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A Rule-Based Expert System for Designing Flexible Manufacturing Systems

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Designing advanced manufacturing systems like flexible manufacturing systems (FMSs) involves the solution of a complex series of interrelated problems. In this paper, we present an expert system to aid this design process for FMSs. The proposed system combines a rule-based expert system with computer simulation in order to capture dynamics of FMSs, evaluate design alternatives of FMSs, and seek effective ones with user friendly interface.

3.1 Introduction

Advanced manufacturing systems like flexible manufacturing systems (FMSs) are capital-intensive. Designing functional, yet cost-effective FMSs is a challenging task because it involves the solution of a complex series of interrelated problems. The importance of early design activities is emphasized for highly automated manufacturing systems. About 80% of the total budget is committed at the design stage (Vollbracht 1986) and 55% of the engineering cost is spent by the project authorization point (Harter and Mueller 1988).

A typical flexible manufacturing system (FMS) consists of groups of versatile numerically-controlled (NC) machines that are linked by a material handling system (MHS). Machines within each group are tooled identically and are capable of performing a certain set of operations. Operations and material movements are all under a central computer control. Since FMSs were introduced in the early 1960s, broader applications of FMSs have been developed in the areas of injection molding, metal forming and fabricating, and assembly. In 1989, roughly 1200 FMSs existed worldwide. According to forecasts, between 2500-3000 FMSs will be operating in the year 2000 (Tempelmeier and Kuhn 1993). FMSs, however, are highly capital-intensive and FMS designers are interested in seeking minimal-cost or minimal resource-usage design alternatives that satisfy performance and technical requirements such as throughput capacity and flexibility capacity.

Given selection of part types to be produced, we study a design problem of FMSs that consist of multiple types of NC machines. This problem seeks minimal cost design subject to meeting throughput requirements.

The decisions to be made include the number of machine groups, the number of machines at each group, the number of pallets, the number of transporters, and batch transfer size. When parts are small, a batch of parts can be mounted on a pallet and transferred together between machine groups in order to reduce material handling operations. At the early design stage of complex manufacturing systems like FMSs, different design issues are highly related and should not be treated independently (Heavey and Browne 1996). Highly significant interactions between the design factors may invalidate simple one-factor-at-a-time procedures for finding a minimum-cost system design. In FMSs, machines are flexible and versatile and there is a large latitude in allocating workload among machine groups. Clearly, there are strong interactions between the workload allocation and the optimal system configuration and between the batch size and the MHS capacity.

Research works on FMS design problems can be divided into three groups based upon the modeling techniques employed. These are queueing networks, integer programming, and simulation. Many researchers have used closed queueing network (CQN) models to solve design problems for flexible manufacturing systems (FMSs). Machines, at each machine group, are modeled as a multiserver station and pallets carrying work-in-process inventories modeled as the fixed job population circulating in CQN. A Markovian closed queueing network model is used by Vinod and Solberg (1985), Shanthikumar and Yao (1988), Dallery and Stecke (1990), Kouvelis and Lee (1995), and Tetzlaff (1995). All of these works deal with specific decisions, assuming that many other design decisions are already known. Also, they make several assumptions for ease of analysis such as exponential service times and large buffer spaces, which are often unrealistic.

Researchers have also used integer programming (Whitney and Suri 1985, Graves and Redfield 1988, Afentakis 1989). These integer programming models do not take into account the aspects of material handling issues and product flows, of resource contention and machine idle time, and of random events occurring on the assembly floor such as machine breakdowns or machine tool jams.

Simulation has been used by several researchers (Thompson et al. 1989, Nandkeolyar and Christy 1992, Winters and Burstein 1992). Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system (Zeigler 1984). Simulation is flexible to represent an FMS at any level of detail realistically. However, it can be also costly and time consuming to develop, validate and run simulations for many design alternatives before one good alternative is chosen. Furthermore, one cannot tell how good the chosen alternative is because simulation does not usually provide an optimal solution or benchmark with which the chosen alternative can be compared. Simulation design processing is a numerical technique without the functions of reasoning and symbolic processing. A relatively high level of training is necessary to perform useful simulation studies. Managers, as unskilled users, may have difficulty building a simulation model, validating the simulation, and interpreting the results of simulations.

An expert system is a computer system that can solve problems using expertise and knowledge of the system environment in ways that mimic a human expert in a specialized problem area (Kusiak and Chen 1987, Rao and Lingaraj 1988). Thus, expert system technology can speed problem solving and address problems in complex and difficult problem domains (Tolar and Platt 1992). Expert systems were first applied in production and operations management. Today, expert systems and easy-to-use expert system shells are used in many business fields.

The relationship between expert systems and simulation is that expert knowledge often reflects time-dependent phenomena, even though that knowledge is usually in a rough form such as natural language or rules. By bridging gaps between qualitative and quantitative approaches, expert systems and simulation can greatly benefit each other (Fishwick 1991). This combined system is called a knowledge-based simulation system or a hybrid expert simulation system (HESS) in the literature. Its theoretical background is presented by Elzas etc. (1989) and Fishwick and Modjeski (1991) and examples of successful applications are presented by Stirling and Sevinc (1991), Eisenberg (1991), and Lee et al. (1996). In this paper, we present a new HESS application to FMS design.

The proposed HESS has advantages over other systems using queuing networks, integer programming, or simulation. Since the HESS uses simulation as a component, it obviates restrictions and assumptions required by queueing networks and integer programming. The proposed HESS has a nice user interface and obviates drawbacks of simulation as follows.

1. With user input for FMS design parameters, it automatically generates correct simulation programs so that users do not need to write simulation programs and verify them.
2. It interprets the simulation results and provides expert suggestions for improvement for FMS design.
3. It allows reiterations with changes of some FMS design parameters until a particular desired design or a small number of potential design alternatives are found. All these activities are seamless and users are not required to have knowledge on simulation or expert systems.

The HESS can be further improved by combining queuing network or integer programming approaches (Lee and Stecke 1996). The latter approaches can provide more effective initial FMS design to the HESS than the user input which usually relies on guess. This will help to reduce the number of iterations the HESS needs to undergo.

The remainder of this paper is organized as follows. In Section 3.2, we give a brief description of a typical FMS, in Section 3.3, we present the structure and user interface of the proposed HESS, and in Section 3.4, we illustrate the proposed HESS with an example.

3.2 Flexible Manufacturing Systems

An example of an FMS appears in Fig 3.1. This FMS produces different sizes of housings for automatic transmissions. It consists of four large 5-axis machining centers (called Omnimills), three 4-axis machining centers (Omnidrills), two vertical turret lathes (VTLs) and an inspection machine. Each machine has a limited-capacity tool magazine that hold tools assigned to it. The 16-station load/unload (L/UL) area provides a queuing area for parts entering the system, finished parts leaving the system, and in-process inventories. Three manual workers work in the L/UL area for loading/unloading and fixturing parts. Two transporters run on a straight track and carry 15 pallets among the machines and the L/UL stations.

Another example of an FMS appears in Fig. 3.2. This FMS has several CNCs and a centralized tool supply system where the tools of the cassettes are preadjusted and prepared for operation at a tool setup area. Afterwards they are either stored at a central tool magazine or transported to a local tool magazine at a machine. Two L/UL stations are located on the left hand side and represent the interface between the FMS and its production environment. Central buffer areas are placed along the transportation track. These buffer areas are temporary waiting spaces for parts that are waiting to be processed by the next machine after the current processing on another machine. These spaces are limited due to a limited floor space or storage facility. With use of the waiting spaces that can temporarily hold parts, a machine can continue operating while the following machines are busy or stopped and under repair.

Parts are loaded on pallets and enter an FMS at the L/UL station and then are routed through different processing resources (stations or machine groups) for various operations. Transport resources (automated guided vehicles (AGVs) or transporters) may be required to route parts from one station (machine group) to another with some attendant travel time. If conveyors move parts between machine groups, there is no or very

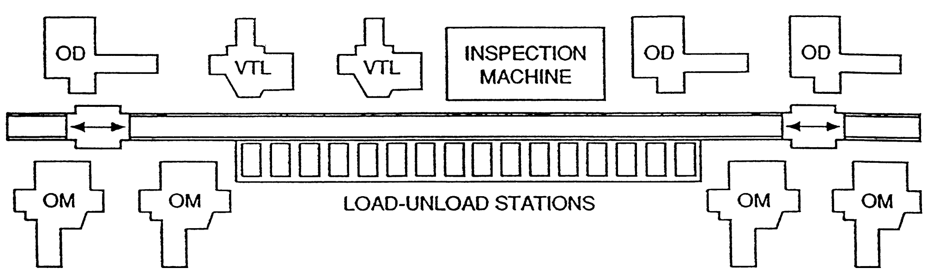


FIGURE 3.1 Sundstrand/Caterpillar FMS.

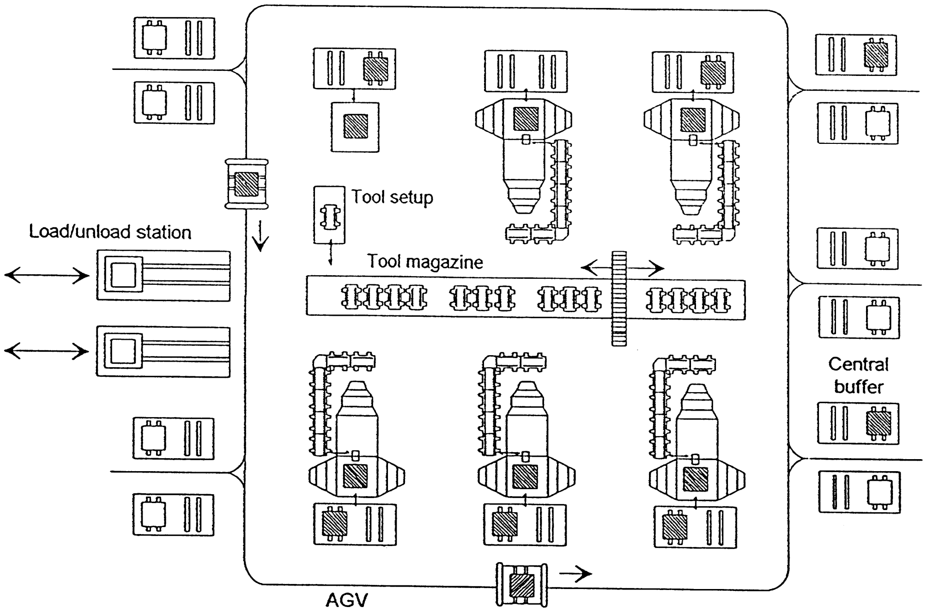


FIGURE 3.2 FMS with two AGVs and a central tool magazine. (From Tempelmeier, H. and Kuhn, H., *Flexible Manufacturing Systems: Decision Support for Design and Operation,* 1993, copyright ©John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.)

little waiting time for transport resources, and only a travel time between processing resources. A processing resource may go through an up and down cycle. For example, a machine breaks down and needs to be repaired.

The number of pallets circulating in the system remains more or less constant during a production period. This is the case when a base part fixed on a pallet enters a system at a loading station and travels through various machine groups for different operations. Upon completion, it travels to an unloading station where a finished part is taken off the pallet and is shipped and another base part is fixed on the pallet and the process repeats. This policy is common in both advanced and traditional manufacturing systems (Lee 1997, Spearman et al. 1990). The number of pallets circulating in the system affects the production rate and is an important decision variable.

Since FMSs simultaneously produce different products, an operating policy has to be specified concerning a process rule and an input rule. A process rule determines which part type is to be processed next on a machine while an input rule determines which part type is to be released into the system at the L/UL station. We use FCFS for the process rule. The input rule we use to choose a part type, such that ratios among completed plus work-in-process parts, are maintained throughout the entire production as close to ratios among their production requirements as possible. These rules help to achieve balancing workloads in machines since different part types require different processing times and at the same time to meet all production requirements. These rules are simple and easy to control yet effective in FMS operation (Lee and Stecke 1996).

3.3 A Hybrid Expert Simulation System

O'Keefe (1986) recognized the important roles of expert systems and simulation in support of decision making and the relative strengths of these two tools and proposed a taxonomy for combining simulation and expert systems into a HESS. The concept of HESS is to integrate existing simulation and expert system tools and exploit the knowledge of the expert system programmer as well as that of the simulation modeling expert (Shannon and Adelsberger 1985). One of the classes in O'Keefe's taxonomy is the use of an expert system as an intelligent user interface or front end to a simulation tool. When the skilled designer builds a hybrid expert simulation system of this sort, the relatively unskilled user is spared the problems of building,

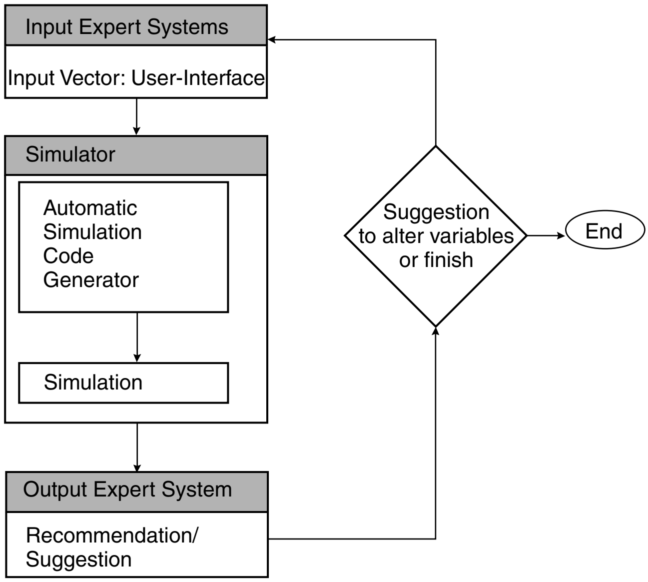


FIGURE 3.3 The conceptual structure of the proposed HESS.

validating, and interpreting the results of a simulation model and the time and effort necessary to get simulation results is considerably reduced. The structure of such a HESS consists of three sub-systems (Input expert system, Simulator, and Output expert system) and is illustrated in Fig. 3.3 (Lavary and Lin 1988).

We developed and implemented a HESS on a PC. The proposed HESS uses Siman V (Pegden et al. 1995) for the simulation tool and VP-Expert (Moose et al. 1989) for the expert system shell. Neither of these tools has provision for interfacing with the other, so we constructed interfaces in Turbo Pascal. Figure 3.4 shows the detail structure of the HESS.

The Input Expert Systems (IES)

The input expert system verifies the compatibility of the components of the input vector through reference to its knowledge base which contains realistic ranges of variables in the input vector. It eliminates unnecessary runs of the simulator by excluding erroneous input vectors and enhances the functionality of the input system with a user friendly interface.

The Input Expert System (IES) is composed of a VP-Expert program and IO.EXE program in Turbo Pascal. These programs provide an easy-to-use interface for entry of basic system variables by users, conveniently capturing the sequence of data necessary for the simulation. The input variables are summarized in Fig. 3.5. With the user input, the IES generates *file*.DAT, a user generated file name, which is the data file to be used by the Simulator for automatic simulation code generation. In addition to the input variables, the user can control the simulation by entering simulation variables such as a run length and a warm-up period to avoid the effect of transient behavior.

The Simulator

The Simulator captures the simulation model of FMSs. It is based on a discrete-state process-interaction modeling approach in which the system state changes at events on discrete-points in time and events are updated as entities (parts) arrive and flow through the system. The core of the simulator is the Automatic Siman Code Generator (ASCG). ASCG automatically generates a complete Siman program based on the system and simulation input data the user enters via IES. Since a Siman simulation program consists of a model frame and an experiment frame, the generated Siman Code leads to two files "File.MOD" and "File.EXP".

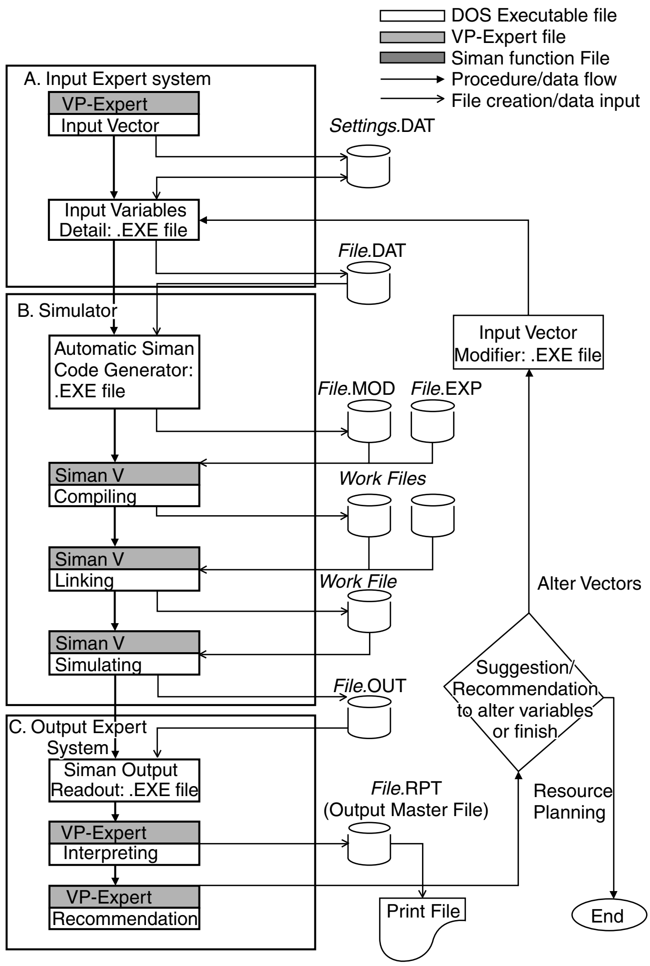


FIGURE 3.4 The detail structure of the proposed HESS.

The model frame describes the logical flow of entities within the system while the experimental frame provides the experimental conditions for executing the model frame. ASCG is written in Turbo Pascal. ASCG has been designed to be flexible and consider a wide range of variables, as the user is given choices and suggested changes on input variables that would lead to more effective FMS design. After the simulation program is generated, the HESS compiles and runs the simulation by use of Siman V.

The Output Expert Systems (OES)

The output expert system interprets and analyzes the simulation results and makes recommendations to the user on changes in the input vector in order to find a more effective FMS design. Thus, the user is shielded from the actual simulation output and is relieved of the task of its interpretation. The Output Expert System (OES) is composed of a VP-Expert and a Readout.EXE program. Readout.EXE reads *file*.OUT, which is the output of the simulator, makes numeric calculations, and returns the information to VP-Expert. The VP Expert program applies expert rules to make recommendations for an improved FMS design. Users then decide whether to accept the recommendations or not. As in the case of the Input Expert System, the Output Expert System is designed with a user-friendly interface.

The rules are based on the empirical experience and heuristic knowledge of experts that allow identification and elimination of bottlenecked and underutilized resources while, at the same time, meeting the system

Objective

Produce the desired number of finished parts with minimal use of resources

Input Variables

Number of stations (m/c groups)
Number of machines at each station
Number of product types
Product mix (ratio of product types)
Distribution type and parameter values for process times at each station[#]
Sizes of waiting spaces at stations*
Machine failure and repair time*
Number of transporters (dispatchers)*
Transfer times between stations
- velocity and distances
Route for each customer type among stations
Demand for each product
Number of pallets
Batch size (parts per pallet)
Machine jam probability and jam clear time*

[#] This is obtained from the initial operation assignment to stations and product mix.
* User-option variables

FIGURE 3.5 Objective and input variables of FMS design.

objective or design requirements. The rules use threshold values for machine and transporter utilizations to determine if each resource type is over-utilized or under-utilized. Both threshold values are tentatively set at 75%. In practice, the threshold values would depend on various factors used in the industries and be supplied by users who find these values through their knowledge of and experimentation with their systems.

The user can control the input variables to meet all product requirements at minimal use of resources. The rules in Fig. 3.6 show the decision tree for recommendations for an improved FMS design. The recommendations are suggested changes on one or more variables of the followings: the number of machines, the number of transporters, the number of pallets, and the batch size. When parts are small, a batch of parts can be mounted on a pallet using a special fixture. For example, a tombstone fixture allows up to four parts to be loaded on a pallet (Luggen 1991). A batch of parts are processed consecutively at a machine and then moved together to the next machine by a transporter. Batch sizing can be effective in increasing throughput when material handling resource causes a bottleneck. However, an unnecessarily large batch size increases the work-in-process inventories and system congestion without increasing throughput.

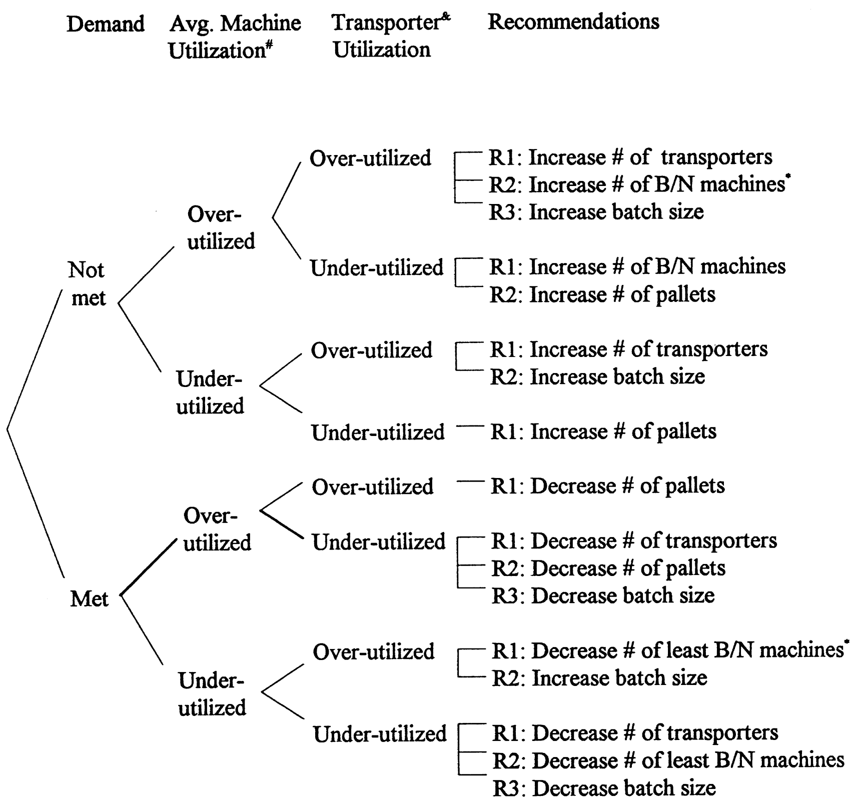
The OES also generates *File*.RPT which contains summary results of every simulation run as the user explores various FMS designs, following recommendations provided by the OSE. Results are written in the file, including a vector of input data, simulation summary result, and recommendations (Levary and Lin 1988). Currently the results are used to avoid redundant simulation runs, but in a more elaborated HESS, the knowledge base of past runs could be used for more sophisticated rules.

3.4 An Example on FMS design with HESS

An FMS produces three different products, each of which has a different route among four machine groups. These three types take 25%, 30%, and 45% of total parts produced. Travel time between machine groups is always 3 minutes. Each operation time is exponentially distributed. Each machine group fails every 4 hours on average and the average repair time is 15 minutes. Both follow exponential distributions. Thirty pallets are available and 2 transporters are used to move parts fixtured on pallets between machine groups. The batch size is fixed to one in this example. Machine type and the number of machines for each group are summarized in Table 3.1.

TABLE 3.1 Number of Machines in Each Machine Group

Machine Group	Machine Type	Number of machines
1	CNC-mill	7
2	VTL	3
3	Drill Presses	6
4	Shapers	4



#Average machine utilization is an aggregate average of machine utilization's over all machine groups.

&Disregard this column and the related rules when a system does not use transporters.

* B/N: A bottleneck machine group is one in which the largest number of parts is waiting to be processed. The recommendation is to increase the number of machines in this machine group or to decrease the number of machines in the least bottleneck machine group.

FIGURE 3.6 Expert system decision tree for FMS design.

As each part moves through the FMS, it is processed at each machine group according to its visitation sequence. (See Table 3.2). At each group, a part waits in the queue, seizes the first available machine, is delayed by the processing time, is released by the machine, and then continues to its next group. On completion, a finished part leaves the system and at this time another base part enters the system.

The FMS is designed to meet weekly demands of three products, (125, 225, 150) with minimal use of resources. It operates in 5 days per week, 2 shifts per day, and 8 hours per shift. The simulation length is set to 5800 minutes, which is the warm-up period of 1000 minutes followed by one week, (i.e., 4800 minutes

TABLE 3.2 Processing Times for Three Product Types

Jobs Operation Type	Percent of Jobs	Sequence Number	Machine Type (group number)	Average Processing Time
1	25	1	CNC-mill (1)	35
		2	Drill Presses (3)	45
		3	Shapers (4)	18
2	45	1	CNC-mill (1)	35
		2	VTL (2)	25
		3	Shaper (4)	45
		4	Drill Press (3)	30
3	30	1	CNC-mill (1)	30
		2	Shaper (4)	20
		3	VTL (2)	15
		4	Drill Press (3)	45

[5 days/week ∗ 2 shifts/day ∗ 8 hours/shift ∗ 60 minutes/hour]). The FMS designer initiates the proposed HESS with the number of machines 7, 3, 6, 4, for the four machine groups. In the first run, the following report is produced:

Summary Report 1

Project title: FMS design
Number of machines in each machine group: 7 3 6 4
Average machine utilization: 72.3%
Number of pallets: 30
Number of transporters: 2
Transportation utilization: 65.1%
Batch size: 1
Average time in system: 278.180
B/N machine group: #4 Queue Size = 7.787
Least B/N machine group: #1 Queue Size = 0.214
Total number of parts produced: 518
Type 1: 131, Type 2: 232, Type 3: 155

All demands are met and the least bottlenecked machine group is group 1. After the first run, the HESS gives two recommendations–R1: Decrease the number of transporters and R2: Decrease the machine number of machine group. The manager selects the second recommendation and decreases the number of CNC1s from 7 to 6. The simulation is run again. Table 3.3 lists a summary of 9 simulation runs and recommendations/actions taken for the 9 successive runs.

The recommended FMS design is 5 CNC-mills, 3 VTLs, 6 drill presses, 4 shapers with 2 transporters and 21 pallets, since this plan requires the minimal level of resources among those that meet demands (see Run number 7 in Table 3.3). The summary report for this FMS design is provided below. The entire session with the proposed HESS for this case study took less than 30 minutes on a PC.

Summary Report 7

Project title: FMS design
Number of machines in each machine group: 5 3 6 4
Average machine utilization: 78%
Number of pallets: 21
Number of transporters: 2
Transportation utilization: 69%
Batch size: 1

TABLE 3.3 Summary of Simulation Runs and Actions Taken for the Successive Runs[&]

Run Number	Resource Plan: (m/c groups), (transporters, pallets)	Demand Met	Average m/c Utilization*	Transporter Utilization	Recommendation/ Action Taken
1	(7,3,6,4), (2,30)	met	72% (under)	65% (under)	decrease m/c group 1 by 1
2	(6,3,6,4), (2,30)	met	78% (over)	71% (under)	decrease transporters by 1
3	(6,3,6,4), (1,30)	not met	74% (under)	97% (over)	increase transporters by 1 and decrease pallets by 3
4	(6,3,6,4), (2,27)	met	79% (over)	73% (under)	decrease pallets by 3
5	(6,3,6,4), (2,24)	met	76% (over)	70% (under)	decrease pallets by 3
6	(6,3,6,4), (2,21)	met	73% (under)	69% (under)	decrease m/c group 1 by 1
7	(5,3,6,4), (2,21)#	met	78% (over)	69% (under)	decrease pallets by 3
8	(5,3,6,4), (2,18)	not met	71% (under)	66% (under)	increase pallets by 2
9	(5,3,6,4), (2,20)	not met	76% (over)	69% (under)	terminate HESS

& Batch size in this example is fixed to one.
* Average m/c utilization is an aggregate average of machine utilizations over all machine groups. 75% is used as the threshold value to determine if machines or transporters are over-utilized or under-utilized.
# This resource plan is recommended since it requires the minimal level of resources among ones that meet demands.

Average time in system: 198.6
B/N machine group: #4 Queue Size = 2.655
Least B/N machine group: #1 Queue Size = .507
Total number of parts produced: 511
Type 1: 129, Type 2: 229, Type 3: 153

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