Proceedings of the 1989 Winter Simulation Conference
E.A. MacNair, K.J. Musselman, P. Heidelberger (eds.)

The MAST Simulation Environment

John E. Lenz
CMS Research, Inc.
605 South Main Street
Oshkosh, WI 54901

Abstract

MAST is a simulation tool first released commercially in 1980. It includes a data driven model for manufacturing with special algorithms for simulation of detailed material handling activity. Its model of detailed material handling with control algorithms is effective for the design and evaluation of low inventory manufacturing systems such as flexible manufacturing systems.

Since that time, the simulation tool has been developed into a problem solving environment. Other tools which have been integrated include a static mathematical model for establishing capacity and feasibility, a detailed model for operator team assignments, a detailed tool requirements model, a queuing theory model for quick results, a graphical interface for both data collection and display of results, finite schedules for each station/operator, and automatic generation of the WIPAC curve.

The intention of MAST is to provide an integrated environment of tools from which the user can choose the most appropriate technique for solving a production problem. The static analysis of capacity prevents the simulation of a system which is infeasible. Time is not wasted trying to solve an integration problem when it is really a capacity problem which exists.

The queuing theory tool provides a quick estimate for inventory and flow time. These results can be produced in seconds and do not require any layout description. Many times, a concept is evaluated for its impact on reducing the cost of production. And in most cases, cost reduction is achieved by either reduced inventory, reduced labor, or increased productivity. The queuing theory model can provide quick estimate for rough cut comparison between alternatives.

The graphical interface is intended to provide the user with specific (tailored) approaches to the class of problem he wants to solve. For example, if his problem is a flow problem such as a conveyor line, then one graphical interface allowing him to start by constructing the layout would be used. On the other hand, if his problem were a flexible production system, then he might choose to start with the process definition. Through a variety of interfaces, the user can select the approach which is most suitable to solving the specific problem.

The operator team model has extensive applications toward U-line and other labor limited production systems. This model includes capacity evaluation from team assignments, and provides a finite schedule for each operator as a result of simulation. The direct comparison between planned loadings and simulation results is an effective method for differentiation between labor limited production and machine limited production. Distinguishing this difference is an important step for producing accurate interpretation of a manufacturing system performance.

The overall objective of the MAST Environment is to provide state of the art tools which are integrated. Integration is achieved by use of one common set of data, and the ability to directly compare capacity (loading) results, with queuing results, with simulation results. All of this provides a tool which can assist the engineer with solving the complex production problem of the 1990's.

This paper is composed of four sections. The first describes the capacity planning model enclosed in MAST, the second describes the queuing theory model, the third is the data driven simulation model, and the fourth is the type of results which can be produced from the various tools.

1.0 Capacity Planning Model

Many capacity planning tools exist for manufacturing systems, but most of these have not been enhanced for the unique characteristics of integrated manufacturing. In traditional planning methods, a part is defined to require machine and transport time. However, the

planning model extends this evaluation to include the amount of in-process storage capacity which might be required. This extension is necessary for accurate evaluations of low inventory systems because parts must be tracked and stored even when they are not at a machine and in operation.

The aggregate planning procedure within the planning model is designed to compute the gross requirements of the planned production and compute its capacity in three distinct areas. First, the station requirement is computed from the cumulation of operations assigned according to the process plan, the amount of time required to perform a pallet exchange and the production requirement.

Secondly, the transporter requirement is computed from the cumulation of the average cycle time for a transporter to pick-up and deliver a pallet times the number of transport moves required according to parts and routes represents the total transporter requirement.

The third requirement computed within MAST is the amount of work in-process required to meet production targets. In-process storage within the manufacturing facility includes the elapsed time when a part has completed an operation and is waiting for transportation or has completed transportation and is waiting for a station. This time is estimated for each part type and is used to estimate a flow time through the facility. This time is used to compute an initial estimate of the number of pallets needed from the production requirement assuming a uniform production level during the planning period.

Respective station, transporter and work in-process requirements are compared to each of their respective capacities. The station capacity is determined by multiplying the number of stations of each type by the planning horizon. The transporter capacity is computed by multiplying the number of transporters by the planning horizon. The storage capacity is assumed to be sufficient to store the total number of pallets and thus no comparison is performed within the planning model. The storage capacity is used to indicate to the designer the amount of storage necessary to meet the planned production within the planning horizon.

When the requirements of the station and transporters are less than their respective capacity, the production plan is considered feasible within the planning horizon. But if any one of the requirements exceed its respective capacity, the production plan is considered infeasible and a strategy must be invoked to bring the system to a feasible configuration.

The planning model contains four distinct strategies for bringing a manufacturing facility into a feasible capacity configuration. These include extending the planning horizon, reducing production quantities, adding stations and transporters, and adjusting part routes. The planning model automatically computes the first three strategies upon the designers request. With respect to altering part routes, too many alternatives exist and thus the designer is left to attend to this through the use of the built in editor within the planning model.

Once a feasible system has been designed, the planning model can automatically produce data input for the MAST simulation. The parts and their process definitions are recorded from the data already provided. All that is needed is a description of the layout of the facility, roles of operators and scheduling algorithm selections. The layout is defined through the use of points and distances between these points. Teams of operators can be assigned to groups of work stations and scheduling algorithms range from random mix to batch. The result of this generation is a data file ready to be read directly into MAST for simulation of all activity in the proposed FMS. The following section describes the features of the MAST simulation language.

2.0 Data Driven Simulation Model

The MAST simulator contains a generalized model for integrated manufacturing systems. This model contains features for representing the system hardware components and the control hierarchy. The hardware model can study multiple part families, a variety of station types, conveyors and/or carts, numerous in-process storage devices, and any system layout. The hardware model is completely described by the data input and no "modeling" or programming is required.

2.1 Hardware Model

The physical components model of the MAST Simulation module includes the following capabilities:

1. **Parts**
Raw materials to finished parts, assemblies, disassembles, sub-components, fabrications, weldments and rework parts.

2. **Work Stations**
Metal removal machines, metal forming machines, robot, work table, assembly stations, transfer line stations, fixture stations, tool load/unload stations, inspection, wash, gauge, weld stations, grind and vision system.

3. **Material Handling Systems**
Manual truck, gravity conveyor, power conveyor, power and free conveyor, transfer line, transfer conveyor, over-head crane, two line vehicle, AGV, rail-type vehicle, jib crane, robot and pick-and-place device.

4. **Facility Layouts**
One-way paths, bi-directional paths, network combined carts and conveyors, multiple types of cart systems, homogeneous transportation system and manual systems.

5. **Storage Facilities**
Input queue for a station, output queue at a station, rotary pallet changer, flow through pallet changer, carousel, pallet stands, automatic storage/retrieval system (AS/RS), non-synchronous conveyor accumulation and accumulating conveyors.

6. **Tools, Pallets and Fixtures**
Individual tool at a station, unique fixtures for parts, general fixtures, pallets for part handling and pallets for batch part production.

7. **Operators/Teams**
Assignment to a group of stations or dedicated to a single station, U-line assignments, assignments for entire operation or operation start only 20% of operation duration), load/unload areas, shift assignments, breaks and set-up operations.

8. **Component Reliability**
Nine distributions for time between failure and repair time descriptions, individual carts, groups of carts, and conveyor sections.

9. **Setup information**
Setup delays for each station can be described. This allows for a from/to part definition for each specific delay.

2.2 Software Model

Along with this hardware model, MAST also contains a model for the computer control or a software model. In this model, the actual control is broken into seven distinct decision areas. For each of the decision areas, MAST contains a library of algorithms. For example, it is possible to switch from cart material handling to conveyor by simply changing one algorithm in the transportation selection decision. The seven decision areas are listed below.

Scheduling. This algorithm is called upon whenever a part can be introduced into the system. Algorithms within MAST include such options as random mix for all part types, assembly and disassembly of part types and batch production.

Operation Sequence. This decision occurs whenever a part has completed an operation and must determine which operation is to be performed next. Algorithms within MAST include fixed sequence, buffering to intermediate storage positions, or operation sequence based upon station availability.

Station Selection. This decision is made whenever a part has found its next operation and one of several stations must be assigned. Algorithms in MAST include highest priority station, idle station, closest station and lowest backlog.

Transporter Selection. This decision involves a part which has found a next operation and station and is ready for transportation. Algorithms within MAST include idle cart, closest cart, conveyor or synchronous conveyor.

In-Process Storage Control. This decision is made whenever a part must wait for a station or transporter. Algorithms in MAST include first in-first out, priority ranking or fixed sequence.

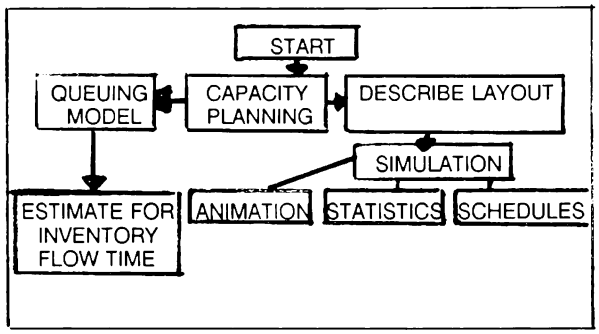
Traffic Control. This decision is made whenever a cart is requested to pick-up, deposit, or relocate to another zone. Algorithms within MAST include a push-pull control, bi-directional trunk line movement or sidings off main loop.

Tooling Control. This decision occurs only when tool data has been provided in the Planning model and a tool has reached its user-specified warning point. Algorithms in MAST include 100% replacement of tools, 100% replacement and replenishment/replacement with batch scheduling.

The combination of the options available in the seven areas described above provides a high degree of flexibility. This flexibility in describing a manufacturing facility makes the MAST environment easy to use, but the results or outputs must be as easy to understand. The effective use of simulation requires that results can be used with confidence.

3.0 Queuing Theory Model

MAST contains a model which evaluates factory operations using queuing theory equations. This model uses the same data which has been collected in the capacity analysis. Once the process definition production requirements and number of stations has been determined, the queuing theory model can produce an estimate for inventory level and flow time. In the MAST environment, the user has the option to use the queuing theory model for rough cut analysis or go directly to simulation for detailed evaluation of a production system. The following diagram illustrates the possible paths the user can choose.



The queuing model has these benefits over the simulation model. The first is that it does not require a layout. In most production systems, the layout constitutes a major part of the data needed to simulate a system. By simply not requiring this, much time can be saved in obtaining results.

The second benefit of the queuing model is its short response time to produce results. For a system with 10 part numbers, and 20 stations, the queuing model can provide estimates for inventory and flow time within 30 seconds on an AT compatible computer. The same system in simulation will require more than 15 minutes of time.

The third benefit of the queuing model is that the skill and education requirements of the user are much lower than that required for simulation. This is evident from the need for control algorithms. In order for the simulation to be effective, it must include operational rules consistent with these found in the actual factory. The process of identifying these rules, and implementing them in simulation is a task which requires a very high skill level and months of training. In fact, one researcher estimated that 500 hours or classroom eduction is required for an engineer to use simulation effectively in solving a manufacturing problem.

These benefits of queuing theory are offset by some disadvantages as well. These disadvantages are the same reason why simulation is still needed for the accurate evaluation of many production problems.

One disadvantage of the queuing model is its lack of including blocking of stations. Blocking is the prevention of a station from operating due to the saturation of the downstream queue. There are techniques for recognizing in the queuing results when blocking would occur, but the solutions are only heuristic method.

Another disadvantage of queuing theory model is its suitability to all production problems. Queuing models work best for flow oriented production. If the problem which need to be resolved is one of scheduling, or balancing capacity to dynamic requirements, then queuing theory results do not add much value to the decision.

The queuing theory model in MAST is intended to provide a quick estimate for an inventory level and approximate flow time of a production system. This information is useful in the evaluation of a concept or when estimating the economics of a proposed production system. It can produce these results within seconds from a minimum of data.

4.0 Integration of Results

The MAST environment provides static analysis results, queuing theory estimate for inventory and flow time and a variety of outputs from simulation. These are highlighted below.

4.1 Color Graphic Animation

Many alternative algorithms exist for each of the seven decision areas within the supervisory computer control. It is essential that these algorithms be evaluated for "optimality" just as it is important to study the operation of the hardware. In many instances, the machinery is selected and the computer control is ignored during the design. Two reasons exist for this incomplete design approach:

1) Computers are assumed to be easily programmed to do anything and,

2) Evaluation of different algorithms via statistical output is difficult. Simulation of detailed operation is needed to study the integration effects of the manufacturing facility and graphic animation provides a visible tool for review of operation.

Background and Enhanced Animation for MAST (Color graphic animation) has the capability to generate a background from the data input for MAST and to animate all activity which took place within a MAST simulation. The background generation produces a graphical layout of the FMS on the computer monitor. This background is quickly obtained through use of either a mouse or arrow keys in a CAD-like fashion. The process requires identifying the appropriate placement in the screen for track zones and boxes for station work tables. Queues are shown as an area between the work table and the track.

The second task for color graphic animation is the animation of the MAST simulated activity. The animation is accomplished by "blinking" images through the background according to the event activity. The event activity is recorded in a file which is read by color graphic animation.

Circles with ID's are used to indicate each specific part type and transporters are described with colored boxes. The animation can be played at various speeds from real time to viewing eight hours of activity in eight minutes of time. As the animation runs, it is also possible to display system performance statistics.

Color graphic animation provides graphical displays of the performance statistics as these are accumulated. These displays include a bar chart showing production requirement, number completed and number scheduled. The part performance is displayed using a pie chart with three sections, one for station time, storage time and material handling time. A line graph of production over time is available for each part type and a summary of total production for the FMS. Station utilization is reported with pie charts for individual stations and station groups. These pie charts show time busy, shuttling, idle and down. Finally, transporter utilization is shown as time moving, shuttling, idle and down in a pie chart. The actual amounts are displayed along with each graphic.

4.2 Performance Statistics

MAST contains reports which are designed specifically for the needs of manufacturing system evaluation. Component utilizations are included as well as part performance, pallet utilization and station blocking. Each of the performance measures are described below.

Part Production Statistics
Part ID, Parts Required, Parts Completed, Percentage, Average Parts per Hour, Average Flow Time, Minimum Flow Time, Maximum Flow Time, Parts Scheduled.

Part Flow Statistics

Part ID, Station Time, Storage Time, Transportation Time, Part Type, Station Percentage, Transport Percentage, Storage Factor.

Work In Process Statistics

Pallet Type, Average Used, In-Use Now, Now Available, Maximum Used, Average Members in System.

Station Utilization Statistics

Station Name, Cycle Time, Cycle Percent, Shuttling Time, Shuttling Percentage, Blocked Time, Blocked Percentage, Idle Time, Idle Percentage, Down Time, Down Percentage, Set Up Time, Set Up Percentage.

Queue Statistics

Station Name, Input Queue Time, Input Average Queue, Maximum Input, Output Queue Time, Output Average Queue, Maximum Output, Buffer Queue Time, Buffer Average Queue, Maximum Buffer.

Operator Utilization Statistics

Team Number, Operator Number, Busy Time, Percentage.

Cart Performance Statistics

Cart Number, Move Percentage, Shuttle Percentage, Down Percentage, Idle Percentage, Distance Moved, Assignment Time.

4.3 Labor Limited Production Analysis

The evaluation procedure of a production system differs for machine limited production and labor limited production. Machine limited production can be evaluated from machine performance of queue lengths. Labor limited production must be evaluated from labor utilization and queue lengths. The difficulty comes in defining which stations have their performance controlled by labor and which do not.

MAST uses a detailed capacity analysis of both machines and labor. This establishes a target use

for station and labor for some required production rate and mix. The simulation results can be used and compared to these targets for accurate identification of these stations which are labor limited and machine limited.

If the simulation would produce the same production rate and mix as asked for, then the evaluation would be easy. However, this becomes the first step in evaluation that is to interpret the station and operator performance according to the difference in production rates and mix between simulation and capacity planning.

MAST makes this interpretation of results as convenient as possible. It provides the capacity targets of work stations for a given production rate and mix. It also, provides target utilization for operators which have been assigned on teams. The MAST model for either the entire operation time or some other specified time. They are permitted breaks during the shift and can assist with breakdown and setup as defined by the user.

The simulation produces a result which contains the actual production rate and mix. Also, utilizations are provided for each station and operator. In this process of interpreting these results, MAST can provide the exact differences between planned mix and actual mix. Also, the actual mix can be put into the capacity planning to establish "normalized" targets for each component. This normalization is an effective means for identifying those stations which are labor limited and those which are machine limited.

Another useful result from simulation is the finite schedules which are produced for both stations and operations.

4.4 Finite Schedule

The finite schedules which are produced from a MAST simulation contain detailed activity for each station and operator. The station schedule includes the start time and stop time for each operation; for each downtime and repair; for each set up; for each blocking; and for idle time. Each operator schedule contains the start and end time for each operation carried out, each set, each downtime/repair at a station, and breaks from active duty.

The combination of these are useful when reviewing the integration between operations activity and stations needs. For example, such issues as how long a station must wait for an operator to start a set up or repair can be identified. How much time a station is waiting for an operator on break and how large/small the queues become during these periods can be identified from those schedules.

These schedules are useful when the production system is experiencing periods of machine limited production, some other times it is labor limited, and other times material shortages occur. Performance statistics average all of these situations together, and animation can not show the intricate linking between cause and effect situations.

The finite schedule in MAST can either be printed or displayed as gantt charts, and they have been used for when the simulation of production systems contain as many dynamics as found in real systems.

Conclusion

MAST started as a data driven simulation program and has evolved over the years into a complete set of tools. The collection of these tools creates an environment from which the manufacturing engineer can solve design and productivity problems. MAST provides a no programming, no modeling approach to factory problem solving. It uses the latest graphics and integrates capacity analysis, queuing model, simulation, animation finite schedules, and provides a formal method for accurate interpretation of results. It is intended for the study and evaluation of any low inventory-high velocity production system. These include U-lines, FMS, pull type assembly systems, just in time systems, factory wide material delivery systems and other advanced manufacturing techniques.

REFERENCES

Lenz, John E., The MAST User Manual, CMS Research, Inc., Oshkosh, Wisconsin, USA.

Lenz, John E., **Flexible Manufacturing: Benefits for the Low Inventory Factory,** Marcel Dekker, Inc., New York. 1989.

BIOGRAPHY

JOHN E. LENZ, President, CMS Research, Inc. since 1980 and is chief architect of the MAST Simulation Environment. CMS Research, Inc. provides consulting services in Flexible Manufacturing and has several International offices.