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MODEL EVOLUTION II: AN FMS DESIGN PROBLEM

A. Alan B. Pritsker
Pritsker & Associates, Inc.
P.O. Box 2413
West Lafayette, IN 47906

ABSTRACT

This paper examines a flexible manufacturing system (FMS) to illustrate procedures involved in model development. The evolution of various SLAM II® models of the FMS are described. The paper demonstrates the importance of alternative modeling concepts and viewpoints and the ease of embellishing models developed for analysis by simulation. The paper presents a sequence of facility diagrams built with TESS ™ showing the evolution of descriptive models. A major conjecture arising from this paper and the paper presented at WSC '86 is that modeling is a difficult process because we do not have measurable criteria for evaluating the worth of a model.

1. INTRODUCTION

The paper, "Model Evolution: A Rotary Index Table Case History" (Pritsker, 1986a) presented at WSC '86, showed the evolution and rationale behind the simplification of SLAM II models of a rotary index table. Six models of the rotary index table were developed, each of which could be used to analyze the rotary index table. The worthiness of the six models could not be evaluated. The paper stated a good model is one that represents the system sufficiently to meet the purpose for modeling, is timely, and is extendable. Also, a good model is understandable, so it can be communicated and documented. Currently, we have no measurable criteria for evaluating a model's goodness.

This paper presents models of a flexible manufacturing system (FMS). The first model makes many assumptions regarding the system to be modeled. These assumptions simplify the modeling process. They are not due to limitations of the analysis procedure. In this regard, modeling for analysis by simulation differs significantly from analytic-oriented modeling procedures. When modeling is not analysis-driven, simplifications and assumptions are based on: (1) the purpose for modeling, and (2) an estimated need for including details in the model which are not considered to have an impact on the final decision process.

This paper presents a problem situation and illustrates model evolution. Problem-solution is not the goal. No attempt is made to provide criteria for establishing model goodness. This topic requires more research.

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2. FMS PROBLEM DESCRIPTION
(Musselman,1984, Pritsker,1986b, Wortman,1984)

A manufacturer of castings wanted to evaluate alternative milling-machine-center configurations to achieve a production goal of 3,520 finished castings per two-shift week (80 hours). The flexible manufacturing system (FMS) in Figure 1 was designed to perform machining operations on the castings. Castings are initially loaded onto pallets which carry 16 castings each, then sent by conveyor to one of two lathes. The castings are turned, then conveyor-transported in pallet loads to a wash/inspection area. After inspection, the castings are sent to the machining center on a wire-guided vehicle.

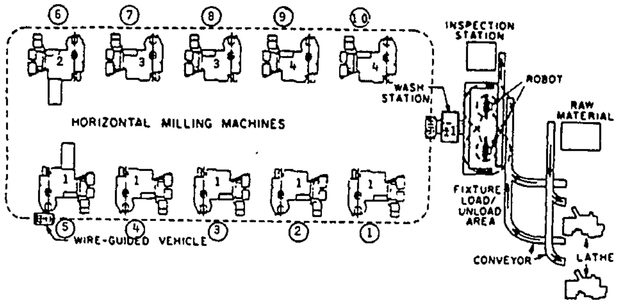


Figure 1. A flexible milling-machine system.

The machining-center design consists of ten identical horizontal milling machines which can perform any one of three operations: OP1, OP2, or OP3. For a particular casting, the milling machines may be dedicated to one operation or provided with sufficient tooling so any of the three operations could be performed. The latter mills are flexible mills. Two fixture types, A and B, are used in this system. Fixture A is used for OP1; and Fixture B is used for OP2 and OP3.

Before a pallet is routed for OP1 machining, each casting on the pallet is attached to fixture A and sent through the wash station. When a machine capable of performing OP1 becomes available, the pallet is transported to it. After the castings are machined, they are returned to the wash/inspection area and attached to fixture B to await OP2. The same procedure is used for OP3, except the castings are rotated 180 degrees on the same fixture. After all three machining operations have been completed, the pallets are sent to final inspection and then depart the system.

The modeling objectives are to: evaluate system balance and productivity; determine additional equipment needs; determine which resources, if any, could be eliminated; and establish the number of dedicated and flexible mills required. Because tooling costs are much higher for flexible mills, a decrease in the number of required flexible mills will help cut manufacturing costs.

3. PRELIMINARY ANALYSIS

The FMS designer identified the greatest concerns as the number of horizontal milling machines to buy, the number to dedicate to each of the three operations, and the number that should be tooled for flexibility. A review of operation and travel times confirmed that operating the milling machines on a component basis would indeed create a bottleneck. Based on this and other data observations, these initial assumptions were made:

(1) A fiirst analysis could concentrate on the mills.
(2) The mills' set-up times could be included in the processing times.
(3) The transporting times on wire-guided vehicles could be included on the operation times.
(4) A dedicated or flexible mill could be assigned when the pallet arrived; no re-assignment algorithm would be needed.
(5) Fixturing need not be included in the analysis.

From the data, it was determined that a pallet of castings would arrive at the wash and inspection station every 22 minutes. Performing operations 1, 2, and 3 would take 120, 40, and 56 minutes per pallet, respectively. Assuming a mill is assigned when the pallet arrives, it waits in a queue until the dedicated or flexible mill assigned is available. Once placed in a queue for a dedicated mill, it is not processed by a flexible mill even if a flexible mill became idle. For this abstracted version of the problem, only the operation and inter-arrival times are needed to develop a first-cut FMS model.

To determine the mill requirement for each operation type based on one pallet arrival every 22 minutes that 220 pallets will arrive in a 4800-minute (80-hour) work-week. To accomplish milling on 220 pallets in 4800 minutes, a pallet must be completed every 21.82 minutes. Dividing the 120, 40, and 56 minutes for each operation per pallet by the required milling schedule of 21.82 minutes determines the machine requirements per operation as:

* 5.5 machines for operation 1 (120 minutes divided by 21.82)
* 1.8 machines for operation 2
* 2.6 machines for operation 3

Since mills have a constant cycle time, it is necessary to select an integer number of machines to perform the operations or to use a flexible machine to accommodate the fractional requirements for mills. In the basic design, the number of dedicated mills was rounded to an integer number, yielding a design of 5 mills for OP1, 1 mill for OP2, 2 mills for OP3, and 2 flexible mills. The proposed design is evaluated in model 1.

4. MODEL 1: FIRST CUT MODEL

Figures 2 and 3 show the network and SLAM II statement models (Pritsker, 1986b) for the situation described in Section 3. At the CREATE node, pallets enter the network every 22 time-units; attribute 3 is established as the arrival time. At node SETA, the first attribute of the arriving pallet, OPERATION, is indexed to 1, which defines the next operation to be performed. On the resource statements, the mills dedicated to OP1 are defined as resource 1; OP2 as resource 2; OP3 as resource 3; and the flexible mills as resource 4.

```
GEN,PRITSKER,FMS,2/28/86;
LIMITS,4,3,500;
ARRAY(1,3)/120,40,56;
EQUIVALENCE/ATRIB(1),OPERATION/
            ATRIB(2),MILL/
            ARRAY(1,OPERATION),PROCESS_TIME;
NETWORK;
      RESOURCE/1,MILL1(5),1/2,MILL2(1),2;                DEFINE 10 MILLS
      RESOURCE/3,MILL3(2),3/4,MILLF(2),4;                AS 4 RESOURCE TYPES
      CREATE,22,,3;
;
SETA  ASSIGN,OPERATION = OPERATION + 1,
             II=OPERATION;                               INCREMENT OPERATION
;                                                        NUMBER AND
;                                                        SET II TO PROPOSED MILL
      ACT,0,NNRSC(II).GT.0.OR.NNRSC(MILLF).EQ.0,SETM;    CONDITIONS FOR
;                                                        DEDICATED MILL
      ACT;
      ASSIGN,MILL=4;                                     ASSIGN FLEXIBLE MILL
      ACT,,,AMILL;
SETM  ASSIGN,MILL = OPERATION;                           ASSIGN DEDICATED MILL
AMILL AWAIT(MILL= 1,4),MILL/1;                           WAIT FOR MILL
      ACT,PROCESS_TIME;                                  MILL PROCESSING ACTIVITY
      FREE,MILL/1,1;                                     FREE MILL
      ACT,0,OPERATION.LT.3,SETA;                         CHECK FOR ANOTHER
;                                                        OPERATION
      ACT;                                               MILL WORK COMPLETE
      COLCT,INT(3),TIME IN SYSTEM;                       COLLECT TIME FOR
;                                                        MILL OPERATIONS
      TERM;
      END;
INIT,0,2400;
FIN;
```

Figure 3. Statement model of a flexible machining system.

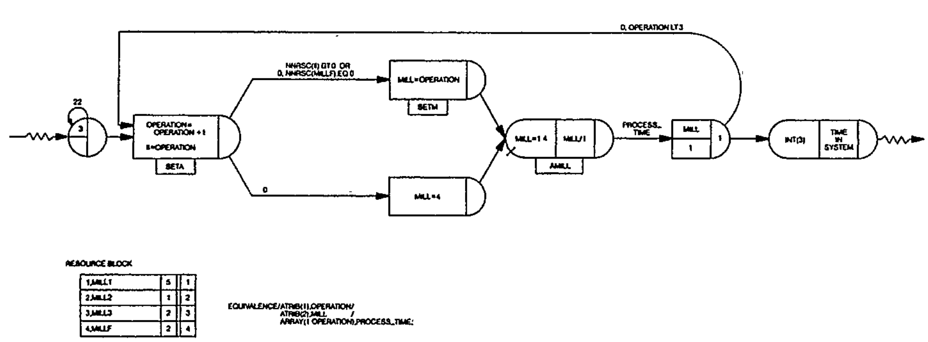


Figure 2. Network model of a flexible machining system.

The activities emanating from node SETA determine if a pallet should be routed to a dedicated or flexible mill. It is assumed that a dedicated mill will be used if available (NNRSC(II).GT.0) or if no flexible mill is available (NNRSC(MILLF).EQ.0). This condition is

NNRSC(II).GT.0 .OR. NNRSC(MILLF).EQ.0

and is specified for the activity leading to ASSIGN node SETM. AT node SETM, the pallet is assigned to a mill by setting MILL=OPERATION, where MILL is defined as attribute 2 of the entity. MILL is used later as both a file number and a resource number.

If the above condition is not satisfied, then a dedicated machine for operation II is not available, and a flexible mill is. In this case, MILL is set to 4 to indicate that the flexible mill is to perform the operation for this pallet. At AWAIT node AMILL, the pallet awaits a mill resource, defined by the value of MILL. The pallet waits in file 1, 2, 3, or 4. When the appropriate mill is freed, the pallet proceeds through the activity whose duration is specified by PROCESS_TIME, which is equivalenced to ARRAY(1,OPERATION). An ARRAY statement (line 3) sets the processing times to 120, 40, or 56, depending on the operation number.

After processing, the mill is freed at a FREE node. If OPERATION is less than 3, the pallet is routed back to node SETA for additional operations. If all three operations are completed, the pallet is routed to a COLCT node, and the time the pallet was in the FMS system is recorded.

4.1 Model 1A: Changing the Number of Mills

The network segment shown in Figure 4 establishes the number of initial mills to be 0, and uses an ALTER node to change resource MILL to a capacity of XX(II). II takes on the values 1 to 4, representing the 4 resources. II is set in the ASSIGN node of Figure 4 to be equal to the number of entities that have completed activity 1, which is the input branch to the ASSIGN node. With this model, an INTLC statement is used to set the values of XX(II). For example,

INTLC,XX(1)=5, XX(2)=1,XX(3)=2, XX(4)=2;

Different combinations of mills for performing the operations can be evaluated using the added network segment.

4.2 Model 2: Adding Set-up Times for the Flexible Mills

Since a flexible mill performs OP1, OP2, and OP3, a set-up time penalty is associated with changing the mill from one operation to another (Pritsker, 1986c). These penalties are shown below in the SLAM II variable ARRAY. Each row shows the set-up time penalty for going from the operation number defined by the row number to the operation number defined by the column number.

ARRAY(1,3)/0,5,7;
ARRAY(2,3)/10,0,8;
ARRAY(3,3)/8,10,0;

For example, ARRAY(2,1) has a set-up time penalty of 10 for performing operation 1 following operation 2.

To include the set-up time, it is necessary to change the network model by adding an additional path from the AWAIT node AMILL to the FREE node. This is shown in Figure 5 where SETUP TIME is equivalenced to a value from ARRAY(PREV_OPER,OPERATION). PREV_ OPER is initially set to 1 (PREV_OPER is equivalenced to the SLAM II variable XX(1)). The network segment in Figure 5 sets the flexible mill time equal to the process time plus the set-up time. An ASSIGN node is then used to set the previous operation PREV_OPER to the operation just performed. The only other change from Model 1 is to change the row for the processing times to row 4 of ARRAY, to allow the use of an operation number directly as a row number in references for ARRAY.

4.3 Model 3: Allowing Reassignment of a Flexible Mill

The FMS design did not include a control system for reassigning a pallet after it was placed in a queue for a dedicated mill. After reviewing the outputs, it became clear that flexible mills were not being utilized sufficiently because of this design limitation. A model was developed which includes control logic to assign flexible mills to pallets waiting for dedicated mills (Pritsker, 1986c). To implement this, a priority for pallets waiting for the three operations was established.

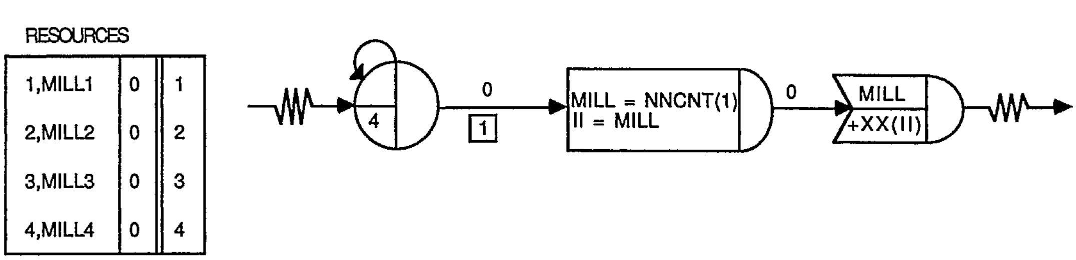
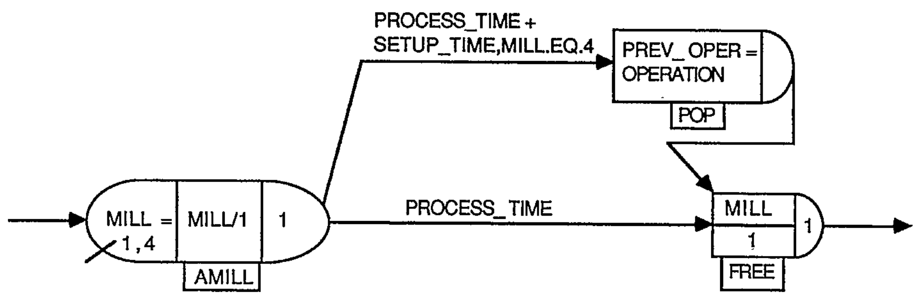


Figure 4. Network segment for changing the number of mills.



EQUIVALENCE/XX(1),PREV_ OPER/
ARRAY(PREV_ OPER,OPERATION),SETUP_ TIME;
INTLC,PREV_ OPER = 1;

Figure 5. Network segment to add set-up times for flexible mills.

Reviewing the calculations to determine the number of dedicated mills in Section 3, the flexible mills should be allocated to perform operation 2, then operation 3, and then operation 1 based on the largest fraction eliminated when rounding to an integer number of dedicated mills.

To allocate a flexible mill to pallets waiting for operation 2, then operation 3, then operation 1, the resource block for flexible mills is changed to:

RESOURCE/ 4,MILLF(2),4,2,3,1;

The last four numbers indicate flexible mills should be reallocated to a pallet waiting in file 4, then 2, then 3, then 1. When the flexible mill is allocated to a waiting entity, the MILL attribute of that entity is specified as 4, using subroutine ALLOC as a specification for the resource required when a pallet arrives to AWAIT node AMILL. Subroutine ALLOC is given in Figure 6.

```
      SUBROUTINE ALLOC(ICODE,IFLAG)
      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MFA,MSTOP,NCLNR
     1,NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      COMMON/UCOM1/ISTATUS(10),TYPE(10),PROCTIME(3)
      IR=ATRIB(1)
C
C  SEIZE DEDICATED MACHINE IF AVAILABLE
C
      IF (NNRSC(IR).GT.0) THEN
        CALL SEIZE (IR,1)
        ATRIB(2)=IR
        IFLAG=1
      ELSE IF (NNRSC(4).GT.0) THEN
C
C  OTHERWISE, SEIZE FLEXIBLE MACHINE IF AVAILABLE
C
        CALL SEIZE (4,1)
        ATRIB(2)=4
        IFLAG=1
      ELSE
        IFLAG=0
      ENDIF
      RETURN
      END
```

Figure 6. Subroutine ALLOC for allocating a resource to pallet entity.

In subroutine ALLOC, IR is defined as the operation number to be performed. If a dedicated machine is available, it is seized, and the resource type is allocated to the pallet entity requesting the resource at the AWAIT node. If a dedicated machine is not available, a check is made to determine if a flexible machine is. If one is, the mill type is set to 4. IFLAG is set to 1, which tells SLAM II to alter the pallet entity attributes which are taken from the file associated with the AWAIT node. Subroutine SEIZE is used to seize one unit of the resource that is allocated to the pallet entity. No other changes are required to implement this new control strategy for the flexible manufacturing system.

4.4 Model 4: Modeling the Wire-Guided Vehicle

Wire-guided vehicles may be modeled in detail using Automated Guided Vehicle (AGV) constructs of the Material Handling Extension to SLAM II. This involves:

* Defining each mill as a resource;
* Providing a description of the guidepath, with control points before each mill and segments connecting the guidepath (Pritsker, 1986c);
* Describing the guided vehicles.

These SLAM II definitions and the statement model are shown in Figure 7, and the corresponding network model in Figure 8.

Two ARRAY rows are used. The first row provides the processing times; the second row defines the type of machine at each location. The ARRAY(5,10) statement establishes that mills 1 through 5 are dedicated to operation 1, mill 6 is dedicated to operation 2, mills 7 and 8 are dedicated to operation 3, and mills 9 and 10 are flexible. Since the transport times are included in this model, a wash/inspection time after each operation of 10 time units is also included. This station is given a resource name of INSP which has 2 inspectors.

```
GEN,PRITSKER,FMS & AGV,7/24/87,1;
LIMITS,8,7,200;
INIT,0,4800;
VCONTROL,0.01,0.1;
CONTINUOUS,0,1,,,,N;
ARRAY(4,3)/120.0,40.0,56.0;
ARRAY(5,10)/1,1,1,1,1,2,3,3,4,4;
EQUIVALENCE/ATRIB(1),OPERATION/
            ATRIB(2),MILL/
            ATRIB(4),TYPE/
            ARRAY(4,OPERATION),PROCESS_TIME/
            ARRAY(5,MILL),MILL_TYPE;
NETWORK;
;
;  DEFINE RESOURCES
 ;
      RESOURCE/1,MILL1(1),4;
      RESOURCE/2,MILL2(1),4;
      RESOURCE/3,MILL3(1),4;
      RESOURCE/4,MILL4(1),4;
      RESOURCE/5,MILL5(1),4;
      RESOURCE/6,MILL6(1),4;
      RESOURCE/7,MILL7(1),4;
      RESOURCE/8,MILL8(1),4;
      RESOURCE/9,MILL9(1),4;
      RESOURCE/10,MILL10(1),4;
      RESOURCE/11,INSP(2),7;
;
;  DEFINE VEHICLE CONTROL POINTS
;
;            CONTROL
;              POINT       LABEL
      VCPOINT,     1/      MILL#1;
      VCPOINT,     2/      MILL#2;
      VCPOINT,     3/      MILL#3;
      VCPOINT,     4/      MILL#4;
      VCPOINT,     5/      MILL#5;
      VCPOINT,     6/      MILL#6;
      VCPOINT,     7/      MILL#7;
      VCPOINT,     8/      MILL#8;
      VCPOINT,     9/      MILL#9;
      VCPOINT,    10/      MILL#10;
      VCPOINT,    11/      INSPECT;
;
;  DEFINE VEHICLE GUIDEPATH SEGMENTS
;
;                     CONTROL  CONTROL
;            NUMBER   POINT 1  POINT 2   DISTANCE   DIRECTION
;
      VSGMENT,  1,       1,       2,        20,        UNI;
      VSGMENT,  2,       2,       3,        20,        UNI;
      VSGMENT,  3,       3,       4,        20,        UNI;
      VSGMENT,  4,       4,       5,        20,        UNI;
      VSGMENT,  5,       5,       6,        60,        UNI;
      VSGMENT,  6,       6,       7,        20,        UNI;
      VSGMENT,  7,       7,       8,        20,        UNI;
      VSGMENT,  8,       8,       9,        20,        UNI;
      VSGMENT,  9,       9,      10,        20,        UNI;
      VSGMENT, 10,      10,      11,        30,        UNI;
      VSGMENT, 11,      11,       1,        30,        UNI;
```

```
;
;  DEFINE AUTOMATED GUIDED VEHICLE FLEET
;
        VFLEET,AGV,1,100,100,0,0,4,,,8/CLOSEST,CRUISE;
;
;  DEFINE NETWORK
;
        CREATE,22,,3;
        ASSIGN,OPERATION=1,MILL=1,TYPE=1;
GON1    ASSIGN,II=MILL,1;
        ACTIVITY,,TYPE.EQ.MILL_TYPE.AND.NNRSC(II).GT.0,AWA1;
        ACTIVITY,,MILL_TYPE.EQ.4.AND.NNRSC(II).GT.0,AWA1;
        ACTIVITY,,MILL.EQ.10,Q123;
        ACTIVITY,,,NXT1;
NXT1    ASSIGN,MILL=MILL+1;
        ACTIVITY,,,GON1;
Q123    QUEUE(TYPE=1,3);
        ACTIVITY(1)/TYPE=1,3,STOPA(TYPE);
        ASSIGN,MILL=XX(1);
AWA1    AWAIT(4),MILL;
        VWAIT(5),AGV,11,CLOSEST;
        VMOVE,MILL;
        VFREE,AGV;
        ACTIVITY/4,PROCESS_TIME;
        VWAIT(6),AGV,MILL,CLOSEST;
FRE1    FREE,MILL,2;
        ACTIVITY,,,VM1;
        ACTIVITY,,,ASN3;
VM1     VMOVE,11;
        VFREE,AGV;
        AWAIT(7),INSP;
        ACTIVITY/5,10;
        FREE,INSP,1;
        ACTIVITY,,OPERATION.EQ.3,TRM1;
        ACTIVITY,,,ASN2;
ASN2    ASSIGN,OPERATION=OPERATION+1,MILL=1,TYPE=OPERATION;
        ACTIVITY,,,GON1;
TRM1    COLCT,INT(3),TIME IN SYSTEM;
        TERMINATE;
ASN3    ASSIGN,XX(1)=MILL,1;
        ACTIVITY,,MILL_TYPE.LE.3,ASN4;
        ACTIVITY,,MILL_TYPE.EQ.4,GON2;
ASN4    ASSIGN,STOPA=MILL_TYPE;
        TERMINATE;
GON2    GOON,1;
        ACTIVITY,,NNACT(2).GT.0,ASN5;
        ACTIVITY,,NNACT(3).GT.0,ASN6;
        ACTIVITY,,NNACT(1).GT.0,ASN7;
ASN5    ASSIGN,STOPA=2;
        TERMINATE;
ASN6    ASSIGN,STOPA=3;
        TERMINATE;
ASN7    ASSIGN,STOPA=1;
        TERMINATE;
        ENDNETWORK;
FIN;
```

Figure 7. Statement model for including a wire-guided vehicle in the FMS model.

Entities are created every 22 time-units and sent to an ASSIGN node, where OPERATION is set to 1 to indicate operation 1 needs to be performed. The next set of statements locates an available mill. If a dedicated mill is not available, a check for a flexible mill is made. If neither are available, the entity is placed in activity 1, 2 or 3 waiting for a mill which can perform operation 1, 2 or 3 to be freed. The mill is allocated at AWAIT node AWA1, and a request for an AGV is made at VWAIT node VW1 for the closest available AGV to come to the inspection station (control point 11). When the AGV arrives, the entity is moved to the allocated mill by the VMOVE activity. On arrival at the mill, the AGV is freed at VFREE node VF1. The entity continues on the network; the AGV is reassigned according to the VFLEET resource statement. If no entities are waiting for the AGV, the AGV will CRUISE the guide path as specified on the VFLEET statement.

The pallet is processed in activity 4 then a request for an AGV is made at the VWAIT node VW2. The location of the pallet is the control point associated with MILL. When the AGV arrives, the MILL is made available at node FRE1. The network segment starting at node ASN3 reallocates the MILL to a pallet waiting for the type of mill that completed the operation. The AGV moves the pallet to the inspection station (control point 11) and is then freed. The pallet awaits inspection, is inspected and washed, and then either leaves the system because all three operations have been performed, or cycles back for its next operation.

This completes the model description of the basic problem. The following subsections present embellishments to Model 4.

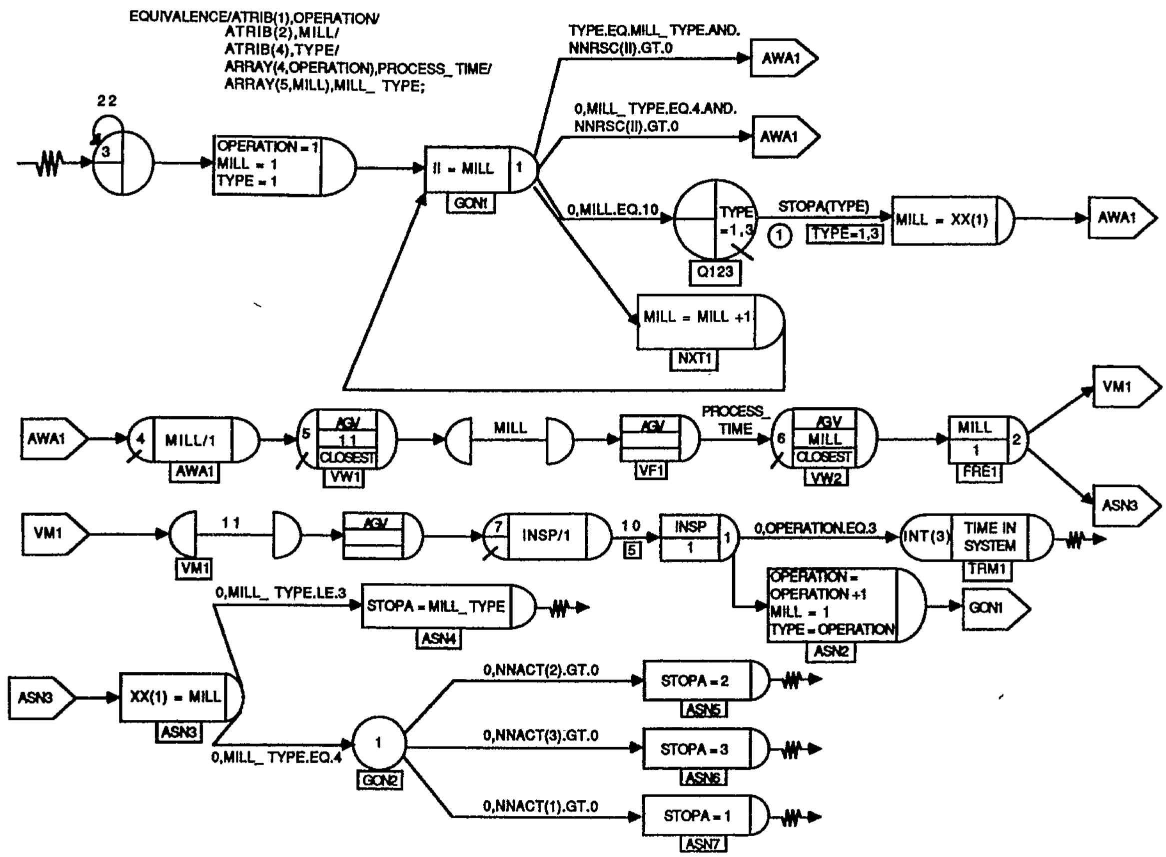


Figure 8. Network model of FMS with wire-guided vehicles.

4.4.1 Model 4A: Increasing the Number of Vehicles.

To increase the number of guided vehicles in the system, the number of vehicles prescribed on the VFLEET statement is changed to 2.

4.4.2 Model 4B: Bidirectional Movement.

To change the guided vehicles from unidirectional to bidirectional movement, the VSGMENT statement is modified to allow each segment to have bidirectional flow. To accomplish this embellishment, replace the UNI specification with a BID input.

4.4.3 Changing the Location of Mill Types

In the current design, mill types are located sequentially along the guide path. This is established in a definition of ARRAY(5,MILL). By changing the values in this ARRAY row, the mills can be located anywhere along the guide path. For example,

ARRAY(5,10)/1,2,1,3,1,3,1,4,1,4;

intersperses, operation 1 mills with mills performing other operations and flexible mills.

5. FACILITY DIAGRAMS

Facility diagrams are descriptive models of systems. Figures 9, and 10 show the evolution of the two FMS facility diagrams described in this paper. These diagrams and others were built using TESS (Standridge, 1987) and evolved as the needs of management changed during the project. TESS stores facility diagrams in its database so they may be recalled and used as the basis for other facility diagrams. In addition, an animation of any of the models presented in Section 4 can be produced for visualizing the simulated FMS operation. This is accomplished by writing rules which translate event occurrences to actions on the facility diagram. These rules are a transformation mechanism which allows the independent evolution of descriptive and analysis-based models. TESS capabilities for building detailed facility diagrams are shown in Figure 10, where hundreds of icons represent the system and its operation. The ability of TESS to store models, facility diagrams, system data and outputs in its database is indicative of the type of simulation support needed for model evolution and comparative analysis, which lead to problem resolution and solution inplementation.

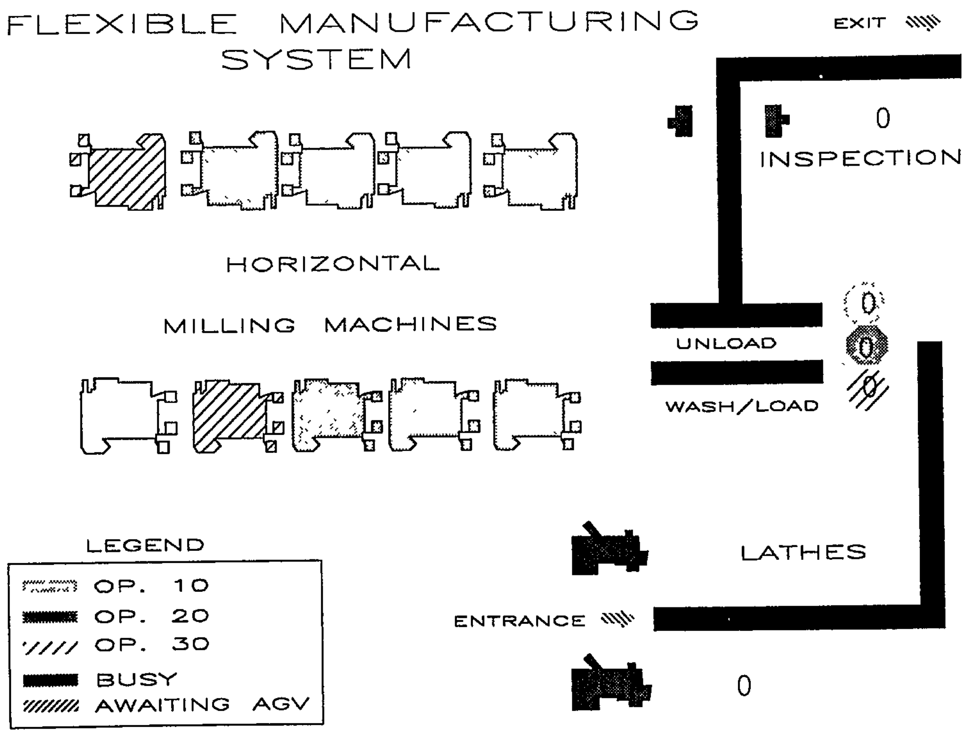


Figure 9. Facility Diagram 1 of FMS System

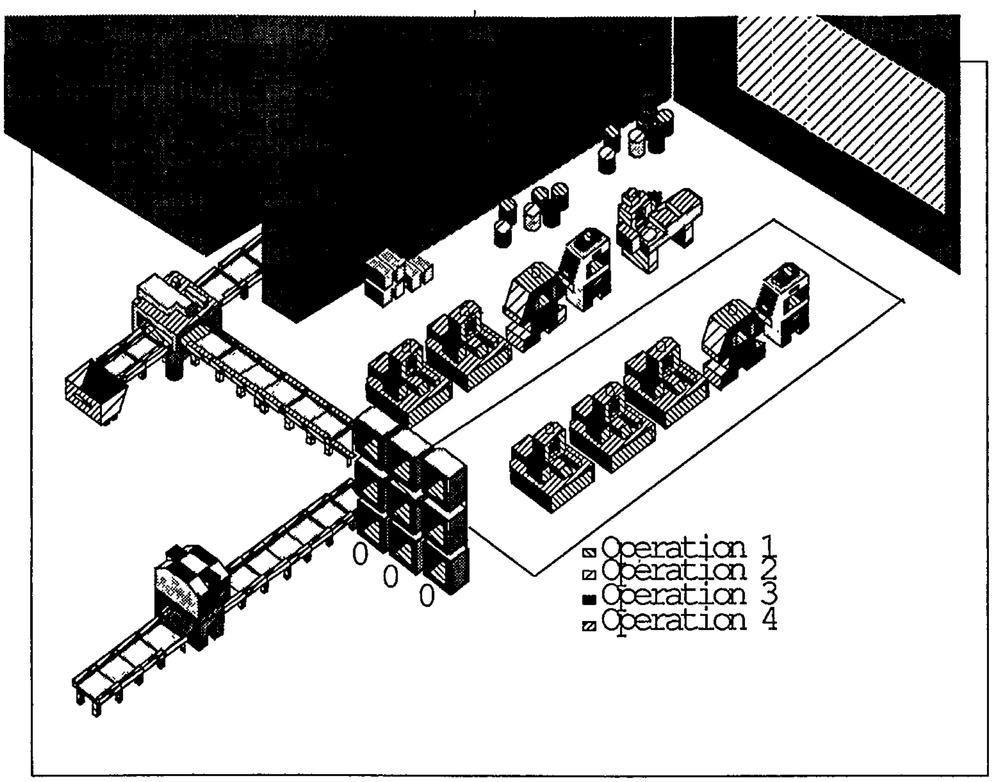


Figure 10. Facility Diagram 2 of FMS System

6. DISCUSSION

Key points made in this paper are:

1) Models built for analysis using simulation are easy to embellish, making an evolutionary modeling approach feasible and desirable.
2) The goodness of any of the models presented in this paper is difficult to determine.
3) Facility diagrams as descriptive models also evolve over time.

An interesting feature of the models presented is that no characterization of randomness is included. All the models are deterministic; yet, analysis by simulation is required.

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AUTHOR'S BIOGRAPHY

A. ALAN B. PRITSKER is Chairman of Pritsker & Associates, Inc. and FACTROL, Inc. He graduated from Columbia University with a BSEE and MSIE. He obtained a Ph.D. from The Ohio State University in 1961. From 1956 through 1962, Dr. Pritsker worked for Battelle Memorial Institute in Columbus, Ohio. From 1962 through 1981, he was Professor of Industrial Engineering at Arizona State University, Virginia Tech, and Purdue University. In 1973, he co-founded Pritsker & Associates.

Dr. Pritsker has published more than 100 technical papers and six books. He is a Fellow of AIIE and recipient of AIIE's Distinguished Research Award and Innovative Achievement Award. He is also a member of the National Academy of Engineering. Dr. Pritsker served as a member of the Board of Directors of the Winter Simulation Conference from 1970 to 1974 and 1979 to 1987, and as board chairman in 1984 and 1985.

A. Alan B. Pritsker
Pritsker & Associates, Inc.
P.O. Box 2413
West Lafayette, IN 47906
(317) 463-5557