Proceedings of the 1987 Winter Simulation Conference
A. Thesen, H. Grant, W. David Kelton (eds.)

DEVELOPMENT AND VALIDATION OF A SYSTEM MACRO MODEL USING ISOLATED MICRO MODELS

Drazen Kostelski
John Buzacott
Kenneth McKay
Xiao-Gao Liu
WATMIMS Research Group
Department of Management Sciences
University of Waterloo
Waterloo, Ontario, CANADA N2L 3G1

ABSTRACT

Joining of micro simulation models can be very difficult and usually impossible. To overcome this obstacle, we often resort to macro modelling. However, building a macro model of a complex manufacturing system is nontrivial and carries with it a number of significant risks and difficulties. There are problems with the mechanics of performing the work and the validation of the final macro model. In this paper we document an approach that addresses both the mechanics and validation issues. The "zero internal banking" approach is presented and used to build a macro model which utilizes information provided by isolated micro models.

1. INTRODUCTION

Today, simulation is a frequently used tool for production facility design. The automotive industry in particular, makes extensive use of simulations when making changes to existing plants or when designing completely new facilities. Due to the size and complexity of modern production systems, simulation modelling is often carried out at several levels, by different groups of people, at different times. Individual pieces of automated production equipment (i.e., robots, robogates, automated guided vehicles, etc.) are studied at the lowest level. Next, micro simulation models of production sub-system are created. At the highest level, the entire facility is simulated. However, rarely is it practical, or even possible, to construct a single detailed model of a complete manufacturing system. Hence, macro modelling that captures the essence of the complete system is used.

This paper deals with macro modelling and has the following objectives: to distinguish between the macro and micro simulation modelling levels; to raise issues involved in building a macro model of a large system; and, through an example, present an approach for developing and validating a manageable size macro model utilizing micro model results. The emphasis is on the approach, rather than on specific results.

The example, through which we present our approach and experiences, is based on a large automotive assembly facility. The standalone models were created by different people within the organization, used different simulation languages and different time units. Thus, to a large extent, in creating our macro model we had to model those aspects of the detailed models that were relevant, trying to balance adequacy of representation with avoiding complexity. The approach that was used in most parts of the system was to represent the production system by nodes, at which there can be no variation in work in process, separated by inventory banks of finite capacity. These inventory banks accommodate the effect of breakdowns and different segment production rates. In modelling automated guided vehicle (AGV) systems the "zero internal banking" approach raised some interesting issues concerning the appropriate number of nodes and segments that should be used. A discussion of our experiences is included.

In a large macro model it is essential to have a range of techniques for model verification and validation. We describe the various approaches we have used, including some approximate analytical modelling.

The paper concludes with a discussion of some of the lessons that we have learned, in particular the need for an overall strategy for modelling both at the micro and macro levels. It is essential to recognize from the beginning that model integration will be required. Some components of the macro model may have to be modelled in increasing detail to get adequate performance prediction.

2. MODEL TYPES

2.1 Micro Models

Micro models are detailed models of individual production sub-systems developed to aid in the design of various components of the overall production system. For example, in the context of an automotive assembly plant, the following micro models may be created: underbody build, rear quarter build, wheelhouse build, side build, the framing line, the paint shop, the trim area, engine dress, chassis, etc. With the help of these models, detailed design of each area of the plant is determined. Often, micro models for different areas are built independently, with possibly different objectives, at different times and at different places in the organization. Some models may be built in cooperation with equipment suppliers or external consultants. Others may be built by internal consultants (central group) or by car assembly plant engineers. As a result, a variety of simulation languages running on various pieces of hardware may be encountered in the final set of micro models. This makes it impossible to gain a "bigger picture" simply by linking micro models together. A more detailed description of difficulties with joining of existing simulation models has been provided by Sargent (1986).

2.2 Macro Models

A macro model is a high level representation of the system. It captures the main characteristics of the system, losing much of the detail found in individual micro models. Hence it is possible to represent the entire production facility as an integrated production system, by a model of manageable size. Because of the high level of the macro model, questions addressed by the macro model are different from those answered by detailed modelling. Typically, macro models provide useful information about overall system performance and interaction between various system components.

3. THE EXAMPLE PROBLEM FORMULATION

The first step in the process is to formulate the problem. The example we are going to use is based on a real system for which we have already developed a macro model.

3.1 The System Description

The system under consideration is a new automotive assembly plant with highly automated production environment. Extensive use of robots working together with new AGV (Automated Guided Vehicle) technology and more traditional automatic transfer line technology characterize the production process.

The plant is organized into numerous production areas separated by inventory banks. Figure 1 illustrates the simplified plant schematic. Work flows from the underbody assembly area to the framing line where left and right side frames are merged with the underbody subassembly. The side build area is supplied by the wheel house and rear quarter production areas. From the framing line jobs go to metal finishing before entering the paint department. After painting, bodies proceed to the trim area. There doors are taken off, instrument panel installed and doors put back on again. Following trim, car bodies are sent to the chassis area where vehicles are completed. Chassis gets components from the underbody chassis line which in turn gets engines from the engine dress area.

3.2 Existing Micro Models

An isolated micro model for each of the plant areas has been developed. The modelling was done by a number of groups without coordination or standardization. As a result, the final set of models was written in three simulation languages (GPSS/H, SIMAN and SEE-WHY). A variety of time units have been used (e.g., 1/60 second, 1/100 minute, seconds).

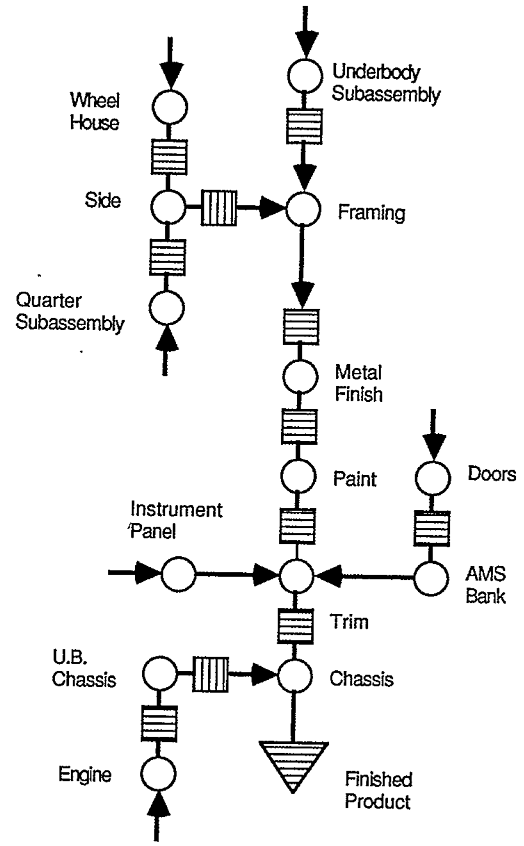

Figure 1: Simplified Plant Schematic

Each micro model was developed to help with the design of the specific area. Only endogenous variables for each production subsystem were studied (i.e., number of robots, number of AGV's, etc.).

Existing micro models provide sufficient understanding of individual plant areas in isolation. However, they are not helpful in analyzing the full interaction between different areas of the plant. Accurate prediction of the integrated production system dynamics is not possible at this simulation level. Therefore, an integrated macro model has to be developed. The data is to be supplied by isolated micro models.

3.3 Questions to be Addressed

Model requirements must be clearly identified. In this section we discuss issues which our model is to address. They are typical of the kind of questions that a high level macro model is expected to answer.

The plant is designed to maintain a certain average hourly net throughput rate. However, a less than perfect equipment reliability resulting from the high level of automation, implies a gross production rate higher than the design hourly net throughput. Depending on the level of automation found in each production area, various gross production rates are to be encountered throughout the plant. Areas with more automation are likely to incur more down time and hence should have a higher gross production rate to meet a given net rate. To achieve a well balanced production system, appropriate gross production rates for individual plant areas must be determined.

Inventory banks separating different production areas also play a significant role in obtaining the given net production rate. By absorbing the temporary imbalance between supply and demand, created between individual production areas by station breakdowns, inventory buffers even out the production. Theoretically, infinite banks provide maximum benefits. However, since there are costs and space restrictions associated with holding inventory, the requirement is to determine minimum buffer capacity necessary to maintain the desired throughput.

A material handling system is shared among three plant areas. This system needs to be understood better and its effect on the entire car plant is to be studied.

There is a possibility of several car body styles being produced simultaneously. The impact of various style mixes on the system throughput needs to be determined.

Finally, the impact of maintenance staff effectiveness is to be studied through across the board reductions in breakdown frequencies and durations.

In all cases, the system is to be studied under steady state conditions.

4. THE MACRO MODEL DEVELOPMENT

Once the problem has been formulated, data needs and sources identified, and model requirements specified, the building of the model can begin.

4.1 Possible Approaches

There are several different approaches that can be taken to develop the integrated model of a production system such as the car assembly plant. They vary from linking the existing code into one or more large models to creation of completely new code; from a pure simulation model to a hybrid simulation/analytic model; from a fully linked model to an iterative model.

In our case, the linking of existing micro model code is quickly eliminated because of the large size and incompatibilities between individual micro models. Due to its relative simplicity, a pure simulation model is chosen in favour of a hybrid simulation/analytic model. An iterative approach utilizing existing micro models loses its attractiveness when the amount of effort and elapsed time, required to obtain results, is considered. A change in a single parameter in a macro model would mean the repeat of the entire iterative process.

Representing the entire production system by a single fully integrated macro simulation model seems appropriate. The "zero internal banking" approach is to be utilized wherever possible.

4.2 Zero Internal Banking Approach

Zero internal banking is a relatively simple method we use for modelling automatic transfer line production systems. The key idea behind the approach is to decompose the production system under study into a series of nodes separated by inventory banks. The decomposition is carried out such that each node corresponds to a specific part of the system with no significant banking within it. In other words, the level of work in progress (WIP) at each node must be relatively constant. Points in the system where significant variation in WIP occur are modelled by inventory banks.

The underlying assumption for zero internal bank modelling is that limited banking (if any) internal to each node is used only to deal with endogenous disturbances, and hence can be ignored when integrating nodes into a system. In reality, internal banks have some small effect (magnitude of effect is proportional to bank size) on cushioning external disturbances. Therefore, throughput results obtained by zero internal bank modelling may, in some cases, be somewhat pessimistic.

A section of the segmented system showing two nodes separated by an inventory buffer is illustrated in Figure 2.

Figure 2: Two Nodes Separated by a Buffer

For discussion purposes let us assume that nodes A(i) and A(i+1) represent automatic transfer line segments with M work stations each. The inventory buffer B(i) represents the bank of capacity N between two line segments. There are four necessary conditions that must be met before the line can index:

1) All stations must have completed their cycle.
2) All stations must be in the working order (i.e., none can be broken down, all repairs complete).
3) There must be a job waiting in front of the line.
4) There must be at least one empty spot in the bank immediately downstream from the line.

The above conditions ensure that an empty spot could never move through the line segment. Therefore, it follows that the level of WIP in each line segment is constant and equal to M. Hence, each line segment can be modelled by a node of capacity one without affecting the system throughput.

Line segments (nodes) interact with each other through buffers. When node A(i) is ready to discharge its job and it finds buffer B(i) full, it becomes blocked. Similarly, when node A(i+1) cannot transfer out its job because bank B(i) is empty, it becomes idle.

Each inventory buffer is modelled as a limited capacity storage with processing time equal to travel time through the bank.

The distribution of job interdeparture times from the line segment (node) is composed of two components: one due to the internal operation of the line segment and the other (external to the line segment) resulting from interaction with other line segments. The internal component results from station cycle time and breakdowns. The external component comes from blockages and idle periods imposed by the operation of other line segments (nodes). Assuming that the internal breakdown frequency and duration of a line segment (node) is not affected by segment (node) interaction, the internal component of the job interdeparture time distribution can be determined by studying the line segment (node) in isolation.

For example, to determine the internal job interdeparture time distribution for the line segment represented by node A(i) in Figure 2, the node is studied in isolation under ideal conditions. A simulation micro model for the line section representing node A(i) is run under conditions allowing no blocking or idle periods in the line segment. The output of the model is the distribution of interdeparture times. Similarly, the distribution for node A(i+1) interdeparture times is determined. A complete model of the line in the Figure 2 can be constructed once the two distributions become available. Nodes A(i) and A(i+1) have a capacity of one job and each is characterized by its own processing time distribution (i.e., internal interdeparture distribution). The bank is described by capacity of N and travel time T. In such a model, the amount of time that a job spends in a node before attempting to leave is a random variable sampled from the appropriate processing time distribution. When processing is complete, a job may leave only if the node is not blocked or forced into idle state. Once a job enters the bank, it must spend the travel time T in the bank before it can be considered available for the next station.

The zero internal banking approach is an approximation. It approximates rather than duplicates the behaviour of original simulation models. As it attempts to simplify the system being modelled, it distorts some aspects of the system. In particular, this approach will not allow one to study the time that jobs spend in the system.

The approach does not lend itself readily to modelling automated guided vehicle (AGV) systems. For such systems the method has to be modified or completely different approaches used.

4.3 The Macro Simulation Model

For simplicity, in the rest of the paper, we shall discuss only a part of the car assembly system. Figure 3 illustrates the chosen portion of the system being modelled. Circles represent robotic or manual work stations. Triangles indicate insignificant inventory banks while larger buffers are represented by segmented rectangles. Dashed boxes outline the eight micro models.

The system macro model should be built in stages (see McKay et al. (1986). A prototype is first built. It is a simple model capable of processing only a single car body style. This is a necessary step to prove that the "zero internal banking" approach can produce a satisfactory macro model. Next, the simple model is expanded to include all important features associated with multiple body style production. In our example, very simplistic bank representation found in the first model has to be modified to allow for parallel style dedicated banks. Specific production rules also need to be implemented. Issues concerning the trade off between the level of detail and the adequacy of representation become pronounced here. Inventory banks couple macroed production processes. Buffer configuration has a direct effect on the production system performance. Furthermore, since studying the size of inventory banks is one of the objectives, adequate representation of each bank is critical. A considerable amount of complexity may have to be introduced into the model to ensure valid representation of banking and specific production logic.

Figure 4 illustrates the full macro model. In comparing it with Figure 3, we can see how individual micro models are collapsed. Micro model one, consisting of thirty-nine robotic stations and five inventory buffers, is reduced to five nodes and five inventory buffers. Eight stations and six buffers in micro model two are reduced to three nodes and three buffers. Eight stations in micro model three and sixteen stations in micro model four are collapsed to two nodes for each model. Micro models six through eight are identical to micro models two, three and four. Only the micro model five, representing the AGV line, is not collapsed. It is left in its original form. The approach we use does not readily lend itself to modelling of this particular AGV system.

4.4 The AGV System Model

The AGV line is a closed loop system with a number of serial and parallel stations. It interacts with its environment through three points: model one interface, models four and seven interface, and the downstream production systems interface. During

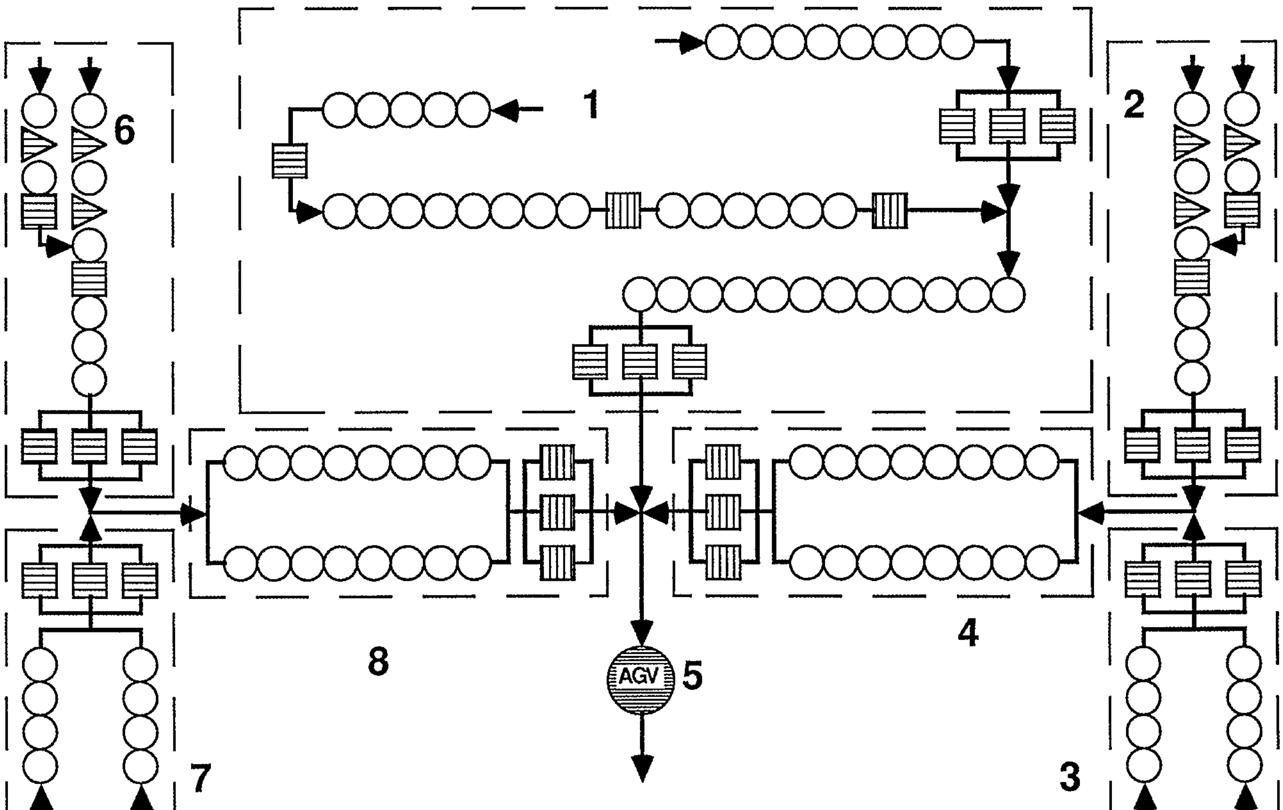

Figure 3: Micro Model System Description

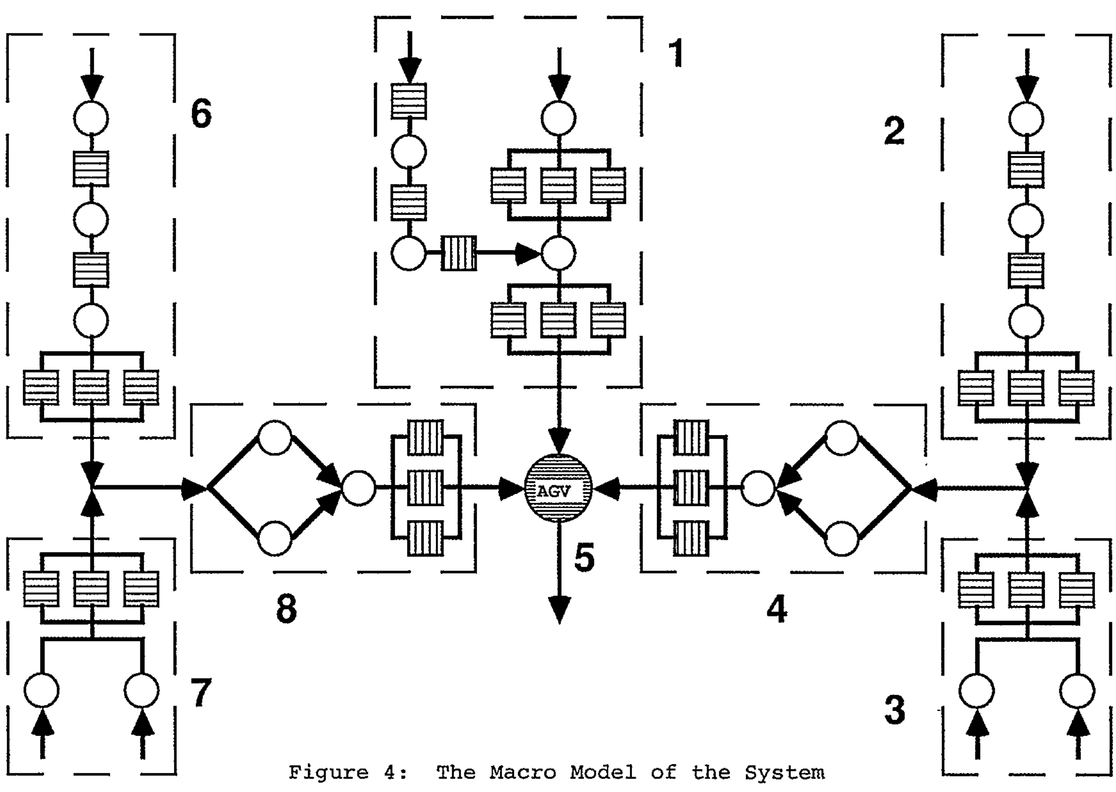

Figure 4: The Macro Model of the System

parallel processing AGV's are allowed to overtake each other, and hence the sequence is not maintained.

The micro model of the system has been written in GPSS/H. It was used to determine the number of AGV's required, test the operating logic and address sequence related questions.

In our experiments, we have attempted to apply a couple of variations of the zero internal banking approach to model the AGV system. In the first approach, the system was initially represented by three nodes (one for each interface point) separated by three banks. Bank sizes corresponded to the number of control points in the section represented by the bank. Travel times through banks were random variables sampled from distributions determined using the micro model. This approximation of the system proved to be too crude, giving conservative throughput results. It was unable to properly model AGV accumulation at various points in the system. However, as the number of nodes was increased, results improved, but not to the acceptable level.

The second approach represented groups of stations by a single node proceeded by a buffer. The node processing times were random variables sampled from interdeparture time distributions determined from the micro model. Bank travel times were zero. This approach yielded better results than the first method. In this case too, breaking the system down into more segments improved the macro model estimation of the throughput. In the final version, two parallel stations were represented by a single node/bank combination. In our tests, under steady state, this level of decomposition yielded results within two percent.

Decomposing the system into more segments increases the complexity of the macro model. The simplicity and compactness advantage of the macro model begin to diminish. In our real system, it was not worth trading off adequacy of representation to gain simplicity. The AGV line is located in a central bottleneck point of the manufacturing system, and the inaccuracies in its model cannot be tolerated.

5. MODEL VERIFICATION/VALIDATION

Normally, model validation and verification are made using real system data. However, when macro modelling a new facility, no real production data can be collected. For the cases where the behaviour of individual sub-systems is well understood through extensive micro simulation modelling, as is the case in our example, a different approach can be used. Verification and validation of different modules making up the final simulation model can be made using existing micro models as reference. An implied assumption is that individual micro models have been properly verified and validated. The following subsection explains the three level approach to macro model verification and validation.

5.1 Node Level

At the node level a distribution of the interdeparture time is determined from the micro model. This distribution is then approximated by a finite set of points. The node distribution is checked against the original to ensure adequate approximation and no coding errors.

5.2 Micro Model Level

The verification and validation at the micro model level are facilitated through a modular approach to the design of the macro model. A section of code corresponding to a micro model is tested against the appropriate micro model. In our example, the average bank levels, average system throughput, and the distribution of the interdeparture times from the system are the important measures for determining macro model validity. For evaluating the performance in terms of average bank levels and average system throughput, the confidence-interval approach can be used. When comparing two simulations, this is a simple and reliable method since the user is in complete control over the data gathering activity. For comparing distributions of the interdeparture times, several approaches of varying degrees of sophistication may be utilized. The simplest is to use inspection by plotting cumulative distributions on the same graph and against each other. Any significant deviations between them quickly become apparent. Goodness of fit tests, such as the Chi-square test and the Kolmogorov-Smirnov test, can also be used to detect deviations between distributions. However, they are much more work than simple inspection. In the case of our models, we have found that it was necessary to apply these tests only when inspection indicated a deviation between two distributions.

A module of the macro model is accepted as valid only if all three performance measures are found to be in agreement with the micro model output. In the cases where significant deviations are detected, the macro model is modified and the validation process repeated.

Approximate analytical modelling can be a powerful tool in the validation process. In our example, ideas found in automatic transfer line modelling can be applied. The method is based on the decomposition approach (Gershwin 1983). The system is separated into a series of two-stage transfer lines with intermediate inventory banks. These correspond to the node and bank network utilized in the macro simulation model. Each two stage line in the analytical model is defined by the bank, corresponding to the bank in the simulation model, and by the upstream and the downstream stages associated with that bank. The approach takes into account the influence of one line segment onto another, modifies the characteristics of the upstream and the downstream stages in the segment, and uses the iterative procedure to find an approximate solution. The usefulness of the approximate analytical modelling can be illustrated by one of our experiences. In the micro model number one, a particular average bank size did not agree with the result from the macro version. The analytical model results agreed with the macro model, indicating a possible error in the micro model. The main usefulness of approximate analytic models, however, is in helping to validate the interaction of nodes in the macro model. This is something which cannot be done from individual micro model simulations.

5.3 Macro Model Level

When there is no complete system performance data to evaluate against, the validation at the macro model level requires the use of techniques different from those used at the micro level.

Close contact with manufacturing engineers involved in design of the manufacturing system being modelled is essential. All simplifying assumptions, made in the transition from micro models to a macro model, need to be discussed and agreed upon with system designers. Throughout model development, specially when consultants are doing the modelling, constant engineering input is required. It is particularly important that the interaction exists during interpretation of results. Plant personnel are in a much better position to pass judgement on validity of results than the simulation analysts are.

The macro model should be built in steps. Modules should be added one at a time. After each module addition, the system response is studied. Only when satisfied with validity of the model do we proceed to add another module. This quickly pinpoints invalid sections of the macro model. In our example, we would join modules two and four together, then add three (see Figure 4). The same is done with modules six, seven and eight, which are then coupled with the already joined section. Next, we couple modules one and five. Finally, the whole system is put together. This process helps in expanding our understanding of interactions between different parts of the manufacturing system under study.

Sensitivity analysis is another method for macro model validation. It allows the analyst to study the system response to controlled changes in certain system parameters. In our example we can vary inventory bank sizes, the product mix, the duration and frequency of station downtimes. For each level of each parameter, the system response in terms of the average throughput and the average bank content can be studied. The results are then validated in collaboration with the manufacturing engineers.

Depending on the complexity of the system, analytic modelling may also be very useful in macro model validation. However, due to the complexity of many systems, full use of this method may not be possible. For example, the centrally located AGV system, which is not easily modelled analytically, makes an analytical model of the described car assembly plant difficult to construct.

6. CONCLUDING REMARKS

We have shown how micro models can be utilized to develop and validate the integrated macro model. The "zero internal banking" approach has been developed and used successfully by the WATMIMS research group to build a macro model of a car assembly plant. However, free flowing AGV systems with parallel processing are difficult to model adequately using this approach.

Macro models are necessary when it comes to modelling of large and complex systems. Even if it were possible to link existing micro models together into a single model, it would not be practical due to the size of the final model. However, modelling at the high level implies aggregation and many simplifying assumptions. There is an inherent trade off between the level of detail and the validity of the model. In some cases, macro modelling of some parts of the system may be inappropriate, as is the case with our example AGV system.

Macro model requirements need to be well defined before model development starts. What questions are to be answered by the model and what performance measures are critical determine the level of aggregation in the model. Trying to use the model to study aspects of the system performance for which the model was not designed could be catastrophic.

The modular approach to model implementation and validation is very helpful. By ensuring that each part of the model is valid and achieves proper interaction with the rest of the model, the confidence in the complete model is increased. This is particularly important when dealing with systems which are under design, and have no field data for model validation.

An organized approach to micro modelling is helpful when building a macro model. Overall modelling strategy should be in place if components of a complex system are micro modelled individually. The strategy is to eliminate duplication of effort when a complete integrated model has to be built. It must outline which models are to be built and how they are eventually going to be used in the final system model. Model structure and type, world views, and data base design should also be addressed. However, our experience indicates that having such a strategy is not common. The strategy is particularly difficult to implement in organizations where simulation modelling is diffused throughout several departments.

Modelling standards and guidelines should be easier to implement than the full modelling strategy. Such standards should specify time units, languages, model boundaries (interfaces), etc. The guidelines for general model structure, data base design, coding and documentation practices should also be provided. This will enable linking of models as necessary, and will make a job of building a macro model much easier. Building a macro model from poorly documented and written micro models can be a very frustrating and lengthy experience.

Information provided by isolated micro models and used in the integrated macro model has to be accurate. This implies proper validation of individual macro models. However, often modelling is performed by engineers who have little or no formal simulation training. As a result, incomplete model verification and validation is not uncommon. When this occurs, the validity of the resulting macro model based on micro models is questionable.

REFERENCES

Gershwin, S.B. (1983). An efficient decomposition method for the approximate evaluation of tandem queues with finite storage space and blocking. Working paper LIDS-P-1309, Laboratory of Information and Decision Systems, Massachusetts Institute of Technology, Cambridge, Massachusetts

McKay, K.N., Buzacott, J.A., Moore, J.B., and Strang, C.J. (1986). Software engineering applied to discrete event simulations. In Proceedings of the 1986 Winter Simulation Conference (J. Wilson, J. Henriksen, S. Roberts, eds.). Institute of Electrical and Electronic Engineers, Washington, D.C., 485-493.

Sargent, R.G. (1986). Joining existing simulation programs. In Proceedings of the 1986 Winter Simulation Conference (J. Wilson, J. Henriksen, S. Roberts, eds.) Institute of Electrical and Electronic Engineers, Washington, D.C. 512-516.

AUTHORS' BIOGRAPHIES

DRAZEN KOSTELSKI, P.Eng., is a Research Engineer with WATMIMS, the University of Waterloo Research Group in the Management of Integrated Manufacturing Systems. He received a B.A.Sc. in Mechanical Engineering from the University of Waterloo in 1983, and a M.A.Sc. in Management Sciences from Waterloo in 1985. His research interests include the simulation modelling of manufacturing systems.

Drazen Kostelski
WATMIMS Research Group
Department of Management Sciences
University of Waterloo
Waterloo, Ontario, CANADA N2L 3G1
(519) 885-1211, ext. 6099

JOHN A. BUZACOTT is a Professor in the Department of Management Sciences at the University of Waterloo and is Director of the WATMIMS Research Group. His interests in manufacturing include the planning of integrated systems and the assessment of their performance, improvement of work flow, control of work in progress, and quality planning and analysis. Dr. Buzacott is also investigating methods for understanding the factors determining the impact of flexible manufacturing systems on industry. He is Departmental Editor in Manufacturing and Automated Production for the IIE Transactions, an Associate Editor for the Naval Research Logistics Quarterly, and on the Editorial Board of Queueing Systems, Theory and Applications of Material Flow. He has been president of CORS and chairman of the NATO Advisory Panel on Advanced Study Institutes.

John A. Buzacott
Department of Management Sciences
University of Waterloo
Waterloo, Ontario, CANADA N2L 3G1
(519) 888-4009

KENNETH N. McKAY is Associate Director or WATMIMS, the University of Waterloo Management of Integrated Manufacturing Systems Research Group, and is responsible for the administration and planning of the group's activities. He has experience in R&D in the computer industry and has developed performance monitoring software, relational database software, and a variety of real-time systems for handling cheques in the financial industry. Mr. McKay's expertise includes: design evaluation, software engineering, software quality, systems architecture, and man-computer interfaces.

Kenneth N. McKay
Associate Director, WATMIMS Research Group
Department of Management Sciences
University of Waterloo
Waterloo, Ontario, CANADA N2L 3G1
(519) 888-4519

XIAO-GAO LIU received a Master of Engineering degree from the Department of Applied Mechanics at Beijing Institute of Aeronautics and Astronautics, Beijing, China, in 1981. He is currently a research assistant with WATMIMS and a Ph.D. student in the Department of Management Sciences at the University of Waterloo. His research interests are the queueing network with blocking and the modelling of manufacturing systems, such as transfer lines, assembly/disassembly lines and AGV systems.

Xiao-Gao Liu
Department of Management Sciences
University of Waterloo
Waterloo, Ontario, CANADA N2L 3G1
(519) 885-1211, ext. 3820