A SIMULATION TEST BED FOR PRODUCTON AND SUPPLY CHAIN MODELING

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ABSTRACT

Production systems and supply chains are difficult to model at the level of detail required to understand factors affecting the behavior of material flow. This is particularly true when use of centralized planning systems, such as MRP or DRP, is of interest. Therefore a test bed, comprised of a planning module and a simulator module, has been developed. This test bed is designed to be simple, transparent and flexible. It supports research as well as training. The planning module uses a spreadsheet-based interface and logic embedded in extensive VBA macros. The simulator module is made up of a generic ARENA program that requires no direct modeling inputs when scenarios are changed. Dynamic communication between the modules is facilitated using VBA. Transient and steady-state behavior can be observed under diverse conditions. Production systems or supply chains using MRP/DRP, reorder points, or Kanban systems can be compared.

1 INTRODUCTION

There is a need for enhanced understanding of production and supply chain performance issues. Obtaining insights through structured experimentation and analysis of real world systems is difficult. One reason is that it is seldom feasible to run multiple scenarios in parallel or even sequentially for the purposes of comparison. As well, commercial software that supports planning and control in real world systems is not well suited to deal with controlled experimentation. Therefore, small scale modeling tools can make a significant contribution in yielding insights otherwise difficult to obtain.

The need to model supply chain scenarios and take analysis beyond the traditional two-stage inventory models has been highlighted as concerns about competitiveness have increased. Slats, et. al (1995) advocated the use of 'logistics laboratories' to easily and quickly build models representing integrated supply chains. Beamon (1998) identified the need to integrate production and inventory

planning and control models with distribution models. As well, the paper reviewed deterministic analytical, stochastic analytical, economic and simulation categories of models and presented a research agenda.

Methodologies based on simulation are attractive when dealing with supply chain systems. They allow both material and information flow to be modeled, as well as sophisticated decision logic for planning and control. Simulation can also deal with stochastic environments, non-stationary demand patterns, multiple performance criteria, capacity constrained resources, assembly coordination, etc. In general, any degree of detail can be modeled, eliminating the need for simplifying assumptions and constraints. Simulation has been used in a number of recent studies. A multi-echelon food distribution system was modeled by van der Vorst, et. al (2000) to determine the effects of delivery frequency on performance, subject to no stockouts. Yu, et. al (2000) introduced a reusable enterprise model and made a case for incremental model development, based on an object-oriented approach. Perea, et. al (2000) developed a hybrid simulation approach based on process dynamics and flow control laws, as opposed to discrete-event simulation. Hung, et. al (2003) introduced a simulation model based on a generic node concept and used it to study pharmaceutical distribution. Linkages to software outside the simulation model supported centralized distribution requirements planning (DRP).

This paper also describes a recently developed simulation test bed, designed to study material flow behavior under diverse scenarios. The design objective was to create a tool that was simple, transparent and flexible. A key requirement was the ability to model dynamic behavior within a production or supply chain based on user-specified demand, product and resource structures. A second requirement was the ability to use different planning and control strategies within the test bed. These requirements were met through the development of two interacting test bed modules. The first is a simulator module. This module simulates material and information flow within the production and supply chain, as well as the demand being

generated by customers. The second is a planning module, which serves as a user interface, database and production or distribution planning system.

An overview of the test bed functionality, based on the use of centralized time-phased planning, is shown in Figure 1. The simulator was implemented using ARENA 5.0 (Kelton et. al, 2002). The planning system was developed within an Excel 5.0 workbook containing approximately 20 worksheets. Visual Basic for Applications (VBA) was used extensively to support planning within the workbook as well as communication between the two modules.
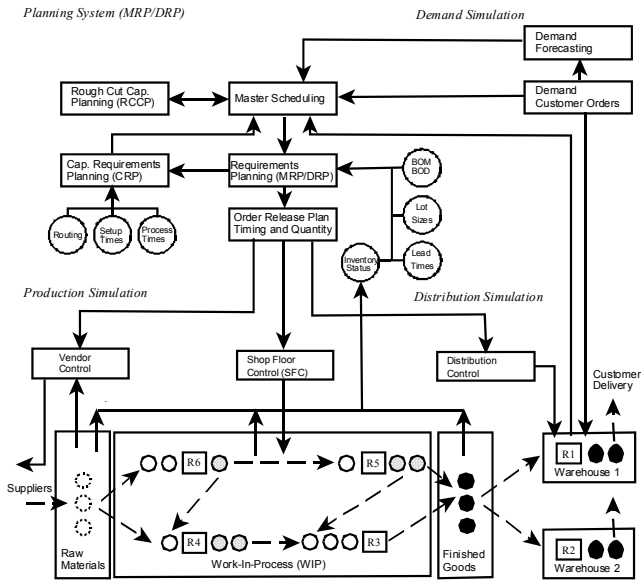

Figure 1: Supply Chain Diagram

The test bed was designed with the ability to monitor both transient and long-term average behavior. This information is of value in at least three types of applications. First, the performance of systems using existing planning and control logic can be better understood. This means that demand patterns, product structure, planning and control logic, and processing characteristics are treated as factors that can be experimentally controlled. Second, various planning and control scenarios can be compared. It is important to be able to compare centralized systems, such as MRP/DRP, against decentralized systems, such those using reorder points or Kanbans. Comparisons under different scenarios allow interaction effects to be determined so that the circumstances under which each planning and control system performs best can be identified. Suwanruji and Enns (2001) provide an example of a study comparing DRP, reorder point and Kanban performance in a linear supply chain scenario. Third, the test bed facilitates developing and comparing new algorithms or approaches to planning and control. For example, Enns and Choi (2001) explored using exponentially smoothed flow time feedback for dynamic planned lead time setting in MRP systems.

The following section gives a general description of the types of scenarios that can be modeled within the test bed. More specific details of material flow implementation follow in Section 3. In Section 4, the planning and control options are described. This is followed by a discussion of the user interface in Section 5 and test bed control and communication in Section 6. Outputs are briefly described in Section 7. Finally conclusions are drawn.

2 MATERIAL FLOW CONFIGURATION

The material in production or supply chain scenarios may flow through serial configurations or through networks involving both convergent and divergent paths. The material moving through the system may be individual items or batches of items. Resources may be capacity constrained (e.g. machines) or uncapacitated (e.g. warehouses). The flow of material between the resources involves transit times, which may be set to zero if desired. Characteristics of production or distribution are considered to be stochastic with respect to setup times, processing times, transit times, scrap rates, machine reliability and machine repair.

The product structure for parts being manufactured is specified through a Bill of Material (BOM), including independent and dependent demand parts. Product distribution is specified through a Bill of Distribution (BOD). Common parts may be located within various levels of any BOM or within BOM's for different parts. Either processing or assembly operations may be modeled at capacity constrained resources.

The configuration of material flow within the test bed can be clarified by considering an example with both production and distribution. The top of Figure 2 illustrates the Bill of Distribution (BOD) distribution for goods supplied from the factory. The Bill of Material (BOM) for part type P3 is illustrated in the lower section of Figure 2. Note that the BOM also shows the quantity of child parts required by each parent. The number in brackets beside the part number shows the requirements for all dependent demand parts.

Figure 3 shows the material flow configuration for this example. As shown in the distribution frame of this figure, P1, P2 and P7 are independent demand parts being delivered from inventory at warehouses R1 and R2. These warehouses are treated as resources with unlimited capacity. Parts P1 and P2 are the same type and are shipped from the factory as P3. In other words, they represent different stock keeping units (sku's) at different geographical locations. P7 is also delivered from R2 and supplied from the factory.

The activity within the factory falls within the production frame illustrated. In this example, R3 performs an assembly operation to combine P4, P6 and P8 into P3. Note that R3 has an inventory storage (represented by a triangle) on the incoming side as well, since it is a capacity-

constrained resource. In other words, inventory before and after processing must be considered at capacity-constrained resources since materials may have to wait in queue for resource availability. P4 and P8 are both processed on R4. P4 requires only raw material (RM4) from suppliers but P8 requires P5 as a component. P6 is processed on R5 and requires P5 as well. While P6 is required by P3, it is also required to fill independent demand and is shipped to R2. This would be typical of spare parts requirements.
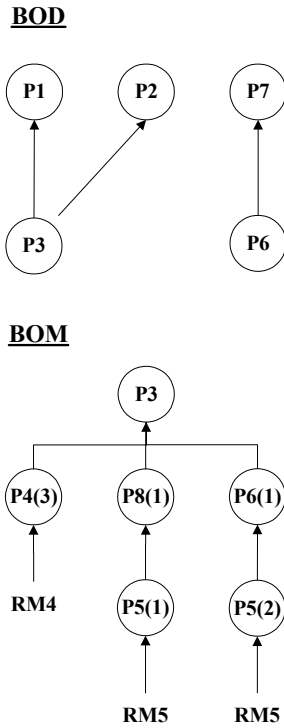
BOD

BOM

Figure 2: BOM and BOD Diagrams

The processing and transit information also needs to be specified. The transit times are shown along side the arrows in Figure 3. The mean transit time to reach the distributor is 20 hours while the mean transit time for incoming materials to the factory is 10 hours. The average time taken to move materials from one resource to the next within the factory is assumed to be 5 hours.

Table 1 shows the part processing time information. The information is used for planning purposes as well as for simulating production and distribution. There are no setup or processing times associated with parts going through resources without capacity constraints. For parts undergoing processing or assembly operations, a setup time and a part processing time may be specified. This table also shows the expected proportion of parts scrapped and the assumed lot sizes for each part type. The lot sizes for parts using capacity-constrained resources are approximately equal to values which minimize lot flowtimes.
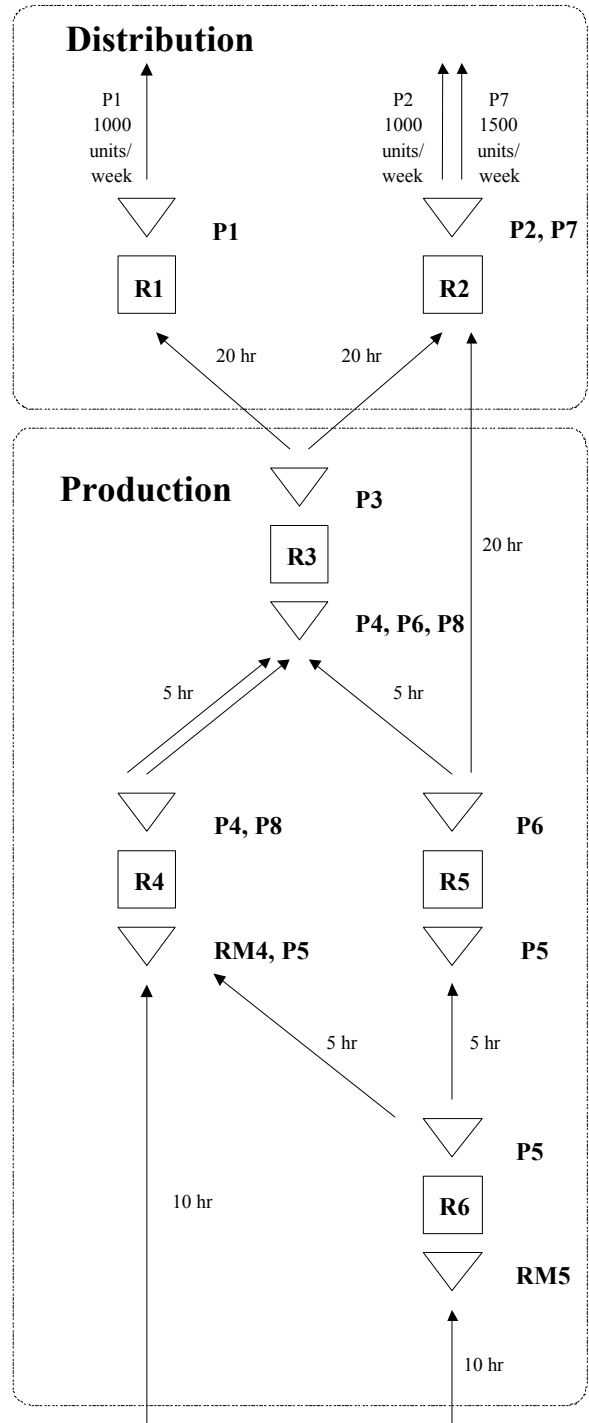

Figure 3: Network Flow Diagram

3 MATERIAL FLOW MODELING

This section shows how the customer demand, product configurations and production environment are specified in the test bed.

Table 1: Part Processing Information

	Setup Time (hr)	Part Processing Time (hr)	Scrap Rate	Lot Size
P1	0	0	0	100
P2	0	0	0	100
P3	0.60	0.014	0.02	150
P4	0.12	0.002	0.01	750
P5	0.50	0.003	0.01	500
P6	0.40	0.006	0.01	105
P7	0	0	0	150
P8	0.80	0.007	0.01	200

3.1 Demand

The demand for end items is assumed to be stochastic and time-varying. The pattern for each end item is assumed to follow a sinusoidal pattern with a cycle length of 52 periods. This is equivalent to one year under the assumption of a period being equal to one week. The mean and amplitude of each demand pattern can be selected independently. In addition, the patterns for different items can be offset from each other by setting a relative lag value, equal to a portion of the cycle length. This allows flexibility in varying the aggregate work loads through time as well as the balance of work loads across resources. The actual demand in each period is uncertain and equal to the sum of five daily demands. The daily demands are based on a Gamma distribution. The degree of demand uncertainty (actual demand around expected demand) for each end item is determined by selecting a demand coefficient of variation (CV).

A sample pattern for one year (52 periods) of end item demand per period is shown in Figure 4. Referring to Figure 3, P7 is assumed to have an expected demand of 1500 per period with no seasonality. The CV of period demand is 0.10. P1 and P2 are both assumed to have a seasonal demand pattern, with a cycle mean demand of 1000 per period and amplitudes of 200 and 250 respectively. However, the lag between the two patterns has an offset of 26 periods. The CV of period demand is again 0.10 for both P1 and P2.

Customer demand for end items is assumed to be accumulated, with shipments or deliveries being made at fixed intervals. This eliminates the need to create entities for each individual end item order in the simulation model. The shipping policy can be set so the total weekly (or period) demand is shipped at the start of the week or at the end of the week. Alternatively, demand can be shipped at the start or end of each day (assuming five days per period). In this case, the daily demand uncertainty is adjusted so that the distribution for the sum of the five daily demands is equivalent to the weekly demand distribution specified. Demand that cannot be filled at the scheduled shipping time is considered to be backordered. Backorders are shipped as soon as inventory becomes available.
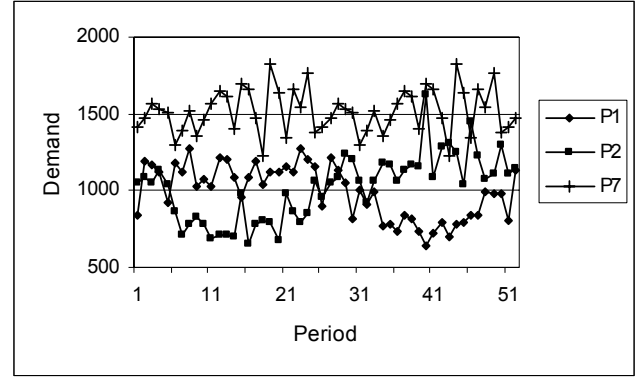

Figure 4: Customer Demand per Period

Under time-phased planning, a forecast is required for master scheduling end items. The rolling horizon used in the test bed is 10 periods long. One option is to base forecasts on the expected demand, given that the underlying demand pattern is known. This results in forecasts which are unbiased or where the bias can be controlled. It also means lag between changes in demand and changes in forecasts can be eliminated. This is beneficial in studies where it is desirable to eliminate the forecasting technique as a factor potentially influencing performance. Alternatively, forecasts may be based on trend-enhanced exponential smoothing. In this case appropriate smoothing constants must be selected. A third alternative is to require user-specified forecasts.

3.2 Product Structures

Product structures may be used to determine either production or shipping channels, depending on whether manufacturing or distribution is being specified. These are represented using a Bill-of-Material (BOM) or a Bill-of-Distribution (BOD), respectively. Both types of bills are specified in a common spreadsheet matrix having rows and columns representing all potential parent and child parts. The values entered in the matrix are the quantity of child parts (rows) required for parent parts (columns). The matrix is designed so positive values can be entered both above and below the diagonal, making it unnecessary to number parts in any particular order. The test bed presently allows a maximum of 8 parts types to be specified.

The matrix allows common parts to be specified for use in different end items. As well, common parts can be used at multiple locations within the product structure for a single end item. The test bed automatically generates an indented BOM or BOD for each product structure. The feasibility of the product structure is checked and error messages will be generated if inconsistencies exist. As well, low level codes (LLC) are generated and gateway parts are identified. Low level codes are used to control the sequence of time-phased calculations under MRP/DRP. Gateway parts are those at the bottom of the product structure. Raw materials for

gateway parts are assumed to come from external suppliers. These suppliers are assumed to always have stock on hand so orders are filled immediately.

3.3 Flow and Processing

Routing, processing and transit time information for all parts is specified within worksheets. The routing information states the resource required. The test bed allows up to six different resources to be specified at present. The processing information includes the mean lot setup time and the processing time per individual part. A sequence-independent setup is assumed to take place every time a new lot of parts arrives at the resource. The expected lot service time is therefore the sum of the mean setup time plus the lot size times the mean part processing time. If the resource is not capacity constrained, setup and processing times are set to zero.

Transit times can be specified for each part type. In the case of a distribution system, this is the delay for the part to be received. In the case of a capacity-constrained manufacturing system, the transit time is the delay for component parts to reach the resource at which the part is being made. These delays are measured from the time the order is filled at the resource supplying the part. If multiple components are required for the same part, such as in assembly operations, all components are assumed to have the same mean transit time. As well, it is assumed that no components are transported until all components necessary for the order are available.

The production or distribution systems are assumed to be stochastic. Actual lot setup times and part processing times are normally distributed, while the transit times are based on an offset negative exponential distribution. The amount of variability is specified by entering a coefficient of variation (CV) in the spreadsheet for each relevant distribution. As well, uncertainty can be introduced with respect to the quality of the parts produced and the reliability of the machines used to produce them. Mean scrap rates can be specified for each part type. Rejected parts, based on a negative exponential distribution, are eliminated and the lot size is reduced after each lot is completed. Machine reliability is specified in terms of mean-time-to-failure (MTTF) and mean-time-to-repair (MTTR) inputs for each capacity constrained resource. MTTF is based on simulation time and negative exponential distributions are assumed for both MTTF and MTTR.

In capacity-constrained scenarios there will also be contention for resources on the shop floor. Dispatch rules are used to determine priorities when there are multiple jobs waiting in queue. These rules are also specified within a spreadsheet by the user. First-come-first-served (FCFS) and earliest-lot-due-date (ELDD) rules have been implemented in the test bed at present. There are assumed

to be no constraints on warehouse storage space nor are there any explicit constraints on transportation capacity.

The material flow and processing inputs are used within the simulation module to model behavior through time. Most of these input values are read into the simulation module from the worksheets in the planning module only at the beginning of an experimental run.

4 MATERIALS PLANNING

The following section briefly describes the three material planning and control options within the test bed. One option must be selected for application throughout the production or supply chain. In other words, different planning and control systems cannot be applied to different parts of the production or supply chain.

4.1 MRP/DRP

The Material Requirements Planning (MRP) / Distribution Requirements Planning (DRP) system uses centralized information and is proactive with respect to demand changes, since forward visibility is incorporated. The MRP option implemented is a closed-loop system with Rough Cut Capacity Planning (RCCP) and Capacity Requirements Planning (CRP) capability. The parameters used for capacity planning are assumed to be the same as the mean values used in material flow simulation. In other words, the values used for capacity planning purposes are unbiased. The master schedules (MPS/MS) for all end-items are based on a ten-period rolling horizon. Lot sizing options for MPS/MS releases include the Fixed Order Quantity (FOQ), Lot-for-Lot (L4L) and Period Order Quantity (POQ) policies. Conventional timing assumptions are used in the logic. For example, orders are due at the beginning of the period in which they are scheduled for receipt. However, an option can be selected to schedule 20% of the MPS quantity to be due at the beginning of each day instead. This helps coordinate production with delivery requirements under some circumstances.

The MRP/DRP system is time bucketed. The number of time buckets per period used in MRP/DRP planning is determined by the user. The options are to select one, five, ten or twenty buckets per period. The explosion or implosion process for determining requirements of dependent demand parts is based on standard MRP/DRP logic. This logic is implemented through the extensive use of VBA code. This code resides in modules within the Excel workbook. Inputs that must be specified include the planned lead time for both the independent and dependent demand parts. These planned lead times must be consistent with a multiple number of time buckets, where the length of the time bucket is dictated by the number of time buckets per period. If they are not, an error message will indicate the problem. Lot sizing policies must also be

specified for each dependent-demand part type. At present the dependent demand lot-size policy options are also FOQ, L4L and POQ. If FOQ is selected, the lot size must also be specified and if POQ is selected, the number of time buckets to be used in determining order quantities must be specified. A safety stock level can also be set for any of the lot sizing policies.

4.2 Reorder Point

The reorder point system is reactive. Replenishment decisions are made independently at each resource serving as a stocking location. Order information is transmitted instantaneously and goods are immediately transported from the upstream resource if stock is available. No partial order shipments are allowed. However, the reorder point system takes backorders at the destination resource into account. As well, released orders that have yet not been filled are considered. These open orders could be due to lack of inventory at the upstream resource, processing delays or transit time delays. If there are backorders for delivery at more than one destination, these are filled on a first-come-first-serve basis.

4.3 Kanban

The Kanban system is also a reactive system, with decisions made based on local information. The Kanban system is assumed to be a single card system so that both processing and transit time must be considered for each card loop. Each lot, or container, of parts is represented by a single Kanban card. As well, these cards are assumed to circulate upstream instantaneously. These assumptions allow more consistent comparisons with the reorder point system to be made. The main differences from the reorder point system are that no backorders are considered under Kanban control and the "reorder point" must be multiples of the Kanban lot size.

4.4 Parameters for Materials Replenishment

Order placement requires a decision with respect to the timing of order placement and the quantity to be ordered. In the example being illustrated the lot sizes are assumed fixed, as indicated in Table 1. The other parameters assumed for each of the planning and control system alternatives are shown in Table 2. These parameters were set so that the average expected demand during the MRP/DRP planned lead times are equal to the reorder point and Kanban inventory positions at the time an order is triggered.

Table 2: Parameters for Material Replenishment

	Planned Lead Time (hr)	Reorder Point (parts)	Kanbans (lots)
P1	28	700	8
P2	28	700	8
P3	12	600	5
P4	20	3000	5
P5	20	4500	10
P6	12	1050	11
P7	28	1050	8
P8	12	600	4

5 TEST BED USER INTERFACE

The experimental inputs are specified in five Excel worksheets. The first worksheet specifies the planning and control mode (MRP/DRP, reorder point or Kanban), the MPS and shipping policies, the number of time buckets per period, the random number streams, the run length for each replication and whether or not an experimental design macro is being used. The second worksheet specifies the demand patterns and forecasting for end items. The third worksheet specifies the Bill of Material (BOM) and Bill of Distribution (BOD) structures. The fourth worksheet specifies the planning and control parameters, routing and processing information and initial inventory positions. The fifth worksheet specifies transit times, scrap rates, and machine reliability characteristics. This includes the coefficient of variability (CV) values associated with these inputs. As well, the dispatching rules used at capacity-constrained resources are specified.

The ARENA simulation model itself is generic and does not require user interaction in setting up different experimental scenarios. Only the initialization (warm up) time per replication and the total number of replications need to be set in ARENA. At the start of each replication, the input information is checked for errors and validity. This is done within the planning module. Error messages indicate if corrections are required. If there are no errors, the information from the input worksheets is read into the simulator.

It is usually desirable to run multiple replications under a given set of experimental conditions to determine within-group variance. As well, it is often of interest to run experiments under different combinations of factor settings. The test bed allows full control of experimental designs so that either random number streams or other inputs can be changed from replication to replication. This is facilitated using a VBA macro in the planning module. This macro causes various parameters to be changed in the input worksheets, based on the replication number. In research studies comparing performance under various scenarios it has proved feasible to run several hundred replications without need for user interaction. Note that the term "rep-

lication" is being used loosely in this description since we are accommodating changes in inputs beyond randomness.

Another feature is the ability to name and save select scenarios for future reference. A VBA user form that allows new scenarios to be saved or old scenarios to be retrieved can be called up from a custom toolbar button in the workbook. When a new scenario is saved the values on all five input worksheets are saved under a user-specified name.

6 TEST BED EXECUTION AND CONTROL

The test bed is currently launched by opening ARENA. Upon starting the simulation run, Visual Basic for Applications (VBA) is used to immediately open Excel and load the planning module. It is assumed that user input information has previously been entered and saved within this module.

The planning module includes worksheets containing the current master scheduling and MRP/DRP records. However, no formulas are contained within the spreadsheet cells. All numerical manipulation within the planning module is performed using VBA macros. The Excel Add-Ins called Analysis ToolPak and Analysis ToolPak–VBA are required. At present there are about 4700 lines of VBA code in the macros of the planning module.

A much simplified representation on the flow of control within the test bed is shown in Figure 5. The encircled numbers represent identification points in the following discussion. The user inputs are initially read into the simulator module at point 1. If a centralized planning system is being used, control is passed to the planning module and a time-phased plan is generated. This occurs at point 2. Control then passes to the simulator module where activity over the next time period is simulated. This includes checking order releases in the plan at the start of each time bucket, as indicate by point 3. If the end of period is reached, as determined at point 4, control is passed back to the planning system for a new time-phased plan to be generated.

Orders which can be filled from stock then proceed as lots to downstream production or distribution resources. Delays in transporting the parts for an order may occur if components are not available from upstream resources. Once all components for the order are ready, the lots are transported to the next downstream resource, as indicated at point 5. If the resource is capacity constrained, there may be a queue time delay as well as a lot service time delay. If the lot is finished goods available to fill customer demand, it is added to inventory at point 7. Otherwise completed lots are added to inventory at point 6. This inventory is held until a requirement is issued based on an order release elsewhere.

If a reorder point or Kanban system is being used, interaction between the simulator module and the planning module every period is not required. However, as indicated at point 8, the inventory position must be monitored
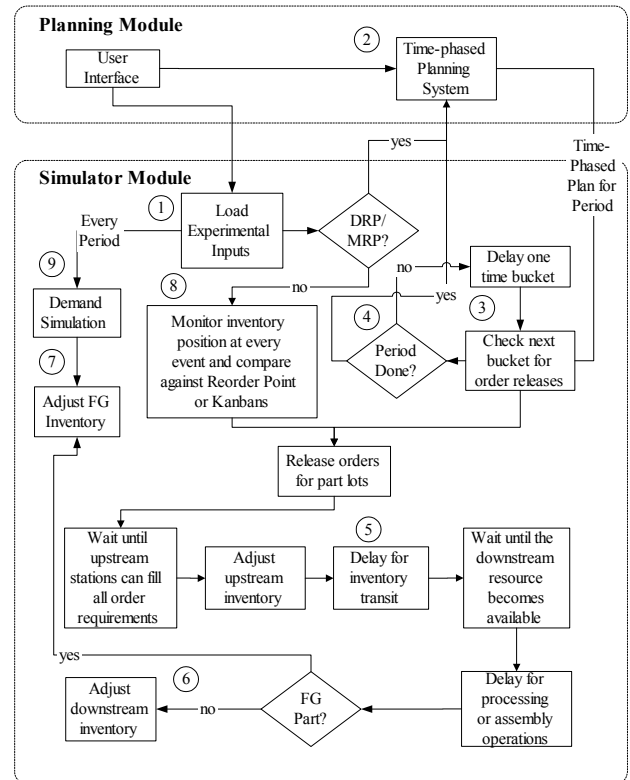

Figure 5: Flow Diagram of Test Bed Control

after every event in the simulation to determine if a new order for another part type has been triggered. Once an order is released, the logic used in the simulation of the production or distribution system follows the same path as under MRP/DRP.

The simulator model is also used in generating the independent demand for customer delivery. This demand, occurring at point 9 in Figure 5, can be generated and shipped on either a weekly (period) or daily basis. In total the simulator module contains about 1400 lines of SIMAN code, the language underlying ARENA, and about 500 lines of VBA code.

Control is passed back and forth between the simulator and planning modules through the use of VBA. This requires that the ARENA Object Library has been added to Visual Basic within Excel and that the Microsoft Excel Object Library has been added to ARENA. Passing data and information back and forth between the simulator and the planning modules is facilitated using a combination of direct and indirect approaches. Most of information is passed between Excel and ARENA directly using VBA. However, communication of the MRP/DRP plans generated at the start of each period uses indirect data transfer. All release order information is written into a text file by Excel after the plan is generated. This file is then accessed by ARENA at the beginning of each time bucket to determine order releases.

The execution of experiments can be paused at any point during a run by having the user activate a custom toolbar button in the Excel workbook. This allows the user to look at the transient performance and the current status of the materials plan. In the case of MRP/DRP, the temporary suspension of execution is controlled to occur at the beginning of a planning period, after a new plan has been regenerated, or at the end of a period

7 TEST BED OUTPUTS

Summary performance is observed by writing the overall results to several worksheets within the planning module at the end of each replication. This format is very easy to read and manipulate since the test bed records a standard set of measures. As well, most of the experimental input values are recorded for reference. At present approximately 400 values are being recorded for each replication, with about 100 of these specifying the experimental inputs. The output measures allowing work flow and delivery performance to be fully diagnosed include counter, tally and time-dependent statistics.

Table 3 provides some summary statistics for the example discussed in Figures 2, 3 and 4 and Tables 1 and 2. These results were generated using transit time CV's of 0.10, part processing time CV's of 0.00 and setup time CV's of 0.30. In addition, the MTTF for all machines was assumed to be 1000 hours and the MTTR was 10 hours. The earliest lot due date (ELDD) dispatch rule was used for priority selection at all capacity-constrained resources. Results are based on three replications of five years at each combination of settings, with one year being used for initialization.

Table 3: Performance Summary

	MRP	ROP	KBN
FG Delivery Performance			
Mean Lateness (hr.)	-9.97	-10.00	-10.06
Mean Tardiness (hr.)	.014	.028	.021
Proportion Tardy	.049	.053	.052
Transit Inventory Counts			
RM in Transit	3857	3858	3855
WIP in Transit	2418	2423	2418
FG in Transit	1749	1749	1751
Stationary Inventory Counts			
WIP in Machine Queues	1751	2247	2139
WIP in Lots at Machine	1694	1695	1696
WIP Completed	3433	3452	3464
FG Completed	835	836	841
Utilizations			
Resource R3	.912	.913	.914
Resource R4	.894	.896	.898
Resource R5	.875	.876	.875
Resource R6	.930	.929	.928

The results in Table 3 are not meant to indicate a good or poor scenario with respect to production planning but rather the nature of the outputs that may be of interest. Further outputs could be provided to indicate due date performance within the shop or details of inventory distribution throughout the system.

Many types of analysis can be done to compare different planning and control systems. A sample plot of comparisons between MRP/DRP, reorder point and Kanban performance is given in Figure 6. In this set of experiments the effect of increasing transit times is illustrated. The lower points on each of the three solid lines is the base case, presented in Table 3. The middle points show the effect of increasing all expected transit times by 10%, while the top points show the effect of increasing the times by 20%.
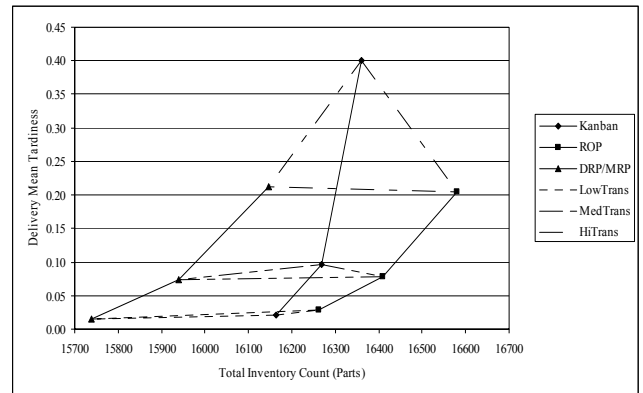

Figure 6: Tardiness versus Inventory Comparisons

Results for each set of transit times are shown connected by a dashed line. A positive slope between any two connected points shows that the planning system represented by the lower point dominates, since both inventory and mean tardiness is lower. A negative slope indicates the best system depends on the relative cost of inventory versus mean tardiness. Clearly, MRP/DRP performs best in this example. However, the choice between a reorder point and Kanban system depends on the desired tradeoff between inventory and delivery performance. The inventory in a Kanban system will not increase greatly but delivery performance will deteriorate very rapidly as transit times increase. The reorder point system will incur greater inventory but less rapid increases in tardiness, due to its ability to include backorders in replenishment decisions.

Transient performance may be of interest as well. Graphs of transient states may be created within the worksheets. Figure 7 shows one example where the aggregate finished goods inventory for P1, P2 and P7 at the distribution warehouses is shown as a function of time.
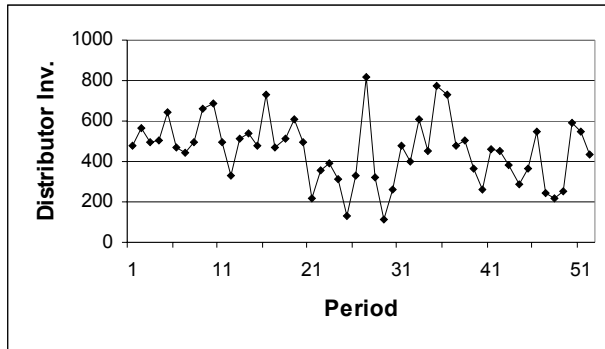
Figure 7: Transient FG Inventory at Distributors

For most research studies, an experimental design requiring many replications is used. In the case of multiple replications taking place under the control of a VBA macro, the summary results for each replication are written sequentially to different rows of the output worksheets.

8   DISCUSSION AND CONCLUSIONS

The test bed described in this paper has proved to meet the objective of being simple, transparent and flexible. It has already proved valuable in three types of research. First, it has supported obtaining insights into the behavior of both production and supply chain environments. Second, it has allowed structured comparison of different planning and control strategies. Third, it is proving valuable in developing algorithms for automatically updating tactical parameters in MRP systems. An additional opportunity exists to use it for educational and training purposes.

The test bed was intentionally designed to work with small problems and therefore is not intended to model real factories or supply chains. Many of the features could be incorporated into a large scale test bed. However, computational and communication efficiencies then become significant considerations. The use of database tools and alternative architectures could make this feasible.

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