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MODELING COMPUTER ASSEMBLY OPERATIONS FOR SUPPLY CHAIN INTEGRATION

Sanjay Jain

Center for High Performance Manufacturing
Virginia Polytechnic Institute and State University
206 N. Washington Street, Suite 400
Alexandria, VA 22314, U.S.A.

Ngai Fong Choong

Suite 301, Block 5, Windsor Court
2290, Hong Qiao Road
Shanghai 200336
PEOPLE'S REPUBLIC OF CHINA

William Lee

Singapore Institute of Manufacturing Technology
71 Nanyang Drive
Singapore 638075, SINGAPORE

ABSTRACT

Factory operations have been modeled for years to understand the relationship between the different design and policy factors and the performance measures of interest. The increasing awareness of the need to manage factories as a link in the supply chain places a corresponding requirement for an enhanced approach for factory modeling. This paper describes the modeling of a computer assembly factory for supply chain integration by including aspects of inbound and outbound logistics and relevant business processes. Lessons are drawn based on the experience.

1 INTRODUCTION

In the current world of global manufacturing, it is no longer a manufacturer competing against other manufacturers. A manufacturer can become highly efficient within its own four walls of manufacturing, but that does not guarantee a good performance in the market or even its survival. It has to ensure that its suppliers are efficient, both in cost and in the delivery of components to its logistics providers. It has to ensure that its logistics providers are able to sustain the right level of responsiveness at a competitive cost. It has to ensure that its products are efficiently carried on to its direct customers and then on through the successive stages until it reaches the end user customers. Indeed the manufacturer, the suppliers, the logistics providers have to jointly work together to get the products to the end-user customer efficiently and cost effectively. They have to integrate together as a supply chain and compete against the other supply chains providing competitive products.

Progressive manufacturers have been using discrete event simulation modeling for supporting the design, analysis and operation of factory operations for a long time. Simulation modeling has proved valuable as a test bed for evaluating alternate designs and policies under widely different environments. To compete effectively, companies had realized several years ago that the use of simulation modeling was required for supporting any large new development or enhancement of the manufacturing facilities. They utilized simulation to iteratively develop and verify that proposed systems and policies will help them achieve their business objectives. It was used to determine that their manufacturing systems can deliver the responsiveness at the costs that they need to compete.

With the competitive frontier now moving to supply chain integration, the manufacturers need to ensure that their operations integrate well into the supply chains. Simulation can be effectively used to model supply chains. Jain et al (1999) report on use of simulation for studying semiconductor manufacturing supply chains. Some industry applications of supply chain simulation have been reported (see for examples, Chatfield, Harrison and Haya 2001, and Parsons and Siprelle 2000). It is noted that most of the current applications are at a high level, intended to determine parameters that help achieve the overall supply chain performance goals. These could include the determination of the inventory levels at various stages in the supply chain to meet a desired service level, or the verification of the design of new business processes and systems for the supply chain and their ability to help achieve the targets of key performance measures (Jain et al 2001b). The high level supply chain simulations have benefited the users significantly. The benefits can be appreciably increased through the use of simulation at more detailed levels. Lendermann, Gan and McGinnis (2001) stress the need for high-fidelity simulation for fast optimization of planning and execution of supply chains and propose a framework to meet this need.

While a few applications of supply chain simulation have been reported, our experience indicates that such use is still in infancy. It is believed that there are a few major roadblocks stopping wider use of supply chain simulation. Many companies have understood the need to integrate themselves in supply chains, but the implementation has happened more through tighter integration with their logistics providers. Where multiple stages have been integrated successfully, usually a large organization controlled multiple stages of the supply chain (see for example, Lee and Billington 1995). There has been no reported case of independent companies in an end-to-end supply chain that have come together for an integration or simulation effort. Usually an independent company supplies its products to competing customers, and it is perhaps not in its best interests to get into a close supply chain partnership with any one of its customers. Also, smaller companies that are participants in supply chains, may not have had the experience or the expertise to utilize simulation.

There is a need for industry to go through the steps to achieve end-to-end supply chain simulation. The companies need to first ensure that their manufacturing facilities are integrated well with the logistics operations, enabling them to serve as an integrated link in the supply chain. They need to ensure that the business processes controlling the information flows are integrated well with the manufacturing and the logistics operations. Simulation can be effectively used to explore options for integration between the logistics, manufacturing and business processes and prove the importance of integration in determining the overall performance.

This paper describes a project that was targeted to help a computer assembly operation improve their competitiveness through better integration of the factory, the logistics operations and the business processes driving these operations. The integrated operations were simulated using virtual factory technologies comprising of innovative applications of discrete event simulation technologies to model major sub-systems. Using these technology developments, the factory management is able to evaluate the performance of alternate modes of operations and policies. The technologies have been developed with the intent of use at other manufacturing sites of the computer manufacturer.

2 BACKGROUND

The simulation model for modeling the operations for supply chain integration has been developed using the virtual factory modeling approach. It has the features that provide it the flexibility of application across the planning and execution stages. Its scope can be described broadly with respect to the Supply Chain Operations Reference (SCOR) model developed by the Supply Chain Council in a cross industry effort (Supply Chain Council 2001). This section provides brief information on the virtual factory modeling approach and its scope in the context of the SCOR model.

2.1 Virtual Factory Modeling Approach

Supply chain management involves managing the flow of material, information and money. Effective simulation of a supply chain requires modeling of the major flows, in particular, material and information flow. These flows need to be modeled through each of the stages in the supply chain. At a manufacturing stage, the material flow process should be modeled with the associated supporting information flows through the business and communication processes.

Virtual factory modeling is an approach for validating all major aspects of manufacturing system design and operation, and in particular, validating the integration of the major sub-systems of a manufacturing system (Jain et al 2001a). A virtual factory can support the manufacturing system development process from the detailed design stage through installation to the operation stage. A virtual factory is an integrated simulation model of the major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability. It allows mimicking the real life operations of the factory. Realistic 3D visualization of a factory can be built for decision-makers to understand, explore and experiment with the virtual factory.

The virtual factory is proposed to be an integrated model itself, with its sub-models representing the major sub-systems in the factory. It goes beyond the typical modeling of one sub-system at a time, such as, the manufacturing model, the business process model and/or the communication network model developed individually and in isolation. In real life, the factory performance is a result of the functioning of the whole system and not just the capacities and policies on the production floor. The performance gets affected by related business processes, external and internal logistics, communication network performance, etc. With advancements in computing technology it is feasible to create a virtual factory that models the major aspects of the factory in an integrated way as shown in Figure 1. The virtual factory will represent the real life factory more closely and will lead to more accurate predictions of the factory performance under different configurations and policies. An integrated model will enable rapid development of a manufacturing system by allowing early identification of the integration problems.

The virtual factory concept can be extended to virtual logistics, comprising of integrated models of logistics operations and associated business processes. Similar to the virtual factory, virtual logistics modeling will allow the study of a logistics system as a whole and exploit the integration of the sub-systems for better design and operation. The virtual factory and virtual logistics models can be integrated together to form virtual supply chain simulations as shown in Figure 2. Taylor et al (2001) describe an environment for integrating simulation models of factories to create a distributed simulation model of the supply chain. The virtual supply chain simulations will offer powerful capabilities for supply chain design, operation and event management.

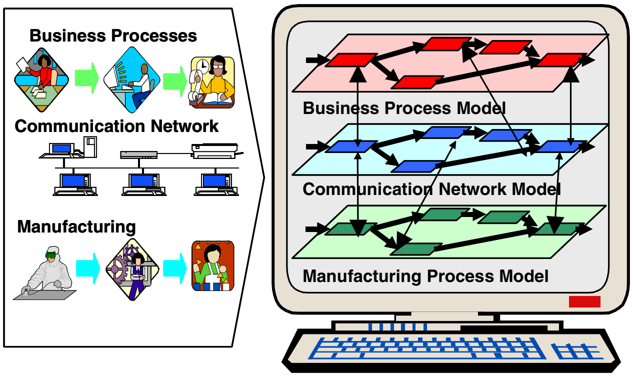

Figure 1: Virtual Factory as an Integrated Model of Real Factory

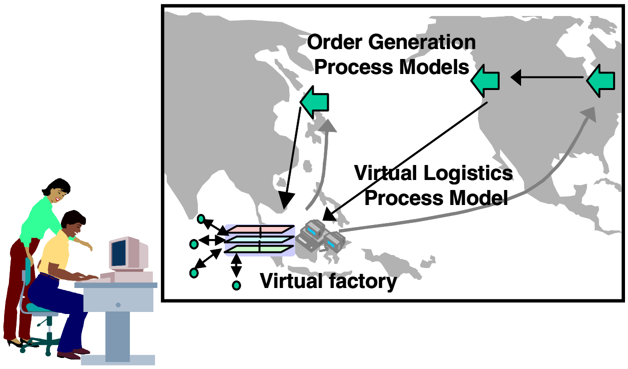

Figure 2: Virtual Supply Chain Simulation Using Virtual Factory and Virtual Logistics Models

The work with the computer assembly operations included modeling the factory operations using the virtual factory approach. With the focus on supply chain integration of the operations, the scope included modeling of inbound and outbound logistics. The modeling of business processes captured the information flow critical to supply chain integration. The communication network was not modeled in this application as it was not seen as a constraint by the operations personnel.

2.2 Scope of Simulation Effort and SCOR Model

Supply chain modeling has been recognized as a cross industry need and a reference model has been developed by the Supply Chain Council composed of a number of industry representatives. The SCOR model classifies the supply chain activities in five major processes (Supply Chain Council 2001):

- PLAN – demand/supply planning and management.
- SOURCE – Sourcing stocked, make-to-order and engineer-to-order products.
- MAKE – Make-to-stock, make-to-order and engineer-to-order production execution.
- DELIVER – Order, warehouse, transportation and installation for stocked, make-to-order and engineer-to-order products.
- RETURN – Return of raw materials (to supplier) and receipt of return of finished goods (from customers) including defective products, MRO products and excess products.

Traditionally, the manufacturing simulation models used in the industry addressed the core of the MAKE process. These models have been useful in determining issues such as manufacturing capacities, configurations, scheduling policies, etc., all with the focus on the performance of the manufacturing system. With the need to integrate the factory into its encompassing supply chain, the models need to expand step by step to the whole supply chain. As a first step, at the detailed level, the manufacturing models need to be enhanced to include the interfaces to logistics activities, i.e., intersection of SOURCE, MAKE and DELIVER processes as shown in Figure 3.

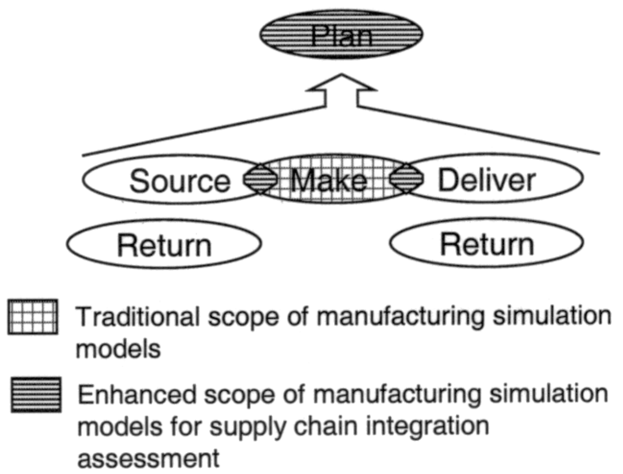

Figure 3: Scope of Effort with Respect to the SCOR Model

The enhancement will provide a capability for developing operational policies and procedures encompassing the complete MAKE process including the interfaces to SOURCE and DELIVER and thus allow better integration of a factory into the supply chain. The other important aspect is to model the PLAN activities that integrate a manufacturing operation into its supply chain. These include activities such as demand fulfillment planning, material delivery planning, and scheduling. The scope of the simulation model in this effort includes the traditional core MAKE activity and the enhancements that enable it to assess the supply chain integration.

3 MODEL DESCRIPTION

The overall goal of the computer manufacturer was to improve their competitiveness through better utilization of the location of its operations as a logistics hub for the region and the associated logistics infrastructure. To address this goal, this project established the objective of building a simulator that was capable of modeling computer assembly operations, logistics operations, and associated business processes. The users required the capability to drive the discrete event simulation model with different inputs to model production schedules and order arrivals representing different supply chain operation philosophies including Assemble-to-Order mode (ATO), Build-to-Order mode (BTO) and Configure-to-Order mode (CTO). With emphasis on improving the factory's integration in the supply chain, the model aimed at providing the relevant performance measures including: resource utilization, cycle time, inventory and cost.

The simulator enables evaluation and comparison of the different supply chain operation philosophies with the current operation mode using a virtual factory and logistics model of the operations. The model provides the following:

- Predictability of the performance under the current and proposed modes of operations.
- Determination of the impact of operation philosophy on the manufacturing operation performance.
- Determination of the impact of operation philosophy on the inbound logistics.
- Determination of the impact of operation philosophy on the outbound logistics.
- Flexibility of use for strategic planning and operational support.

The virtual factory simulator for the computer assembly operation included:

- Development of sub-system models for manufacturing, and the associated business processes. The integration of the order processing business process and manufacturing schedule was approximated due to the proprietary and complex scheduling engine in use at the operation.
- Development of sub-system models for the inbound and outbound logistics and the associated business processes.
- Integration of the manufacturing simulation model, logistics simulation models and their respective business process simulation models.

The development was carried out in following major phases:

1. Detailed Design – Created functional specification and detailed design.
2. Manufacturing process – Built the base virtual factory model including sub-system model of the manufacturing process and the major business processes.
3. Inbound logistics – Built the sub-system model of the inbound logistics and integrated it into the virtual factory model.
4. Outbound logistics – Built the sub-system model of the outbound logistics and integrated it into the virtual factory model.

The following sub-sections describe the virtual factory simulator, the sub-models of the computer assembly operation virtual factory model, and the validation procedures used.

3.1 Virtual Factory Simulator Overview

The simulator offers support for different stages of manufacturing system life cycle. It can be used in two different modes of execution, namely the operational simulation and the strategic planning simulation. Applications of the operational simulation are daily production schedule verification, predictions of production cycle time and throughput. The information can be used to plan manpower and capacity requirements. This type of execution requires input of actual production plan and material delivery schedule to drive the simulation.

The second mode of execution is intended for strategic planning of the future, the immediate next quarter or several quarters in the future. Many what-if analyses can be carried out, such as predicting the capacity required in the material storage, production and shipping areas for meeting the forecasted demand trends or the planned introduction of new product families. The only information required for this mode of execution is the forecast of customer demands while other input data required to drive the simulation such as production plans and material delivery schedules are generated by corresponding business process models described in section 3.3.

The simulator also provides flexibility to update the simulation models quickly when major changes occur in a factory. With its data driven structure, it can also be used for modeling different computer assembly operation factories. Data used by the simulator to generate the simulation model are input via a set of text files. For operational simulation use, information for driving the simulation model may be input by the user either manually or through a download from the company information systems. For strategic planning simulation use, information can be generated using an event generator and historical data. Figure 4 shows the input and outputs of the virtual factory simulator.

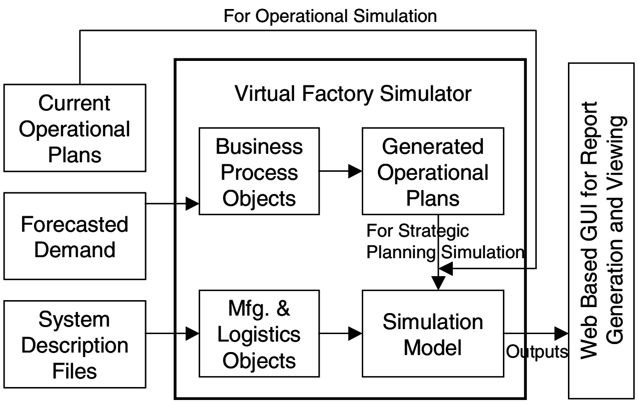

Figure 4: Overview of the Virtual Factory Simulator for the Computer Assembly Operations

3.2 Manufacturing Sub-system Model

The manufacturing sub-system model included the assembly, test, rework, burn-in, packaging and a simple scheduling system for modeling the information flow and the relevant business process. The sub-model includes the product flow from the first workstation on the assembly line to the final packing station. The components were assumed to be available as needed on the assembly lines. The simulation models of the sub-system and components were developed using eM-PLANT (Heinicke and Hickman 2000), an object oriented tool that allows hierarchical and modular structure. The models and sub-models can be developed as independent objects that can be assembled together in different arrangements representing different manufacturing system configurations. For manufacturing sub-system, the following objects were developed:

1. Assembly stations
2. Test stations
3. Rework stations
4. Conveyor modules
5. Material handling logic
6. Burn-in lanes
7. Final packaging stations
8. Human resource
9. Shift pattern

These are then assembled dynamically in the model based on the configuration defined in the data input file. This approach allows simulation model to dynamically track the changes in manufacturing system configuration.

3.3 Major Business Process Models

Modeling of a manufacturing operation with the objective of evaluating its integration in a supply chain necessitates modeling of information flows through the major business processes. Objects have been built to model the following business processes:

1. Customer order processing – To model the processing of customer orders. It also includes the generation of future customer order arrivals based on the given customer demand forecast and the past customer order arrivals data. The generation capability is used for strategic planning simulation. The output of this process is the input to the scheduling process.
2. Scheduling process – To sequence the daily customer orders into production plans. This object is executed only in the strategic planning simulation mode. The logic of this process approximates the company's scheduling process that generates the daily production schedule to drive the manufacturing system simulation. In modeling operational simulation execution, a detailed file generated by the scheduling software used by the company can be fed into the model.
3. Material requirements plan process – To plan the weekly material requirements using the inputs on customer demand and material purchasing. This object is executed only in the strategic planning simulation mode. The logic of this process approximates the material requirements planning (MRP) logic. In the operational simulation execution mode, a detailed material delivery schedule is expected from the material purchasing system of the company.
4. Demand fulfillment process – To determine whether to use the inventories that are staged in the factory or warehouses at strategic locations or build fresh products to fulfill the requirements of a customer order.

3.4 Inbound Logistics Sub-System Models

The inbound logistics sub-system included the delivery of materials to the goods inward dock, internal material storage, material handling, material staging, material pull to production line, material return to storage and associated information flows. Similar to the manufacturing sub-system, the inbound logistics sub-system model was developed using the object oriented approach. A number of objects were developed for modeling the inbound logistics sub-systems, including:

1. Component
2. Storage areas

3. ASRS
4. Forklift
5. Material flow logic

Again, these can be assembled together to define the specific inbound logistics system configuration using data files.

3.5 Outbound Logistics Sub-System Model

The outbound logistics sub-system model includes the movement of products from the manufacturing facility to the end customer and associated information flows. The objects for modeling outbound logistics activities include:

1. Land transport
2. Freight resources
3. Customs
4. Holidays, actual operating hours and time zone
5. Warehouse operations
6. Inventories

Again, these can be assembled together to define the specific outbound logistics system configuration using data files.

3.6 Model Validation

The model was validated after completion of each sub-system model. A number of critical measures were captured from the model runs and compared against the corresponding measures from real factory. For example, after completion of inbound logistics sub-system model, the following measures were compared:

- Quantity and time of material deliveries into ASRS.
- Quantity and time of material withdrawal from ASRS.
- Cycle times to replenish material to assembly lines.
- Cycle times from first station on assembly lines to packing.

While some of the measures matched quite well, some did not. For the measures that did not match, reasons for discrepancies were identified. The investigations identified either some unusual circumstances in real factory that were not included in the model or some errors in the calculation of measures for the real factory. In most cases, removal of the products affected by unusual circumstances from the model and their exclusion from real life measures led to good agreement between the two. Correction of errors in calculations of real life measures helped achieve agreement in other cases. Finally, in a few cases the reasons for remaining differences were understood and agreed upon as the identifiable causes for the gaps by the operation personnel.

The simulator was also used to verify the value of modeling the inbound logistics for its impact on accuracy of the results. The actual cycle time from the real factory were compared to that of the model with (a) only the manufacturing sub-system model and (b) with the model with integrated manufacturing and inbound logistics sub-models. The results presented in Figure 5 show a better agreement between the actual cycle time and the model with the integrated manufacturing and inbound logistics sub-models. The model that included the manufacturing sub-system only provided low cycle-times as the product flow was not constrained by the material replenishment activities.

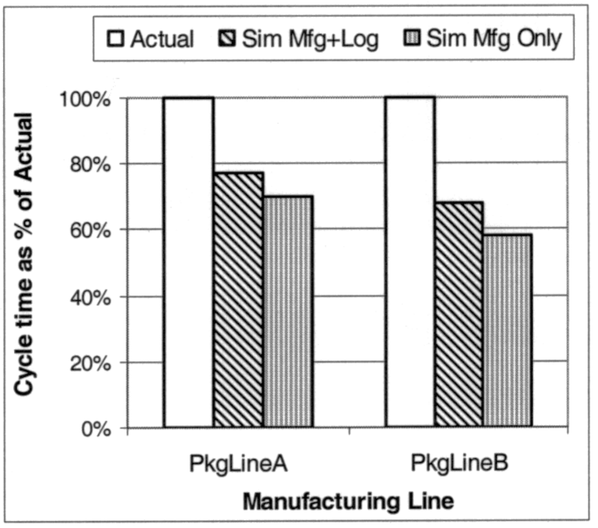

Figure 5: Increased Accuracy of Cycle Time Using the Integrated Model of Manufacturing and Logistics Sub-systems

4 APPLICATION OF THE VIRTUAL FACTORY MODEL FOR SUPPLY CHAIN ISSUES

The virtual factory model can be used for supporting a large number of supply chain decisions ranging from the selection of incoming material ordering policies to outbound shipment scheduling. This section describes an application of the model for determining parameters controlling the flow of material from suppliers to the computer assembler.

The computer assembler is a progressive organization using leading industry practices including vendor managed inventory for a majority of components. Vendors deliver the components to the ASRS at the factory and maintain its ownership until the assembler withdraws the components from the ASRS into an staging area near the assembly lines. It is in the interest of the computer assembler to withdraw only as much material as needed and thus take the ownership of the components for shortest possible time. However, the assembler has to withdraw the inventory in standard pack sizes from the ASRS. Also, frequent withdrawals of smaller amounts requires a higher workload on the material handling personnel. The computer assembler thus has to tradeoff the cost of owning the inventory, the space requirement on factory floor and the requirement of material handling manpower. The objective is to reduce the inventory in the staging area and assembly line while not constraining the cycle time performance.

The computer assembler follows a Reorder Level (ROL)/ Reorder Quantity (ROQ) policy for the replenishing material for the assembly lines. The model was used for the following experiments to determine the involved tradeoffs:

1. Base – with current levels of ROQ and ROL.
2. ROQ/2 – with ROQ reduced to half its current level and ROL maintained at current level.
3. ROL/2 – with ROL reduced to half its current level and ROQ maintained at current level.
4. ROQ/2-ROL/2 – with both ROQ and ROL reduced to half their current levels.

The results of the experiments are shown in Figure 6. It can be seen that reducing the ROQ by half leads to 16% increase in ASRS inventory indicating a corresponding reduction in the inventory owned by the computer assembler. On the down side, the ROQ reduction requires frequent replenishments leading to a 48% increase in manpower utilization.

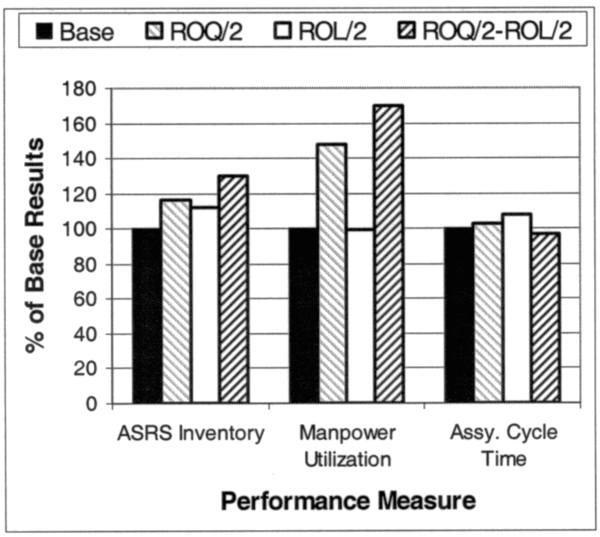

Figure 6: Results of Experiments with ROL and ROQ for Component Replenishments to the Computer Assembly Line

Reducing ROL by half leads to a 12% increase in ASRS inventory (reduction in computer assembler's owned inventory) with no impact on manpower utilization but an 8% increase in cycle time. Essentially, with a reduction in ROL, the line experiences component shortages and delays.

Halving both the ROQ and ROL results in a 30% higher inventory in the ASRS. However, this comes at the cost of a 70% increase in the manpower utilization compared to the current levels due to more frequent replenishments. The smaller replenishments are executed within the time allowed by a reduced ROL. Hence there are no shortages and no significant impact on the assembly line cycle time.

The above results from the model can be used together with the proprietary cost information to determine the ROQ and ROL levels and thus the velocity of material movements to the assembly lines. The model can thus support establishing the long term line replenishment policies. The model can also be used in the short term for determining the ROQ and ROL given the number of material handlers available on a given day such that the cycle time performance is not affected.

The virtual factory model can be used for supporting long term and short term decisions as shown by the above application example. The computer assembler has analyzed several decisions using the capability.

5 LESSONS LEARNED

The simulation model was developed with the goal of being a virtual factory, an image of the real factory that allows study of a wide range of issues. While the availability of a virtual factory provides a very powerful tool, it requires people with the ability to comprehend the possibilities, an understanding of overall vision and the capability to relate the vision to the tactical issues. Real factories are complex and a model close to reality is nearly as complex. It was found that some of the personnel of the company that provided the data did not appreciate the power of the tool. The model was used for studying some tactical issues, but its strength in studying the supply chain integration issues is yet to be fully exploited. The model has been delivered to the company recently and it is hoped that the senior level sponsors of the project will lead the way in harnessing the power of the virtual factory concept.

The effort of building and maintaining a virtual factory is substantial. It is a data intensive application and requires a large effort for data collection and interfacing. The virtual factory concept is based on the scenario of a developed information infrastructure that allows easy access to organized data for populating the model. The partner company's infrastructure was in a fluid state and that consequently placed enormous demands on the team members for data collection and interfacing.

The virtual factory concept is based on the notion of being close to reality. However, a model is after all a model of reality, and it will not be a worthwhile effort to include representations of all possible rare occurrences. Unfortunately, the rare occurrences do prevent the model results from matching the actual results, and this can lead to questioning of the validation results by people who do not appreciate the nature of the modeling technique. Training sessions helped alleviate the problem to certain extent.

It is imperative to maintain strong support of a management sponsor. The project was initiated with such support, but rapid changes in the business situation caused diversion of sponsor's attention. It is hoped that better business environment will allow more support of the project and allow the sponsor to achieve the original goals of improving supply chain integration with the support of the virtual factory and logistics model.

6 CONCLUSION

This paper described the concept, development and use of simulation for studying a computer assembly operation with respect to supply chain integration. The model was developed using the virtual factory approach that incorporated simulating the flow of material integrated with the flow of information through business processes. Inbound and outbound logistics activities were included to enable the evaluation of the operation as a link in the supply chain rather than a standalone manufacturing facility. Individual plant and logistics models developed using these guidelines can be integrated together to form high fidelity models of the end-to-end supply chain. These virtual supply chains can be used to support a supply chain through out its life cycle including design, planning and execution.

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REFERENCES

Chatfield, D., T. P. Harrison and J. C. Hayya 2001. SISCO: A supply chain simulation tool utilizing Silk™ and XML. In *Proceedings of the 2001 Winter Simulation Conference*, ed. B.A. Peters, J.S. Smith, D.J. Medeiros, and M.W. Rohrer, 614-622. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Heinicke, M. U. and A. Hickman. 2000. Eliminate bottlenecks with integrated analysis tools in eM-PLANT. In *Proceedings of the 2000 Winter Simulation Conference*, ed. J. A. Joines, R. R. Barton, K. Kang, and P. A. Fishwick, 229-231. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Jain, S., C.C. Lim, B.P. Gan and Y.H. Low 1999. Criticality of detailed modeling in semiconductor supply chain simulation. In *Proceedings of the 1999 Winter Simulation Conference*, ed. P. A. Farrington, H. B. Nembhard, D. T. Sturrock, and G. W. Evans, 888-896. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Jain, S., N.F. Choong, K.M. Aye and M. Luo. 2001a. Virtual factory: an integrated approach to manufacturing systems modeling. *International Journal of Operations and Production Management*, 21(5/6): 594-608.

Jain, S., E.C. Ervin, A.P. Lathrop, R.W. Workman and L.M. Collins. 2001b. Analyzing the supply chain for a large logistics operation using simulation. In *Proceedings of the 2001 Winter Simulation Conference*, ed. B.A. Peters, J.S. Smith, D.J. Medeiros, and M.W. Rohrer, 1123-1128. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers..

Lee, H. L. and C. Billington. 1995. Evolution of supply chain management models and practice at Hewlett-Packard company. *Interfaces*, 25 (5): 42-63.

Lendermann, P., B.P. Gan and L. McGinnis. 2001. Distributed simulation with incorporated APS procedures for high-fidelity supply chain optimization. In *Proceedings of the 2001 Winter Simulation Conference*, ed. B.A. Peters, J.S. Smith, D.J. Medeiros, and M.W. Rohrer, 1138-1145. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers..

Parsons, D. J., and A. J. Siprelle. 2000. A supply chain case study of a food manufacturing merger. In *Proceedings of the 2000 Winter Simulation Conference*, ed. J. A. Joines, R. R. Barton, K. Kang, and P. A. Fishwick, 1090-1094. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

Supply Chain Council 2001, Supply-chain operations reference-model overview of SCOR version 5.0. Available online via `http://www.supply-chain.org`, accessed March 8, 2002.

Taylor, S. J. E., R. Sudra, T. Janahan , G. Tan and J. Ladbrook. 2001. Towards COTS distributed simulation using GRIDS. In *Proceedings of the 2001 Winter Simulation Conference*, ed. B.A. Peters, J.S. Smith, D.J. Medeiros, and M.W. Rohrer, 1372-1379. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

AUTHOR BIOGRAPHIES

SANJAY JAIN is a Research Associate Professor with the Grado Industrial & Systems Engineering Department at Virginia Tech. He is working with the Center for High Performance Manufacturing, a state funded entity with the objective of improving the performance of manufacturers in Virginia. The center has participation from a number of departments across several leading universities in Virginia. Prior to joining Virginia Tech, he accumulated several years of industrial R&D and consulting experience working at Accenture in Reston, VA, USA, Singapore Institute of Manufacturing Technology, Singapore and General Motors North American Operations Technical Center in Warren, MI, USA. His research interests are in the area of using modeling and analysis techniques in development and operation of supply chains and manufacturing systems. He received a Bachelors of Engineering from University of Roorkee, India in 1982, a Post Graduate Diploma from National Institute for Training in Industrial Engineering, Bombay, India in 1984, and a PhD in Engineering Science from Rensselaer Polytechnic Institute, Troy, New York in 1988. He is a member of Institute of Industrial Engineers, APICS- The Educational Society for Resource Management and of the editorial board of *International Journal of Industrial Engineering*. His email and web addresses are <sanjay.jain@vt.edu> and <www.eng.vt.edu/chpm/Faculty/Dr_Jain.htm>.

NGAI FONG CHOONG is currently taking a break from her professional career for family reasons. She was most recently working as a Research Fellow with the Manufacturing Planning and Scheduling Group at Singapore Institute of Manufacturing Technology (formerly Gintic Institute of Manufacturing Technology). Her current research interest is in virtual factory and logistics modeling using object-oriented technology. She received a Bachelor of Engineering (honors) degree in Mechanical and Production Engineering from National University of Singapore in 1990, and later obtained her Master of Engineering in Mechanical and Production Engineering from the same university in 1993. Prior to joining Gintic in 1996, she had more than six years of experience working as a Development Engineer in the area of Computer Integrated Manufacturing (CIM) and as a Senior Engineer in Manufacturing Simulation doing simulation studies on layouts and operations for green-field factories. She is a member of Institute of Industrial Engineers. She can be reached via e-mail at <nfchoong@yahoo.com.sg>.

WILLIAM LEE is an Associate Research Fellow with the Manufacturing Planning and Scheduling Group at Singapore Institute of Manufacturing Technology (formerly Gintic Institute of Manufacturing Technology). His current research interest is in the analysis of factory mechanics and supply chain operations using discrete event simulation modeling. He received a Bachelor of Engineering (honors) degree in Mechanical and Production Engineering from National University of Singapore in 1998, and later obtained his Master in Engineering in Mechanical and Production Engineering from the same university in 2001. He can be reached via email at <gklee@SIMTech.a-star.edu.sg>