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EXPERIENCES WITH ANALYTIC AND SIMULATION MODELING FOR A FACTORY OF THE FUTURE PROJECT AT IBM

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ABSTRACT

Simulation models have been used extensively for manufacturing systems design analysis. Simulation modeling is a flexible and powerful technique but model development, debugging, modification, and analysis is a time consuming process. Because of this, it is possible to address only a limited number of design issues using simulation models alone.

This paper discusses the application of an analysis methodology employing two techniques, queueing network and simulation modeling, to effectively address a variety of issues during the design of a factory of the future at IBM. The queueing network model was used for the initial analysis to quickly reduce a wide range of design alternatives. The simulation model was used to further study alternatives that had been selected using the queueing network analysis. The model included details which were not considered during the initial analysis.

Our experience from this project indicates that queueing network models are effective at the initial analysis level. Simulation models should be used only after the alternative choices have been substantially reduced. They can be used, however, to address issues not included previously and to ensure that the assumptions made earlier are still valid. Results from the queueing network models also can be used to design as well as debug and verify simulation models.

1. INTRODUCTION

Manufacturing management is continually faced with a variety of decisions. Typical decisions include:

- Number and types of equipment required.
- Number and types of material handling and storage devices necessary.
- Desired equipment layout.
- Buffer requirements.
- Desired part volumes and mixes.
- Alternative material routings.
- Operating policy alternatives and their implications.

Insight gained from a good analysis methodology provides the basis for good management decisions. Generally, an effective analysis methodology includes an initial stage in which a wide range of alternatives are investigated rapidly, and less desirable alternatives are eliminated; and a final stage in which selected few alternatives are evaluated in detail. The number of alternatives to be evaluated is reduced as one proceeds from the initial to the final analysis stage. A desirable analysis philosophy is illustrated in Figure 1. Poor analysis methodologies are likely to miss the most desirable alternative at the initial stage. As a result, the wrong alternative may be selected for recommendation to management.

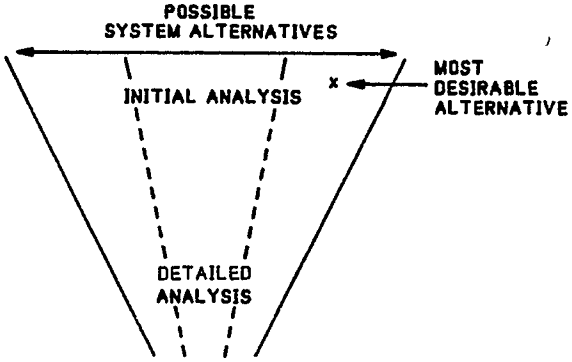

Figure 1: A Desirable Analysis Philosophy

Modern manufacturing systems are complex and have many interconnected components of hardware and software. As a result, it is virtually impossible to determine the impact of varying important operational parameters on the system without a model. Additionally, most decisions consist of multiple objectives which must be weighed against one other.

Analysts continually face the challenge of having to explore the widest range of alternative solutions for a given problem in the limited available time. Traditionally, simulation modeling has been used as the primary technique for analyzing manufacturing systems, and analysts have used it extensively at all stages of problem solving. Typically, general purpose simulation languages were used as the tools for building simulation models. Although these languages are powerful and flexible, the attention to detail required by them makes model building a tedious and time consuming effort.

This paper discusses an analysis methodology which used two modeling tools in a fashion which allowed the authors to respond rapidly to a variety of questions raised during the design of a printed circuit board manufacturing facility.

The paper includes an overview of the factory of the future project, followed by a summary of some of the significant objectives of the analysis. The methodology developed for the analysis is discussed. A brief description of the tools used in the analysis follows the methodology. Finally, the analysis highlights and conclusions are presented.

2. PROJECT OVERVIEW

The objective of the project was to design a new factory for the production of printed circuit boards. The factory will incorporate state-of-the-art process technology and a high degree of computer integration. Individual processes will be tied together with automated material handling systems, and the amount of work-in-process (WIP) between adjacent stations should be minimized. This design philosophy imposes a high level of interdependence among the pieces of equipment. It is this complexity that the analyses were designed to address.

2.1. The Product

Printed circuit boards serve two basic functions: they provide mechanical support to electronic components and they provide electrical connections among the components. The complexity of these boards varies considerably; some can have as many as ten layers of circuits.

The demand for printed circuit boards within the IBM Corporation is high. Printed circuit boards appear in virtually all IBM products, from the largest mainframe to the least expensive Personal Computer and printer. Not only are the volumes high, but the variability is enormous. The manufacturing system being designed must be capable of producing many types of printed circuit boards. In addition, the line must be capable of fast product changeovers.

2.2. The Process

Printed circuit boards are manufactured in a complex sequence of chemical and mechanical processes. A typical product may pass through as many as fifty process steps. The first step is to laminate pieces of copper foil on either side of insulating glass cloth. Using a standard photolithographic process, circuits are drawn on the two copper planes. This intermediate product, called a "core", is the basic component of a circuit board. Additional circuit planes can be added by sequentially laminating and circuitizing. Alternately, several cores, separated by insulating layers, may be laminated together.

Before the external layers are circuitized, holes are drilled in the board. These provide support for the pins on the electronic components and, when plated with copper, allow for interconnection of the circuit planes. After the external layers have been circuitized, a coating is applied to protect the fragile circuitry.

Figure 2 presents an overview of the process flow.

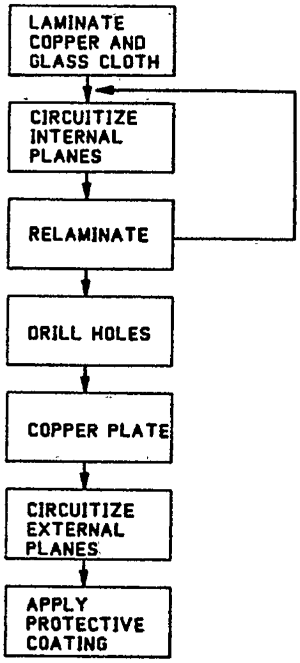

Figure 2: Circuit Board Manufacturing Process Flow Overview

3. ANALYSIS OBJECTIVES

The fundamental objective of the analysis performed in this project was to develop the information needed to evaluate alternative options at each design step. Some of the key objectives in the analysis were as follows:

- Initial assessment of the of the reliability requirements for the equipment.
- Preliminary line balancing.
- Determination of appropriate lot sizes.

- Determination of the size of a storage device under different material flow requirements.
- Determination of the correct choices for the transportation of materials for each sector. The choices were conveyors, monorails, material handling crews, and AGVs.
- Assessment of the impact of constraining workstation buffers on equipment utilizations.
- Determination of the impact of processing equipment and material handling reliabilities on workstation buffers, product cycle times, and total production throughput.

The above analysis objectives are listed in order of increasing information requirements.

Based on the analysis results, capital and floor space requirements were determined for each alternative.

4. ANALYSIS METHODOLOGY

It was imperative that the adopted analysis methodology meet given project deadlines. The methodology used was based on the analysis philosophy previously described, that being to perform extensive parametric analyses at a high level and to use a simulation model to perform a detailed analysis of the selected alternatives as well as verify the high level analysis conclusions.

The detailed simulation model was designed to consider the material handling logistics omitted during the initial analysis.

It was not practical to perform the entire analysis with a detailed simulation model for the following reasons:

- Preliminary information on a number of issues was needed very quickly.
- Some issues were better resolved at an aggregate level.
- A number of issues had to be resolved before a detailed simulation model could be designed properly.

The use of a general purpose simulation language was not considered satisfactory for building models for initial analysis simply because of the time needed to develop, debug, and modify even a high level model. Additionally, concerns about the length of simulation runs, warm-up periods, and confidence levels of each output parameter would have excessively delayed the initial analysis. Special purpose simulation software designed to allow rapid development of models of manufacturing systems at a high level could have been used. This type of software will reduce model development and modification times. However, model execution speed typically is slow for PC-based simulation software products. Furthermore, statistical issues in the output must still be resolved.

Because of the above considerations, it was decided to use a queueing network model for a high level, steady state, parametric analysis. The information obtained from the initial analysis was used to design the simulation model for subsequent, more detailed analysis.

Because of time limitations, the model had to be flexible enough to allow fast and easy modification during the evaluation of different scenarios. Furthermore, since some members of the project team who needed to use the model had little simulation experience, user-friendliness of model input and output was essential.

5. ANALYSIS TOOLS

It was necessary to select tools for developing queueing network and simulation models which would allow the analysis team to implement the philosophy and methodology discussed earlier.

5.1. Queueing Network Model

The following features were considered necessary in a queueing network modeling tool:

- All technical details on queueing network theory should be masked from the user.
- The input and output schemes should use simple and easy to understand manufacturing terminologies.
- Rapid development and modification of the model should be possible.
- Model execution time should be less than one minute for a high level analysis. This is necessary for rapidly performing extensive parametric analysis in a reasonable time period and for keeping the thought process uninterrupted as much as possible.
- The tool should be capable of modeling multiple products, equipment breakdowns, process set-up, lot sizing, equipment yield, and feedback flow loops.

A queueing network modeling tool called MANUPLAN was selected because it satisfied all of the above requirements. MANUPLAN uses node decomposition and approximation techniques which are based on mean value analysis. It also incorporates reliability modeling. MANUPLAN is designed primarily for modeling manufacturing systems and, as such, it provides a structure which is convenient for manufacturing engineers to use. For additional information on MANUPLAN, see Suri and Diehl (1985).

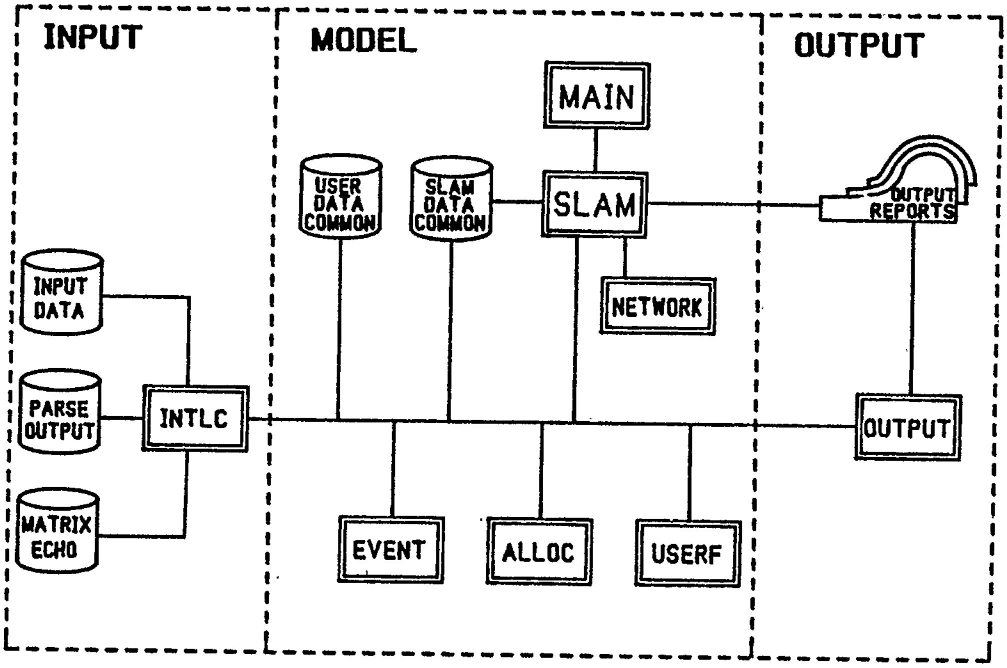

Figure 3: Simulation Model Structure

5.2. Simulation Model

The goal in the design of the simulation model for detailed analysis was to make the model flexible, powerful, and simple to use. Model complexities such as assignment of resource capacities, entry of data into matrices, etc. were masked from the user.

Specifically, the model design objectives were as follows:

- Data entry must be simple using a template fill-in scheme.
- The model must accommodate multiple products.
- The model must accommodate several types of material handling devices.
- The model must accommodate different types of process equipment (batch, flow-through, etc.).
- The output must be clear, uncluttered, and should use terminology familiar to the user.

These objectives ruled out the standard input and output found in most, if not all, of the general purpose simulation languages available today. Because it allows an easy interface with FORTRAN for customizing the input and output, the SLAM II simulation language was chosen for model development. For additional details on SLAM II, see Pritsker (1984).

The structure of the model design is shown in Figure 3. As can be seen, the model consists of three main sections: a preprocessor for the input data, the model, and a post-processor for output. The generalized input, decision logic, and output were written in FORTRAN, and they interfaced with the network portion of the model.

INTLC is the highest level subroutine in the preprocessor section of the model. INTLC includes a collection of subroutines which read data from a fill-in-the-blank template, error check the data and set up the model matrices. If the data contains no errors, the output matrices are placed in the UCOM section of named program COMMON. If the data contains errors, the user is notified and the parse output file created by INTLC must be edited.

All material handling devices/crews, equipment, and operators are referred to by names rather than numbers in the input data file. INTLC handles the conversion of names to ID numbers for program use.

INTLC and the data template work together to make the model powerful and easy to use. Many complex production issues can be modeled and modified quickly using the data template scheme. For example, each product has its own routing in the template which describes, probabilistically, the flow of that product from a given operation to the next. Likewise, for the same product an operation might be performed by several different types of equipment, known in the model as equipment groups. The equipment groups themselves have unique characteristics such as capacity, type of process (flow-through or batch), automatic or manual setup and/or processing, and failure and repair characteristics.

The material handling specification is also quite powerful. Moves are defined from one equipment group to another. For the move, a distance and a material handling device/crew name are specified. The material handling choice specified could be a conveyor, monorail, a material handling crew, an AGV, or a group of AGVs serving a sector. This allows for powerful, fast analysis of material handling layout designs.

The flow of transactions through the model and the passage of time is controlled at a high level by the network portion of the model. The bulk of the work in the model, however, is accomplished by the EVENT, ALLOC and USERF sub-programs shown in the model hierarchy. The template is the only portion of the model that the user interfaces with.

Subroutine OUTPUT is used to create a custom report detailing the results of the simulation run. To make the output readable, equipment, buffers, material handling devices/crews and operators are referred to by the user entered names rather than numbers or SLAM RESOURCE labels. Of the standard SLAM II output, only that judged to be relevant to the user (as opposed to the model developer) is displayed in the customized report.

6. ANALYSIS HIGHLIGHTS

At the initial level a number of issues were explored. The impact of equipment reliability on system production throughput and cycle time was investigated thoroughly to determine the acceptable reliability levels of the equipment. Equipment load balance analysis was performed for each configuration. Additionally, impact of lot sizes on system performance was studied and the optimal lot size as well as required equipment capacities, were determined.

The choices for the number and types of equipment, lot sizes, and storage requirements were narrowed down through the initial analysis. However, the impact of constraining the buffer sizes of equipment, and the selection of appropriate material handling configuration required further investigation. It also was necessary to verify the validity of the conclusions made at the initial analysis level once material logistics issues and buffer constraints were introduced in the system.

The highlights of only two specific studies will be discussed to show how the modeling techniques were used to effectively address two different issues during the design process. First, an example of the use of a queueing network model for the study of the lot size issue is presented. Next, a detailed analysis in which only a simulation model could provide the required insight, is described.

In addition to describing the two studies, some brief comments will be made on how results from a queuing network model were used both in designing and verifying the simulation model.

6.1. Initial Analysis Example

The lot size issue was addressed with a queueing network model. At the project outset, Continuous Flow Manufacturing (CFM) was identified as a desirable philosophy to incorporate in the design of the manufacturing system. IBM's CFM concept is similar to the widely known concept of Just-In-Time manufacturing. Both manufacturing philosophies share the goal of achieving a lot size of one unit.

In reality, a number of issues preclude the attainment of the unit lot size. In particular, several of the pieces of equipment in the circuit board manufacturing process require substantial set-up time for each product change. As a result, the objectives of the analysis were as follows:

- Determine whether the attainment of unit lot size is feasible, given the constraints of set-up times.
- If the unit lot size is not attainable, identify the optimal lot size in terms of work-in-process (WIP) and equipment utilization. Early identification of the probable lot size would assist the design of the material handling system. Thus the development of the simulation model and the design of the material handling system could proceed in parallel.

A large number of queueing network model runs were made to identify the effect of lot size on system work-in-process (WIP) and process equipment requirements. Such an extensive parametric analysis required very fast computation of each iteration. This was facilitated by the queueing network model. The results of the analysis were clear: a lot size of one panel is not attainable without the addition of a large number of equipment.

Figure 4 suggests that system work-in-process (WIP) can be minimized by judicious choice of the lot size. This analysis implies that, to minimize WIP, the optimal lot size is approximately twenty boards. Smaller lot sizes incur a penalty due to set-up, and larger lots tend to increase the work-in-process.

These results, and the fact that a twenty board lot can move in a single container, provided some basic specifications for the simulation model design. Without this information, we would have been forced to design a much more detailed and complex simulation model capable of handling multiple container lots.

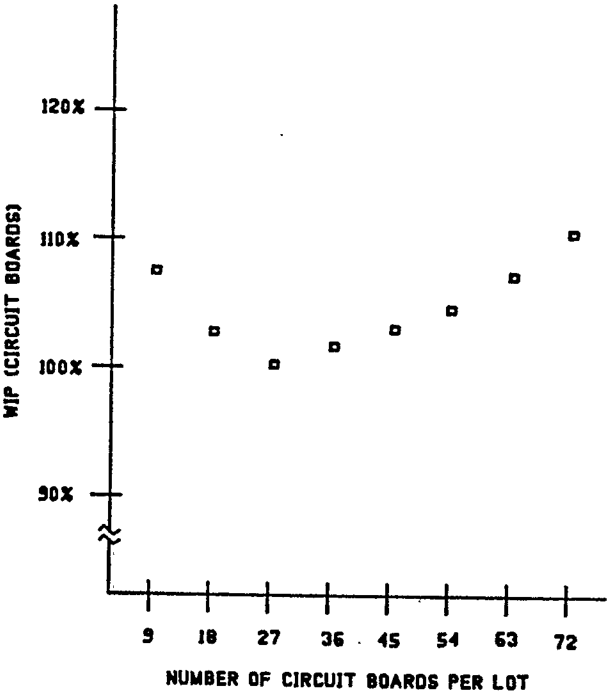

Figure 4: Work-In-Process Versus Lot Size

6.2. Detail Analysis Example

The queueing network model used in the preliminary analysis was incapable of modeling constrained buffers. Thus, the implications of equipment integration were studied with the simulation model. Using the same data set as the queueing network model, the simulation model was used to determine the minimum buffer sizes required between adjacent pieces of equipment.

Buffer constraints tended to increase the utilization of the process equipment. This result is attributable to blocking effects due to equipment and material handling device breakdown, and operator unavailability. Figure 5 illustrates the effect of equipment integration on utilization for a segment of the manufacturing process. Note that, despite having constrained buffers, utilization of all equipment was maintained below the desired target of 80%.

6.3. Simulation Model Verification

In any analysis, model verification is both challenging and extremely important. For this analysis, the final verification of the simulation model was achieved by comparing the simulation results with those provided by the queueing network model. The scenario tested was, by necessity, a limiting case. Since the queueing network model can not accommodate constrained buffers, both models were run with infinite buffers between processes.

The queueing network model proved to be an effective means of verifying the simulation model. Through this comparison, some errors in the simulation model were identified and corrected, and the two models were brought into close agreement quickly. Figure 6 compares results from the two analysis methods for equipment utilizations.

Typically, the two models provided equipment utilization results that agreed to within two percent. The utilization values from the simulation model are in general higher than the values from the queueing network model. This is attributable to the fact that the queueing network model did not capture any blocking effect on the equipment due to operator and material handling device/crew unavailability. Two pieces of equipment did show differences of more than five percent. These differences were traced to unique batching logic in the simulation model which could not be duplicated in the queueing network model.

7. CONCLUSIONS

Queueing network and simulation models complement each other and provide a mechanism for an effective analysis methodology for manufacturing system design. Queueing network models work well as pre-simulation analysis tools to address rapidly a wide range of high level design issues in order to select a handful of desirable design alternatives.

Simulation models are effective for detailed analysis where material logistics issues confronting the selected designs are addressed. Attention should be given to making the simulation models flexible and user-friendly. This allows people, other than model developers, to use and modify the simulation models conveniently.

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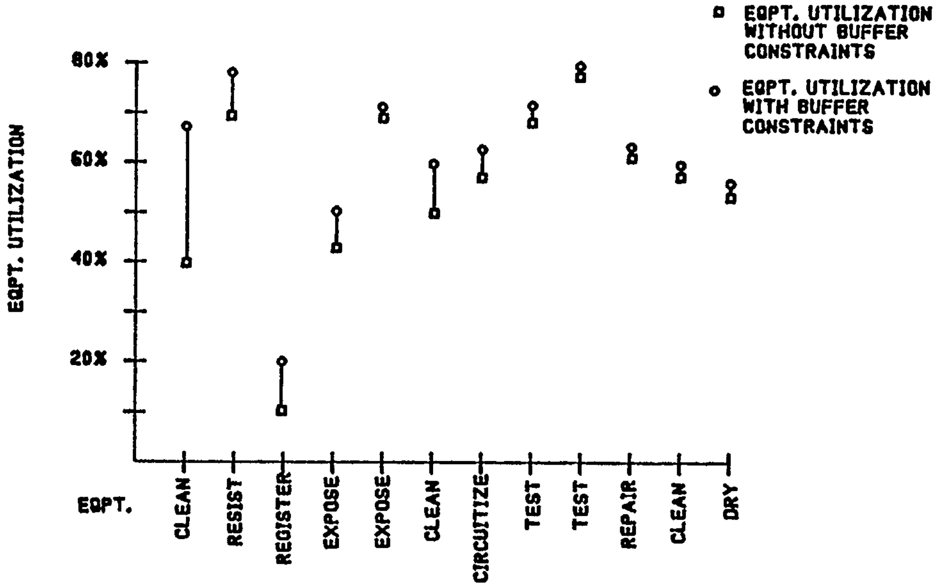

Figure 5: Effect of Buffer Constraints on Equipment Utilization

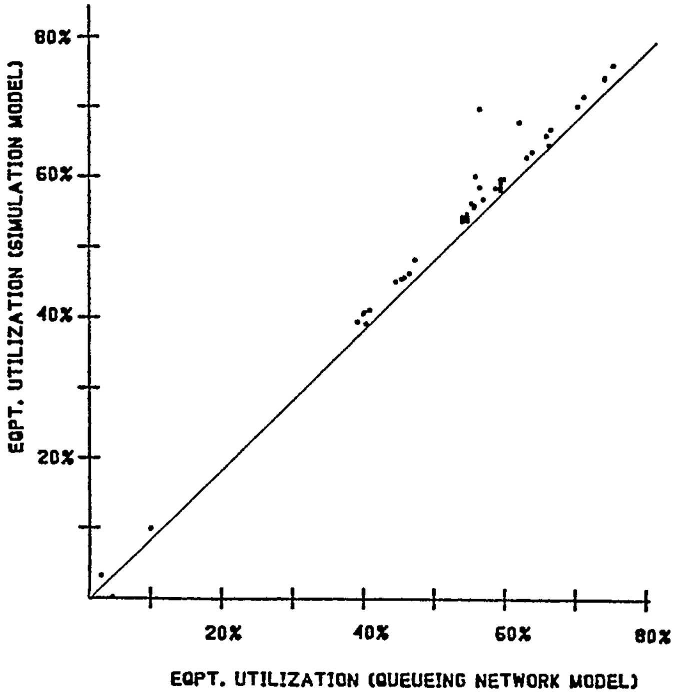

Figure 6: Simulation Model Verification Using Queueing Network Model

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