the block diagonalization and similarity measure techniques [Shalaby and Zahran, 1990]. The technique is a hierarchical one in the sense that it starts by identifying the machine cells, and as a second step assigns the parts into these cells. The technique starts by specifying an upper limit on the number of machine types allowed to exist in a machine cell. Then, a key machine type is specified as the machine type of the highest load. Attributes such as the machine cost, number of machines available from each type, and number of user parts are used to break the probable ties. As a given machine type is selected as the key one, the other types most frequently used with it are identified to make a machine cell. The only constraint on adding other machine types into the cell is the upper limit on the number of machine types clearly specified. As a cell is decided, it is compared to the processing routes of the various parts, and the matching parts are ignored in the subsequent grouping analysis. The cycle is repeated until the total machine loads are exhausted. The cells obtained from this phase of the analysis might be merged into a smaller number of cells on the basis of the similarity of these cells measured by Jaccard's similarity coefficient.

Parts are assigned to the cells in the next phase of the analysis to form the part families. This process starts by defining the set of possible assignments for each part. The parts of single assignment are first assigned to their appropriate cells. Parts of multiple assignments are then assigned into the cells of low average machine utilization. Exceptional parts, i.e. parts that can not be completely processed on any of the cells, are assigned to cells which can afford the majority of their processing operations.

After deciding the machine cells and part families, the number required from each machine type for each cell is computed on the basis of the load inserted annually by the part family assigned to the cell. A computerized layout technique is then applied to locate the cells relative to each other, and to locate the machines within each cell.

Changing the upper limit on the number of machine types allowed to exist in any machine cell can provide more alternative configurations for the cellular system. Machine costs, number of exceptional parts, number of cells, and average number of parts in a part family are suggested factors for evaluating these alternatives.

4.2 Product Families

The end products of the company were classified into A, B, C, and D categories based on their degree of importance as determined by marketing. The components of the end products took on the classifications of the end products. Since the most efficient method of production was desired for the A and B parts, these parts were first run through the cell formation algorithm. Prior to running the cell formation algorithm, equipment that would not fit in a cell, owing to process requirements, were eliminated from the equipment list. The resulting cells formed were verified through discussions with company personnel. Some of the cells formed were eliminated since the equipment was being phased out. A few of the remaining cells were merged.

Once the cells were formed for A and B parts, the C and D parts were analyzed by part code. It was noted that the C and D parts could be classified into groups which had similar operations sequence. The routings for the parts within the groups were not the same, however, mainly because of the different sizes of parts in the groups. Both process and cellular layout alternatives are evaluated for the manufacture of C and D parts.

4.3 Plant Layout

Planning a cellular layout consists of two major steps. The first is the allocation of cells relative to each other, and the second is the allocation of machines within the cells. The cell formation algorithm used in this research and all other cell formation algorithms only specify the types and numbers of machines to exist in each cell. The algorithms end with this result and do not deal with the layout planning phase.

Moreover, it was recommended to keep the current position of a particular set of machines on the shop floor. Such machines were either heavy enough to make their movement impossible or must be isolated in a special position because the processing tasks they perform would not assist in having a clean floor. Many modifications were done for the machine cells and part families introduced by the cell formation algorithm to satisfy this recommendation.

The cellular layout development was mainly based on the analysis of the flow intensity of parts. Cells were located relative to each other according to the volumes exceptional work moving between each pair of cells. Machines were also arranged inside each cell according to the major flow pattern of the part family assigned to such cell.

The factory layout was created using AUTOCAD and analyzed using FACTORY FLOW, a layout program which interfaces with AUTOCAD. A special icon was developed for each machine type, and those icons were positioned as needed to effect a given layout.

Six alternative configurations for the newly suggested cellular system were developed by providing different values from ten through fifteen as the upper limit on the number of machine types allowed to exist in any cell. The same procedure was followed in planning the layout for each of these alternative configurations.

5. SLAM-II MACROMODEL OF FACTORY OPERATIONS

As illustrated in Figure 3, the core of the bi-level simulation modeling approach discussed here is a macromodel of overall factory operations. The model consists of SLAM-II network statements integrated with FORTRAN 77 code. In this model, batches of parts (i.e., reorder quantities) are represented as entities which flow through the system. Three aspects of the system are considered: 1) the inventory control subsystem (a reorder point system), 2) the material handling subsystem (consisting of fort trucks and elevators), and 3) the parts/end item processing subsystem (e.g., machining processes, heat treat, and assembly).

The inputs to the model include:

1) For each manufactured part or end item, the process routing (cycle time, set up time, operation number, and work center for each operation), bill of material data (i.e., component parts), initial inventory level, reorder point, reorder quantity, and part type (A, B, C or D), and the maximum number of pieces that can fit into a tote (container) for this part type.
2) For each purchased part, the initial inventory level, reorder point, reorder quantity, part type (A, B, C, D), and projected lead time.
3) For each resource (which could be a material handling device such as a truck or an elevator, a work center consisting of two or more identical machines, or a single machine), the number of units of that resource and its location.
4) For each end item, projected inventory depletions, by time period.

Because of the large numbers of part types (6500), end item types (1842) and resources (252), the input files used were very large.

Output from the model includes:

1) Resource utilizations for each of the 252 resources.
2) Throughput times by part/end item types (A, B, C, D).
3) The amount of time spent by batches in setup, waiting, moving and production.
4) Work-in-process inventories (queue lengths) for the resources.
5) Inventory levels over time for each part type/end items.

The model is driven by end item depletions; that is, depletions can occur at the beginning of any 8-hour shift. Inventory levels are reduced accordingly, and a check of the new inventory level versus the reorder point for the end item is made. When the end item inventory level is at or below the reorder point, an order for another production order quantity of that product is scheduled for the next shift.

An end-item order released at the beginning of a shift causes reductions of component part inventory levels, based upon the bill of material for the end item. Whenever part inventory levels are reduced, a check is made of the new level versus the reorder point for the part. If the level is below the reorder point, an order release for a production lot of that part is scheduled to occur at the beginning of the next shift.

As noted above, batches (reorder quantities) of identical parts/end items are the entities for the model. Batch moves are handled implicitly by the model. That is, whenever a batch is finished processing at a work center, a check is made as to where its next operation is to be performed (i.e., the location of the next work center). Based upon the locations of the previous work center and the next work center, material handling resource(s) are selected (e.g., a fork truck, or a fork truck and an elevator). The time required to move a batch from one workcenter to another is completed as a function of the number of totes required to contain the batch, and the locations of the previous and the next workcenters. This part of the logic of the model is handled through the use of FORTRAN code interfaced with the SLAM network code.

Because of the lack of accurate data relating to WIP inventories and throughput times, model validation was accomplished through the use of interaction with plant engineers. That is, the plant engineers were heavily involved in the model development process in order to assure that a model with high face validity was achieved. In addition, various outputs (utilizations, from-to-data, etc.) from the model of the as-is system were evaluated by the plant engineers for their reasonableness.

The model has been employed in a variety of experiments, involving studying the effects of:

1) Elevator "removal" (i.e., studying the effect of conversion to a single floor facility, where the elevator is not a bottleneck).
2) Changing the capacities of specific workcenters.
3) Increasing demands for valves and fittings.
4) Reducing reorder points and reorder quantities.

Each model run was conducted for a simulated period of two years (100 80-hour weeks), but data was only collected for the last 75 weeks to allow a sufficient warm-up period. Experimental results indicate that:

1. As expected, the majority of throughput time (about 70%) for the "average" batch is spent in queues, waiting for resources to become available.
2. Conversion to a single floor facility will, in and of itself, result in a 10% reduction in queue time per batch. In particular, the as-is run resulted in 920,000 batch-hours of queue time as compared to 828,000 batch-hours of queue time for the no-elevator run.
3. If no changes are made to the system, a 15% increase in end item demand will result in a 79% increase in mean queue time per batch; a 35% increase in end item demand will result in a 178% increase in average queue time per batch.
4. Nine particular workcenters/machines are system bottlenecks. Increasing the capacities of these workcenters/machines will yield the greatest improvements in productivity.

6. SIMAN MICROMODELS OF MANUFACTURING CELLS

As shown in Figure 3, the key components of the micromodeling approach are a SIMAN macromodel of part fabrication operations and SIMAN micromodels of individual manufacturing cell operation for more than 30 cells. A "cell" is loosely defined as any organization of machines upon which a part or a family of parts is processed. It could consist of a transfer line for machining valve bodies, a series of machines arranged in a production flow line, or a flexible cell which can accommodate a variety of part routings.

The procedure for forming cells was the Serial Manufacturing Program, depicted in Figure 3 and discussed earlier in this paper. The SIMAN macromodel of factory operations, very similar in development to the SLAM-II model discussed earlier, models the flow of batches of manufactured parts through the plant. Unlike the SLAM-II macromodel, the SIMAN model looks only at parts, and does not treat product end items. Output from the model include statistics for the following measures of performance:

- Time a batch of parts spends in the system, from order entry to release to assembly.
- Number of batches of parts waiting for a given machine center or process area.
- Utilization of each resource (machine, machine center, or process area).

Material handling equipment is not explicitly modeled, nor is tooling (tools, jigs, fixtures and gages) considered.

The SIMAN macromodel was used to compare the planned single-floor layout with the existing seven-floor layout, and to compare a cellular layout with a process-oriented layout. Table 1 gives a comparison of mean time in system and the mean number of batches produced per week for Class A and Class B parts for the three alternatives considered over a two-year period.

Table 1. Comparison of Plant Layout Alternatives Using a SIMAN Macromodel

Layout	Part Type	Mean Time in System Hours	Mean Production Rate Batches/Week
Existing 7-floor with process layout	A: B:	62.9 26.9	11.3 35.9
New single-floor with process layout	A: B:	89.0 57.7	18.0 58.5
New single-floor with cellular layout	A: B:	69.5 38.1	18.0 59.1

This comparison shows that, although mean time in the system is greater for the proposed new single-floor facility, there is a 70 percent increase in the mean production rate. (Thus the increased time in system is very likely explained by the fact that the sample size is so much larger for the single-floor facility). The elevators used to move tote bins between floors in the existing facility had huge queues, which is confirmed by actual observation in the plant.

The cellular layout of the new single-floor facility gave almost exactly the same production rate as the process layout, but with reduced time in system. This is explained by the fact that movement time of parts between machine is greatly reduced in the cellular layout.

The SIMAN micromodel starts by creating the arrival of batches of parts at the manufacturing cell. When the cell is free, a batch is selected from the queue and the cell is set up with tooling for the particular part type. When setup is complete, the parts are taken from the tote bin one-at-a-time and processed through the machines in the cell according to the specified process sequence. This cell operation is shown in Figure 1.

Figure 4 shows Cell 10A, one of three segments of a manufacturing cell for the production of high-volume, large valve bodies. Forged parts enter the cell at machine 188, an Ingersoll machining center designed for machining valve bodies. Parts then slotted on machine 77 and deburred on machine 1198, before exiting the cell. Figure 5 shows the SIMAN model frame for Cell 10A. Figure 6 shows the SIMAN experiment frame for this cell. Figure 7 gives a SIMAN summary report for a simulation run of 4160 hours, or 52 eight-hour work weeks. This report shows that 20 different parts were scheduled for production on Cell 10A. The fact that machine 188 was utilized 100 percent of the time, including set up for each part type, indicates the need for a more capable machine for this function.

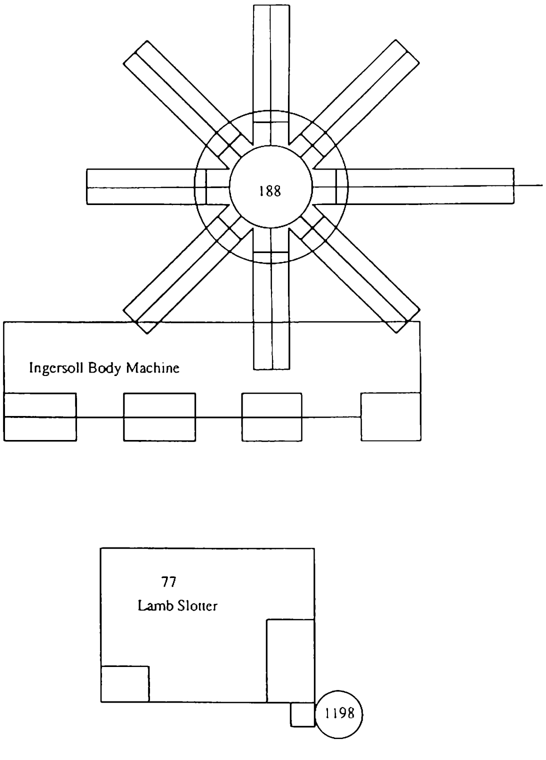
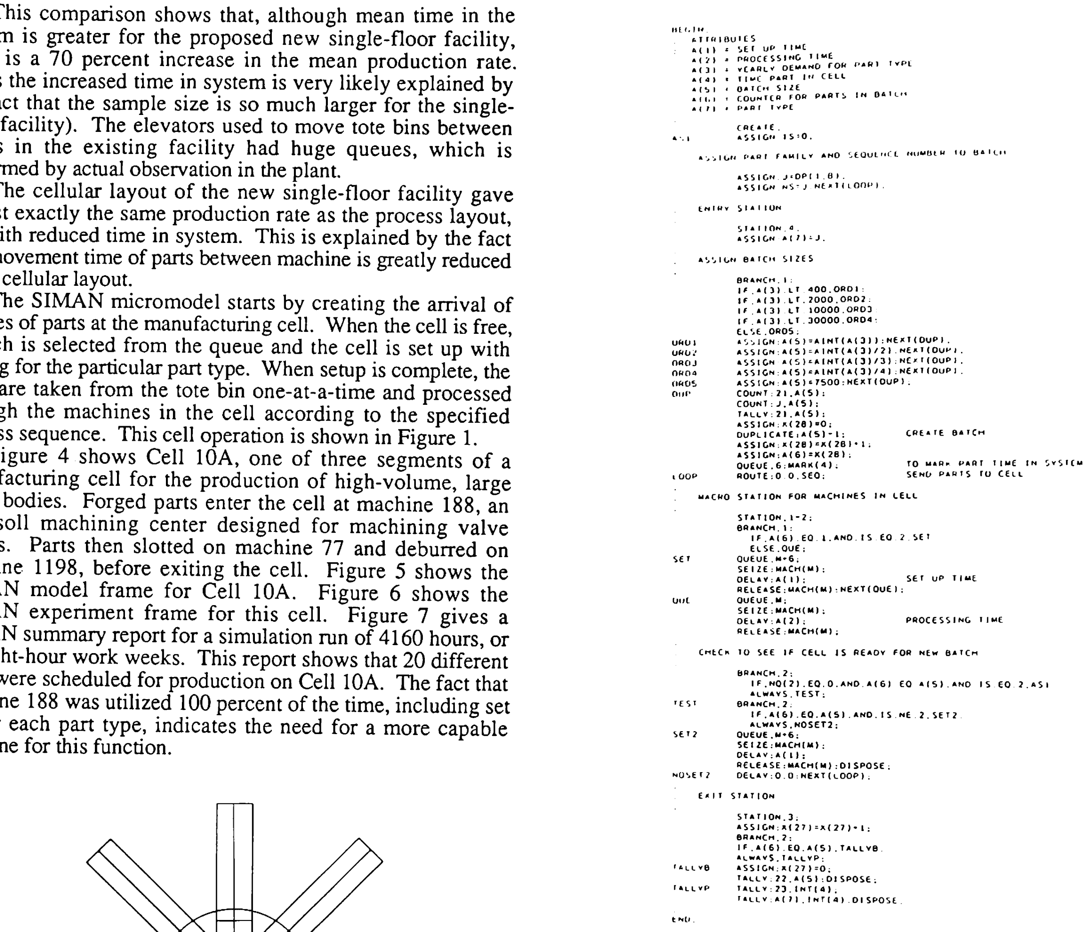
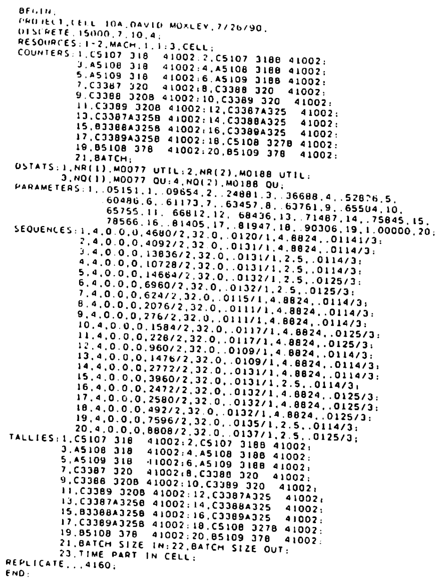


Figure 4. Configuration of Manufacturing Cell 10A for High-Volume Production of Large Valve Bodies



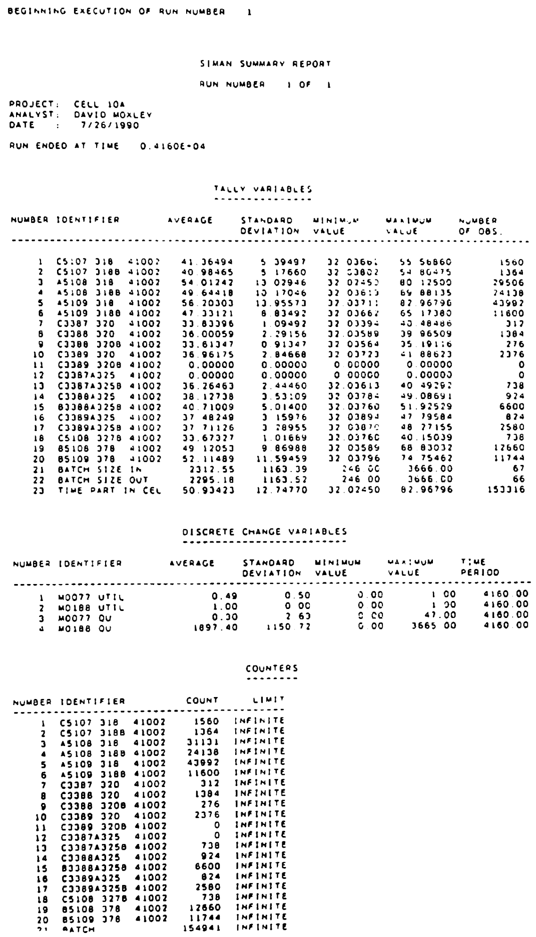
```
BEGIN.
;   ATTRIBUTES
;   A(1) = SET UP TIME
;   A(2) = PROCESSING TIME
;   A(3) = YEARLY DEMAND FOR PART TYPE
;   A(4) = TIME PART IN CELL
;   A(5) = BATCH SIZE
;   A(6) = COUNTER FOR PARTS IN BATCH
;   A(7) = PART TYPE

        CREATE.
A:1     ASSIGN IS=0.

;   ASSIGN PART FAMILY AND SEQUENCE NUMBER TO BATCH

        ASSIGN J=DP(1,8).
        ASSIGN NS=J NEXT(LOOP).

;   ENTRY STATION
;
        STATION,4.
        ASSIGN A(7)=J.

;   ASSIGN BATCH SIZES
;
        BRANCH,1:
        IF,A(3).LT.400,ORD1:
        IF,A(3).LT.2000,ORD2:
        IF,A(3).LT.10000,ORD3:
        IF,A(3).LT.30000,ORD4:
        ELSE,ORD5:
ORD1    ASSIGN:A(5)=AINT(A(3)):NEXT(DUP).
ORD2    ASSIGN:A(5)=AINT(A(3)/2):NEXT(DUP).
ORD3    ASSIGN:A(5)=AINT(A(3)/3):NEXT(DUP).
ORD4    ASSIGN:A(5)=AINT(A(3)/4):NEXT(DUP).
ORD5    ASSIGN:A(5)=7500:NEXT(DUP);
DUP     COUNT:21,A(5):
        COUNT:J,A(5):
        TALLY:21,A(5):
        ASSIGN:X(28)=0:
        DUPLICATE:A(5)-1:             CREATE BATCH
        ASSIGN:X(28)=X(28)+1:
        ASSIGN:A(6)=X(28):
        QUEUE,6:MARK(4):              TO MARK PART TIME IN SYSTEM
LOOP    ROUTE:0.0,SEQ:                SEND PARTS TO CELL
;
;   MACRO STATION FOR MACHINES IN CELL
;
        STATION,1-2:
        BRANCH,1:
          IF,A(6).EQ.1.AND.IS.EQ.2,SET
          ELSE,QUE:
SET     QUEUE,M+6:
        SEIZE:MACH(M):
        DELAY:A(1):                   SET UP TIME
        RELEASE:MACH(M):NEXT(QUE):
QUE     QUEUE,M:
        SEIZE:MACH(M):
        DELAY:A(2):                   PROCESSING TIME
        RELEASE:MACH(M):
;
;   CHECK TO SEE IF CELL IS READY FOR NEW BATCH
;
        BRANCH,2:
          IF,NQ(2).EQ.0.AND.A(6).EQ.A(5).AND.IS.EQ.2,AS1
          ALWAYS,TEST:
TEST    BRANCH,2:
          IF,A(6).EQ.A(5).AND.IS.NE.2,SET2
          ALWAYS,NOSET2:
SET2    QUEUE,M+6:
        SEIZE:MACH(M):
        DELAY:A(1):
        RELEASE:MACH(M):DISPOSE:
NOSET2  DELAY:0.0:NEXT(LOOP):
;
;   EXIT STATION
;
        STATION,3:
        ASSIGN:X(27)=X(27)+1:
        BRANCH,2:
        IF,A(6).EQ.A(5),TALLYB
        ALWAYS,TALLYP:
TALLYB  ASSIGN:X(27)=0:
        TALLY:22,A(5):DISPOSE:
TALLYP  TALLY:23,INT(4):
        TALLY:A(7),INT(4):DISPOSE.
;
END.
```

Figure 5. SIMAN Model Frame for Manufacturing Cell 10A



```
BEGIN;
PROJECT,CELL 10A,DAVID MOXLEY,7/26/90,
DISCRETE,15000,7,10,4;
RESOURCES:1-2,MACH,1,1:3,CELL;
COUNTERS:1,C5107 318  41002:2,C5107 3188 41002:
         3,A5108 318  41002:4,A5108 3188 41002:
         5,A5109 318  41002:6,A5109 3188 41002:
         7,C3387 320  41002:8,C3388 320  41002:
         9,C3388 3208 41002:10,C3389 320  41002:
         11,C3389 3208 41002:12,C3387A325  41002:
         13,C3387A3258 41002:14,C3388A325  41002:
         15,B3388A3258 41002:16,C3389A325  41002:
         17,C3389A3258 41002:18,C5108 3278 41002:
         19,B5108 378  41002:20,B5109 378  41002:
         21,BATCH;
DSTATS:1,NR(1),M0077 UTIL:2,NR(2),M0188 UTIL:
     3,NQ(1),M0077 QU:4,NQ(2),M0188 QU;
PARAMETERS:1,.05151,1,.09654,2,.24881,3,.36688,4,.52876,5,
            .60486,6,.61173,7,.63457,8,.63761,9,.65504,10,
            .65755,11,.66812,12,.68436,13,.71487,14,.75845,15,
            .78566,16,.81405,17,.81947,18,.90306,19,1.00000,20;
SEQUENCES:1,4,0.0,0,4680/2,32.0,.0120/1,4.8824,.01141/3:
          2,4,0.0,0,4092/2,32.0,.0131/1,4.8824,.0114/3:
          3,4,0.0,0,13836/2,32.0,.0131/1,2.5,.0114/3:
          4,4,0.0,0,10728/2,32.0,.0131/1,2.5,.0114/3:
          5,4,0.0,0,14664/2,32.0,.0132/1,2.5,.0125/3:
          6,4,0.0,0,6960/2,32.0,.0132/1,2.5,.0125/3:
          7,4,0.0,0,624/2,32.0,.0115/1,4.8824,.0114/3:
          8,4,0.0,0,2076/2,32.0,.0111/1,4.8824,.0114/3:
          9,4,0.0,0,276/2,32.0,.0111/1,4.8824,.0114/3:
          10,4,0.0,0,1584/2,32.0,.0117/1,4.8824,.0114/3:
          11,4,0.0,0,228/2,32.0,.0117/1,4.8824,.0125/3:
          12,4,0.0,0,960/2,32.0,.0109/1,4.8824,.0125/3:
          13,4,0.0,0,1476/2,32.0,.0109/1,4.8824,.0114/3:
          14,4,0.0,0,2772/2,32.0,.0131/1,4.8824,.0114/3:
          15,4,0.0,0,3960/2,32.0,.0131/1,4.8824,.0114/3:
          16,4,0.0,0,2472/2,32.0,.0132/1,2.5,.0114/3:
          17,4,0.0,0,2580/2,32.0,.0132/1,4.8824,.0125/3:
          18,4,0.0,0,492/2,32.0,.0132/1,4.8824,.0125/3:
          19,4,0.0,0,7596/2,32.0,.0135/1,2.5,.0114/3:
          20,4,0.0,0,8808/2,32.0,.0137/1,2.5,.0125/3;
TALLIES:1,C5107 318  41002:2,C5107 3188 41002:
        3,A5108 318  41002:4,A5108 3188 41002:
        5,A5109 318  41002:6,A5109 3188 41002:
        7,C3387 320  41002:8,C3388 320  41002:
        9,C3388 3208 41002:10,C3389 320  41002:
        11,C3389 3208 41002:12,C3387A325  41002:
        13,C3387A3258 41002:14,C3388A325  41002:
        15,B3388A3258 41002:16,C3389A325  41002:
        17,C3389A3258 41002:18,C5108 3278 41002:
        19,B5108 378  41002:20,B5109 378  41002:
        21,BATCH SIZE IN:22,BATCH SIZE OUT:
        23,TIME PART IN CELL;
REPLICATE,,,4160;
END;
```

Figure 6. SIMAN Experiment Frame for Manufacturing Cell 10A



```
BEGINNING EXECUTION OF RUN NUMBER    1


                              SIMAN SUMMARY REPORT

                              RUN NUMBER    1 OF   1

PROJECT:   CELL 10A
ANALYST:   DAVID MOXLEY
DATE    :   7/26/1990

RUN ENDED AT TIME    0.4160E+04


                                TALLY VARIABLES
                                ---------------

NUMBER IDENTIFIER            AVERAGE      STANDARD    MINIMUM      MAXIMUM      NUMBER
                                          DEVIATION   VALUE        VALUE        OF OBS.
-----------------------------------------------------------------------------------------

    1  C5107 318   41002    41.36494      5.39497    32.03661    55.56860        1560
    2  C5107 318B  41002    40.98465      5.17660    32.03802    54.80475        1364
    3  A5108 318   41002    54.01247     13.02946    32.02450    80.12500       29506
    4  A5108 318B  41002    49.64418     10.17046    32.03613    69.88135       24138
    5  A5109 318   41002    56.20303     13.95573    32.03711    82.96796       43992
    6  A5109 318B  41002    47.33121      8.83492    32.03662    65.17380       11600
    7  C3387 320   41002    33.83396      1.09492    32.03394    40.48486         312
    8  C3388 320   41002    36.00059      2.29156    32.03589    39.86509        1384
    9  C3388 320B  41002    33.61347      0.91347    32.03564    35.19116         276
   10  C3389 320   41002    36.96175      2.84668    32.03723    41.88623        2376
   11  C3389 320B  41002     0.00000      0.00000     0.00000     0.00000           0
   12  C3387A325   41002     0.00000      0.00000     0.00000     0.00000           0
   13  C3387A325B  41002    36.26463      2.44460    32.03613    40.49292         738
   14  C3388A325   41002    38.12738      3.53109    32.03784    49.08691         924
   15  B3388A325B  41002    40.71009      5.01400    32.03760    51.92529        6600
   16  C3389A325   41002    37.48249      3.15976    32.03894    47.79584         824
   17  C3389A325B  41002    37.71126      3.28955    32.03870    48.77155        2580
   18  C5108 327B  41002    33.67327      1.01669    32.03760    40.15039         738
   19  B5108 378   41002    49.12053      9.86988    32.03589    68.83032       12660
   20  B5109 378   41002    52.11489     11.59459    32.03796    74.75462       11744
   21  BATCH SIZE IN         2312.55      1163.39      246.00     3666.00          67
   22  BATCH SIZE OUT        2295.18      1163.52      246.00     3666.00          66
   23  TIME PART IN CEL     50.93423     12.74770    32.02450    82.96796      153316


                          DISCRETE CHANGE VARIABLES
                          -------------------------

NUMBER IDENTIFIER            AVERAGE      STANDARD    MINIMUM      MAXIMUM      TIME
                                          DEVIATION   VALUE        VALUE        PERIOD
-----------------------------------------------------------------------------------------
    1  M0077 UTIL               0.49         0.50        0.00         1.00     4160.00
    2  M0188 UTIL               1.00         0.00        0.00         1.00     4160.00
    3  M0077 QU                 0.30         2.63        0.00        47.00     4160.00
    4  M0188 QU              1897.40      1150.72        0.00      3665.00     4160.00


                                    COUNTERS
                                    --------

NUMBER IDENTIFIER              COUNT      LIMIT
-----------------------------------------------
    1  C5107 318   41002        1560   INFINITE
    2  C5107 318B  41002        1364   INFINITE
    3  A5108 318   41002       31131   INFINITE
    4  A5108 318B  41002       24138   INFINITE
    5  A5109 318   41002       43992   INFINITE
    6  A5109 318B  41002       11600   INFINITE
    7  C3387 320   41002         312   INFINITE
    8  C3388 320   41002        1384   INFINITE
    9  C3388 320B  41002         276   INFINITE
   10  C3389 320   41002        2376   INFINITE
   11  C3389 320B  41002           0   INFINITE
   12  C3387A325   41002           0   INFINITE
   13  C3387A325B  41002         738   INFINITE
   14  C3388A325   41002         924   INFINITE
   15  B3388A325B  41002        6600   INFINITE
   16  C3389A325   41002         824   INFINITE
   17  C3389A325B  41002        2580   INFINITE
   18  C5108 327B  41002         738   INFINITE
   19  B5108 378   41002       12660   INFINITE
   20  B5109 378   41002       11744   INFINITE
   21  BATCH                  154941   INFINITE
```

Figure 7. SIMAN Summary Report for a One-Year Simulation of Manufacturing Cell 10A

7. MACRO/MICRO MODELING IN A DISTRIBUTED SYSTEM

The current simulation modeling effort is being conducted on a VAX cluster of super mini-computers. The SLAM-II macromodel of overall plant operation requires close to one hour for a 2-year simulation. SIMAN micromodels of manufacturing cell operation requires from 20 to 30 minutes on an IBM PS/2 Model 80 microcomputer for a 2-year simulation. Thus, the micromodeling of 30 manufacturing cells would require some 6 to 7 hours of computing time. If the SLAM-II macromodel on the VAX machine could somehow be linked with a network of microcomputers which are simulating micromodels of manufacturing cells, the time required to execute the total simulation would be paced by the plant macromodel.

The next phase of this research will address a distributed simulation framework for the macro/micro modeling approach to simulating factory operations. The Department of Industrial Engineering at the University of Louisville now has a STARLAN networking linking some 13 workstations. The next research effort will focus on developing a task control module for coordinating the operation of nine nodes, configured as a body-centered cube, on which micromodeling simulation is performed. This control module, positioned as the center-node in the nine-node cubic cluster, would also be linked with the VAX mainframe on which the macromodel runs. No linkage between the macromodel and the cell micromodels has been accomplished to date. Rather, these models are used to study very different issues in the factory.

It should be noted that this means of distributing simulation tasks differs markedly from any reported to date. It does not distribute events to different nodes, but instead simulates entire cells for the duration of the simulation.

8. SUMMARY AND CONCLUSIONS

This paper has described a unique approach to the modeling of complex manufacturing systems. Although the focus here is on cellular manufacturing systems, the bi-level modeling approach discussed here is applicable to any system for which one would simulate a macroscopic view of the system at one level and microscopic views of subsystems at a more detailed level. Although we have reported model development in two languages — SLAM-II and SIMAN — modeling could actually involve a single language or an assortment of languages.

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