Proceedings of the 2002 Winter Simulation Conference
E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, eds.

A FRAMEWORK FOR STANDARD MODULAR SIMULATION

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ABSTRACT

The primary reason for building manufacturing simulations is to provide support tools that aid the manufacturing decision-making process. Simulations are typically a part of a case study commissioned by manufacturing management to address a particular set of problems. The objectives of the case study determine the types of simulation models, input data, and output data that are required. Neutral model libraries and interface data standards could simplify the simulation analyst's job and significantly improve the simulation case study process. This paper describes a proposed framework for simulation standards development. The framework is comprised of four major component elements: 1) industry sector, 2) hierarchical level of the manufacturing organization, system, or process, 3) simulation case study area, and 4) manufacturing model and data types.

1 INTRODUCTION

The Manufacturing Simulation and Visualization Program at the National Institute of Standards and Technology (NIST) is focused on accelerating the development of standards for simulation model libraries and data. As a part of our program strategy, we are developing a framework for manufacturing simulation data standards. Simulation standards for models and data could help to accelerate the modeling process and reduce modeling costs.

Simulation textbooks typically recommend that a ten to twelve step process be followed in the development of simulation models. The recommended approach usually involves the following steps: (1) problem formulation, (2) setting of objectives and overall project plan, (3) model conceptualization, (4) data collection, (5) model translation into computerized format, (6) code verification, (7) model validation, (8) design of experiments to be run, (9) production runs and analysis, (10) documentation and reporting, and (11) implementation (Banks et al 1996). Unfortunately, this approach often leaves considerable work and possibly too much creative responsibility to the simulation analyst. Using this approach, the process of modeling and simulation is perhaps as much an art as it is a science. Simulations are often developed from scratch, so the skill of the individual analyst may figure significantly in the quality of the results that are obtained. There is little opportunity for the analyst to build upon the work of others since each simulation is built as a custom solution to a uniquely defined problem. Input data from other manufacturing software applications is not often in the format required for simulation, so data must often be abstracted, reformatted, and/or translated. Furthermore, pressure from manufacturing management to obtain quick results may have a negative impact on the performance of the simulation analyst and the quality of results obtained.

How could the manufacturing modeling and simulation process be improved? Today simulation analysts typically code their models from scratch and build custom data translators to import required data. A better solution would be to simplify the process through modularization, i.e., the creation of re-usable simulation model building blocks. Simulations would be constructed by assembling or configuring, modular building blocks. Similarly, neutral interface formats for transferring data between simulation and other manufacturing applications are also needed. Data would ultimately be imported directly into the simulators without translation using standard data input formats.

Simulation software vendors often provide their customers with a small set of sample models to help them get started using their tools. These basic models are almost never sufficient to meet individual industrial needs. Unfortunately, these vendors do not appear to have either the staff resources or access to proprietary technical data that would allow them to build extensive model libraries to meet actual user needs. In some cases, simulation vendors provide consulting services where they build custom models with the technical assistance of their clients. Unfortunately, these models usually become the proprietary property of the client and are never made available to other customers.

The development of neutral, vendor-independent data formats for storing simulation models could greatly improve the accessibility of simulation technology to industry by enabling the development of reusable models. Such neutral, simulation-model formats would enable the development of reusable models by individual companies, simulation vendors, equipment and resource manufacturers, consultants, and service providers. Model libraries could be marketed as stand-alone products or distributed as shareware.

Neutral model formats would help enlarge the market for simulation models and make their development a more viable business enterprise. Standard formats for models would make it possible for simulation developers to sell model libraries much the same way clip art libraries are sold for graphics software packages today. Simulation model libraries could be expected to increase the value of manufacturing simulators for industrial users much the same way graphics libraries increase the value of photo processing, paint, and graphics illustration software packages to their users.

In the absence of standard formats, the development of simulation model libraries is probably not a viable independent business proposition. Why? Let's say a consultant that specialized in simulating material handling systems wanted to sell a library of models on the international market. Currently, the consultant would have to code the models in perhaps a dozen different formats to cover as many manufacturing simulators as possible. Furthermore, the consultant would probably have to provide multiple language front-ends to be successful internationally. As each of the target simulators evolved, the model library would require constant revisions to maintain compatibility with each vendor's product. The consultant would probably have to obtain licenses and hire staff that have expertise on each simulator. One can easily see how costly and risky this business proposition becomes. If the consultant only had to develop one set of the material handling system models that could be imported into all of the simulators, the viability of his or her business improves considerably.

How can we determine what simulation standards need to be developed? It is the authors' contention that the same basic analytical and model development processes are being repeated over and over again by simulation analysts around the world. Although a simulation analyst may think that each modeling problem is unique, we believe that considerable commonality can be found in each problem's component elements. If the different types of modeling problems addressed by simulation analysts could be classified according to a uniform scheme, commonalities could be exploited.

In his regular column in Industrial Engineering Solutions magazine Jerry Banks suggested that a taxonomy be created that could be used by simulation software vendors to identify the types of modeling problems that their tools could be used to solve (Banks 1999). Although our proposed simulation framework could be used to classify software products, our primary objective is to provide a scheme for the identification of the modules and data required to address various classes of simulation problems.

What factors might be considered in creating a uniform framework for classifying the various aspects of manufacturing simulation problems? The major aspects of a simulation modeling problem are:

- the industrial market sector
- the hierarchical level of the manufacturing organization, system, or process
- the simulation case study
- model elements, input, and output data

The next sections briefly introduce each of these aspects of the proposed framework.

2 INDUSTRIAL MARKET SECTORS

Perhaps the most significant discriminating factor to be considered in developing a classification system for manufacturing simulation is industry market sector. The sector identifies the end-products that are to be manufactured. The hierarchy of organizations, systems, and processes that are often unique to individual manufacturing sectors. Thus, the models and data required for a simulation case study is thus determined first by the sector and next by the manufacturing hierarchical level. By including industry sector as the first attribute, the framework will be comprehensive in that it accounts for most, if not all, types of manufacturing simulation.

An appropriate classification scheme for industry market sectors has already been developed. The North American Industry Classification System (NAICS) was developed jointly by governments of the United States, Canada, and Mexico to provide new comparability in statistics about business activity across North America, see (NAICS 2002). These codes are used by businesses and other entities in order to complete grant requests, tax returns, and other forms gathered along industry lines. It allows researchers to make better analyses and comparisons of different industries. The latest version of the code was completed in 2002 and replaces the U.S. Standard Industrial Classification (SIC) system. NAICS also provides for increased comparability with the International Standard Industrial Classification System that was developed by the United Nations.

The NAICS is based on a 6-digit code. The code prefixes 31-33 are used to denote manufacturing industries. The next level of manufacturing industry decomposition (to the third digit of the code) is listed below:

31-33 Manufacturing
- 311 Food manufacturing
- 312 Beverage and tobacco product manufacturing

313 Textile mills
314 Textile product mills
315 Apparel manufacturing
316 Leather and allied product manufacturing
321 Wood product manufacturing
322 Paper manufacturing
323 Printing and related support activities
324 Petroleum and coal products manufacturing
325 Chemical manufacturing
326 Plastics and rubber products manufacturing
327 Nonmetallic mineral product manufacturing
331 Primary metal manufacturing
332 Fabricated metal product manufacturing
333 Machinery manufacturing
334 Computer and electronic product manufacturing
335 Electrical equipment, appliance, and component manufacturing
336 Transportation equipment manufacturing
337 Furniture and related product manufacturing
339 Miscellaneous manufacturing

An example of the lowest level of detail found in the classification scheme is machine tool manufacturing (metal cutting types). It has the 6-digit code 333512 within the machinery manufacturing (333) and the metalworking machinery manufacturing (3335) sectors. The full listing of all of the areas within the manufacturing sector beyond the scope of this paper.

3 HIERARCHICAL MODELING LEVELS

The second attribute of the proposed simulation classification framework is the hierarchical modeling level of the organization, system, or process. Various hierarchical and activity decompositions for manufacturing have been proposed by researchers over the years. Activity decompositions differ from the hierarchies in that only the activities and/or functions may be identified at each level of the structure. Different industries have different numbers of levels, grouping of elements, and naming conventions in their decompositions. Discussion of some typical decompositions may be found in the following publications: manufacturing in general (Harrington 1984, Rembold et al 1993, Scheer 1998), small batch manufacturing (McLean et al 1983), computer-integrated manufacturing (CIM) enterprise (Appleton 1985, Compton 1988, ESPRIT 1989, Williams 1989), automated manufacturing (Jones and McLean 1986), manufacturing systems environment (Barkmeyer et al 1997), shipbuilding (Storch et al 1995), semiconductor manufacturing (Eng 1996). Since no particular decomposition is necessarily right or wrong for all industries, the simulation hierarchical classification scheme must account for variations in hierarchies across industries. The proposed framework contains a meta-hierarchy that can be used to relate the various hierarchies and models used in different market sectors.

In our scheme, we have identified the following meta-levels. At any particular level in our meta-hierarchy, a particular industry may have zero or more levels in its industry-specific hierarchy. Since there is no universal agreement between the different manufacturing sectors, the same level names may be used by different industries at the same or different meta-levels.

What are the significant meta-levels as far as simulation is concerned? It is possible that simulation analysts may eventually want to simulate a number of manufacturing levels. The rationale for partitioning the manufacturing meta-hierarchy is that there are significant differences in the nature of the models and data required to simulate each level. The simulation meta-hierarchy from highest to lowest level is:

- economy
- market
- supply chain
- enterprise
- facility
- department
- line, area, or cell
- station
- equipment
- device
- process

Each hierarchical modeling level is briefly introduced below. Elements at each level in the hierarchy may cross the boundaries of elements at the next higher level.

Economy – The highest level of the framework potentially represents multiple markets in a geographical region of interest. Models of this type may include manufacturing market models as a component element. These models may typically be developed by economists or researchers at regional, state, or federal government. The economies of certain regions of the country are closely tied to specific manufacturing market sectors, for example: Detroit – automobile manufacturing, Seattle – aerospace, San Jose – semiconductor, etc. Factors in this type of model may include expected consumer behavior, cost of money, labor, materials, state of the national economy, etc. Outputs of these models may be used as inputs to develop market forecasts that ultimately translate into planned production levels, hiring plans, etc.

Market – Multiple competing and cooperating supply chains in a market sector interact to produce similar families of products. Market level models correspond to individual sectors, group of sectors, or subdivisions of sectors in the industry market sector classification scheme. Company simulation analysts may need to model market sectors for forecasting demand, prices, etc.

Supply chain – At this level, multiple enterprises work cooperatively to deliver end products. Some examples of the functional elements of a supply chain may include component part and raw material suppliers, transportation networks, distributors, warehouses, final assembly plants, and retailers. Typically, some elements of a supply chain will cross enterprise boundaries. Simulation analysts building supply chain models may interact with peer analysts in other enterprises that use different simulators for their enterprises. Complete internal information on each supply chain element may not be available to the analyst due to proprietary issues.

Enterprise – The term enterprise has a number of different meanings within industry. The enterprise level in our hierarchical model defines the boundaries of the corporation. An enterprise may be located at one or more facilities and decomposed organizationally into multiple departments. Typically a supply chain would be comprised of multiple enterprises, i.e., corporations that focus on specific types of products or services.

Facility – Facility is used to model the organizations, systems, and processes at a single site, possibly under one roof. Each facility in an enterprise may require certain departments, equipment, etc. due to the fact that it is at a unique site. Goods moving between facilities may involve significant transportation issues. Locating production operations at multiple facilities may require duplication of support operations, equipment, etc.

Department – A facility is typically composed of multiple departments, i.e., organizational units, that perform different business processes. Departments may be located at multiple facilities, i.e., cross facility boundaries. Departments may be decomposed into smaller departments. Some examples of departments might include: engineering, sales, production, finance, and procurement.

Line, area, or cell – This level is physical grouping of stations and/or equipment for the purpose of manufacturing a product, a family of products, or to perform a similar set of processes. Lines, areas, and cells may be decomposed into smaller lines, areas, or cells. Units at this level may cross multiple departmental and/or facility boundaries.

Examples of a production line would include lines to assemble power tools, appliances, and automobiles. A cell may be a group of stations that produces a family of similar parts, for example, valve bodies. An area might be a welding area where a variety of welding operations may be performed.

Station – Stations are places where work is performed by operators or robots. A station may include one or more pieces of equipment, operators, buffer storage areas, etc.

Equipment – Examples of equipment include manual and computer-controlled machine tools, robots, automatically guided vehicles, cranes, conveyors, storage and retrieval systems.

Device – Devices are typically separable component elements of equipment level systems, including various sensors and actuators. The tool magazine on a machine tool or a robot end effector are both examples of devices.

Process - The lowest level is the physical manufacturing process, for example machining, die-casting, wafer fabrication, or mechanical assembly. This is the level where the physics, mechanics, kinematics, chemistry, etc. of the particular manufacturing process is represented.

For a comprehensive taxonomy of about 300 processes used for modifying the geometry or properties of engineering materials, see (Todd et al 1994). The taxonomy does not include semiconductor wafer fabrication processes, although soldering processes are included.

4 SIMULATION CASE STUDIES

The third attribute of the framework is the simulation case study. In discussions with manufacturing managers that are unfamiliar with simulation, we are often asked questions to the effect of "Will the simulation tell us whether we should do X?" The remainder of the question, the "X," typically concerns changes in staff, equipment, job scheduling policies, etc. The common misunderstanding is that simulation will not tell you anything directly. As defined in (Banks 1998), simulation is: *"…the imitation of the operation of a real-world process or system over time. Simulation involves the generation of an artificial history of the system and the observation of that artificial history to draw inferences concerning the operational characteristics of the real system that is represented. Simulation is an indispensable problem-solving methodology for the solution of many real-world problems. Simulation is used to describe and analyze the behavior of a system, ask what-if questions about the real system, and aid in the design of real systems. Both existing and conceptual systems can be modeled with simulation."*

Simulation case studies are conducted to analyze and improve the efficiency and effectiveness of manufacturing organizations, systems, and processes. Studies are designed to solve specific problems and get answers to specific questions. Studies often model some aspect of current operations and validate the effect of some hypothetical change(s) to those operations. The performance of current and proposed systems are evaluated according to some set of metrics. If the simulation validates that sufficient improvements can be expected, then the proposed changes are implemented.

Simulation case study objectives define the reasons for performing the simulation. Some examples of study objectives might be to evaluate the best site for a new plant, create a better layout for an existing facility, determine the impact of a proposed new machine on shop production capacity, or evaluate alternative scheduling algorithms. High level study objectives can be further decomposed into individual questions that may be answered directly from simulation results. If the study objective is site selection, one question might be: Which site would result in the lowest expected overall operating costs given several different projected levels of production for a selected set of products?

With respect to the simulation framework, a number of different types of simulation studies may be associated with each meta-level in the manufacturing meta-hierarchy. A particular study may apply to several levels, but not necessarily all levels. Mapping case studies into specific levels is beyond the scope of this paper.

Individual case studies should be able to be used as modular building blocks and templates to solve more complex manufacturing problems. For example, a real manufacturing problem might involve issues of site selection and plant layout. The resulting composite simulation case study may be constructed by assembling models and data from two different case study types.

Ideally, case study areas identified in the framework should be "atomic," i.e., unique, indivisible, and non-overlapping. A rigorous analysis should be used to ensure that each case study forms a clean, basic building block. The analysis should aim to assign any objective or question to only one type of case study. A major reason for this rule is to avoid the infinite proliferation of custom-defined case studies as is currently the practice in industry today.

On the other hand, different case studies may use the same models, input, and output data. This can be demonstrated by example. Scheduling and plant layout might be two unique, non-overlapping case study areas. The same simulation output metric, e.g., system throughput, might be used as a performance metric to evaluate layout and scheduling changes.

This paper identifies an initial sampling of simulation case study types. Each study is briefly defined below:

Market forecast – model past, present, and future economic and market trends to forecast future demand for products and estimate required production levels.

Logistics network – model order processing, warehousing, inventory, and transportation activities to optimize performance of a supply chain and meet customer performance levels, see (Shapiro 2001).

Site selection – evaluate the cost and expected performance of a plant given different projected operating levels at various sites based on differences in the cost of real estate, transportation, utilities, labor availability, etc.

Business process – model the flow and sequence of business processes, events, conditions on users and organizational units to optimize overall system performance through the reduction of bottlenecks, duplicate, and non-value added activities.

Scheduling – evaluate the effect of changes of scheduling policies and algorithms on operational cost, performance, throughput, etc.

Plant layout – evaluate the effects of different layout configurations on the performance of a system, floor space requirements, material handling costs, buffer storage requirements, throughput, interactions between systems (vibration, heat, cleanliness issues), etc.

Capital equipment – model production operations with changes to capital equipment configurations to evaluate changes in production capacity and operational costs.

Work force – determine effects on operational costs of changes in workforce including modifications to employee skill levels, work calendar, shift schedules, layoffs, use of contract workers, absenteeism, etc.

Product mix – evaluate the effects of changes of product mix on performance including cost of operations, capacity, resource utilization, schedule, etc.

Capacity analysis – model existing and projected workloads to determine available (unused) capacity of production and support resources.

Line balancing – model changes in flow line performance, throughput, cycle time, etc. due to changes in the line configuration, assignment of operations and workers station on the production line.

Cost Estimation – simulate actual production operations for a product or order to generate expected labor, material, and processing costs.

Process validation – simulate the execution of manufacturing plans, programs, and processes to validate that data is correct and will produce expected results.

Process capability – model systems to determine whether production capabilities are sufficient to meet process requirements including the use of statistical process control techniques to determine whether processes can be kept in control range.

Tolerance analysis – model the effects of tolerance stack up on overall tolerance budget for a product or machine setup configuration to determine the probability that an instance of the product will meet specifications.

Ergonomic analysis – evaluate ergonomic aspects of worker tasks for efficiency of operation, theoretical production rate, risk of injury, rest requirements, etc.

Tooling – model various tool management plans, definition of standard tool sets, tool wear monitoring, tool crib stocking levels, and allocation strategies to evaluate their impact on overall system performance and production costs.

Inventory – evaluate impact on system performance, reduction of work-in-process, and carrying costs due to changes in inventory management policies. Policies include size, location, allocation strategies for storage areas, reorder point and safety stock levels, Just-in-Time (JIT) delivery from suppliers, security systems, inventory tracking mechanisms, etc.

Material handling – model the effects of changes to material delivery, storage and retrieval systems, shipping and receiving, kitting stations, etc. on performance, operational costs, etc.

Maintenance – model the effects of changes in preventive maintenance schedules, maintenance personnel, availability of repair parts, equipment maintenance costs, equipment reliability, etc. on the overall performance of the plant and cost of operations.

This set of simulation case study definitions is not necessarily complete or comprehensive. Some of these case study types may be able to be subdivided further. The list is intended to illustrate the wide variety of different reasons for performing simulation case studies.

5 MODELS AND DATA

The last attribute of the framework is simulation models and data. It identifies common model, input, and output data interfaces that could be standardized given an industry market sector, hierarchical modeling level, and simulation case study. The data required depends on the details and level of complexity of simulation study and analysis objectives.

Simulation data may be divided into the following major groups: models, transactions, inputs, and outputs. The lines between these groups are blurred. Transactions, i.e., data that are transferred between distributed simulation models, are inputs to one simulation and outputs from another. Output reports from one simulation could be used as inputs to a run of a different simulation. Models are certainly inputs to a simulation and might also be generated as outputs.

In order to address this problem, our project team is working on the development of one integrated data format for importing and exporting simulation data. Our approach would allow that all types of data could be stored in a single file. Multiple files could be used to store data, but all files have the same basic structure. The same structure could also be used to transfer data in messages between systems. The Extensible Markup Language is used to code the data, (DuCharme 1999, Goldfarb 2002). For a more complete discussion of the current NIST data model, modeling approach, activities, data requirements to support machine shop case studies, see (McLean et al 2002) and for assembly line studies, see (Kibira and McLean 2002).

The data formats that have been developed so far have been divided into the following groups:

- general and miscellaneous
- organizational structures
- product and process specifications
- production operations
- resource definitions
- layout

Although a complete exposition of models and data is beyond the scope of this paper, a brief summary of initial simulation data groups is provided below.

General and Miscellaneous – "Revisions" structure provides a mechanism for identifying versions of subsets of the data, revision dates, and the creator of the data. "Units of Measurement" structure specifies the units used in the file for various quantities such as length, weight, currency, speed, etc. "References" structure identifies external digital files and paper documents that support and further define the data elements contained within the simulation data structure. "Probability Distributions" define statistical distributions that are used to vary processing times, breakdown and repair times, availability of resources, etc.

Organizational Structures – "Departmental Structure" defines the departments within the organization, their relationships to each other, and the positions and employees in each department. "Organization Directory" is used to maintain organizational data and contact information on customers and suppliers. Part, order, and purchase order data is cross-referenced to organizations and contacts in this directory.

Product and Process Specifications – The "Parts" structure provides elements for part specifications, group technology codes, customers and suppliers; as well as links to bill of materials, process plans, drawings, part models, and other references. The "Bill Of Materials Group" structure cross-references the parts and quantities required in a hierarchical bill-of-materials. It is also used to define assembly structures for parts and tools. "Process Plans" structure defines the routing sheets, operation sheets, and equipment programs that are associated with production and support activities. Routing and operation sheets correspond to the job and task level in the work hierarchy. The plans define the steps, precedence constraints between steps, and resources associated with the production of parts and performance of support activities.

Production Operations – "Calendars" structure identifies the shift schedules, breaks, and holidays that are in effect for a period of time. "Work" structure specifies the hierarchy of work items to be processed, i.e., orders, jobs, and tasks. Precedence constraints defined in process plans are mapped to associated work items. Scheduling data and resource assignments for each work item are maintained in the structure, as well as other data. Jobs and tasks are cross-referenced to each other as well as routing and operation sheets respectively. "Purchase Orders" structure identifies the internal and external purchase orders that have been created to satisfy part inventory requirements.

Resource Definitions – The "Resources" structure describes all the resources that may be assigned to work in the facility, their status, scheduled assignments to specific work items, significant events, and utilization levels. Current resource types available include: stations and equipment, cranes, employees, tools and tool sets, fixtures and fixture sets. Standard setups are also defined. "Skill Definitions" structure lists the skills that an employee may possess and the levels of proficiency associated with those skills. Skills are referenced in employee resource requirements contained in process plans. "Operation Definitions" structure specifies the types of operations that may be performed at a particular station or group of stations within the facility. "Inventory" structure identifies the instances and locations for part, materials, tool, and fixture inventory.

Layout – The "Layout" structure defines the location of reference points within the site or facility, area boundaries, paths, resource, and part objects. It contains reference pointers to external graphics files that may use appropriate graphics standards to further define these elements.

The proposed elements for the models and data attribute of the framework are by no means complete. The initial focus of data type definitions has been on machine shops and small assembly lines. Even within this area work is not complete, data types for managing batches and lots remain to be developed. Although the current data types provide considerable functionality, many additional types need to be defined and tested.

6 CONCLUSIONS AND FUTURE WORK

The simulation framework outlined in this paper provides a basis for initiating discussions on simulation standardization. At this point in the time, the goal of the framework has been to identify the boundaries of manufacturing simulation and offer an initial skeleton that can be used to organize requirements for simulation model and data standards. As we engage in research projects with various industrial partners, simulation software vendors, and academic researchers, we expect to continue to flesh out the details of this framework. We welcome suggestions of additions or modifications to this structure. Our ultimate objective in this area is to promote the establishment of a standard data interface for manufacturing simulators based upon this work.

REFERENCES

Appleton, D. 1985. *Introducing the New CIM Enterprise Wheel*. Dearborn, MI: Society of Manufacturing Engineers.

Banks, J., Carson, J., Nelson, B. 1996. *Discrete Event Simulation.* Upper Saddle River, NJ: Prentice-Hall.

Banks, J.(ed.). 1998. *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*. New York: John Wiley and Sons.

Banks, J. 1999. Let's Talk Taxonomy, *IIE Solutions*, *31 (6)*.

Barkmeyer, E. Christopher, N., Feng, S., Fowler, J., Frechette, S., Jones, A., Jurrens, K., McLean, C., Pratt, M., Scott, H., Senehi, M., Sriram, R., and Wallace, E. 1997. SIMA Reference Architecture Part I: Activity Models. NISTIR 5939. Gaithersburg, MD: National Institute of Standards and Technology.

Compton, W. (ed.). 1988. *Design and Analysis of Integrated Manufacturing Systems*. Washington, DC: National Academy Press.

DuCharme, B. 1999. *XML: The Annotated Specification*. Upper Saddle River, New Jersey: Prentice Hall.

Eng, L. 1996. Computer Integrated Manufacturing (CIM) Application Framework Specification 1.3, SEMATECH Technology Transfer #93061697F-ENG. Austin, TX: SEMATECH.

ESPRIT Consortium AMICE. 1989. *Open System Architecture for CIM*. Berlin: Springer-Verlag.

Goldfarb, C. 2002. *XML Handbook*. Upper Saddle River, New Jersey: Prentice Hall.

Harrington, Jr., J. 1984. *Understanding the Manufacturing Process: Key to Successful CAD/CAM Implementation*. New York, NY: Marcel Dekker.

Jones, A., McLean, C. 1986. A Proposed Hierarchical Control Model for Automated Manufacturing Systems. *Journal of Manufacturing Systems 5 (1).*

Kibira, D., McLean, C., 2002. Virtual Reality Simulation of a Mechanical Production Assembly Line. *Proceedings of the 2002 Winter Simulation Conference.* ed. E. Yücesan, C.Chen, J. Snowdon, and J. Charnes. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

McLean, C., Barkmeyer, E., Mitchell, M. 1983. An Architecture for Small Batch Manufacturing. *IEEE Spectrum 20 (5).*

McLean, C., Jones, A., Lee, T., Riddick, F. 2002. An Architecture for a Generic Data-Driven Machine Shop Simulator. *Proceedings of the 2002 Winter Simulation Conference.* ed. E. Yücesan, C.Chen, J. Snowdon, and J. Charnes. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers.

NAICS. 2002. *North American Industry Classification System (NAICS): United States, 2002*. Lanham: Bernan Publishers.

Rembold, U., Nnaji, B., Storr, A. 1993. *Computer Integrated Manufacturing and Engineering*. Wokingham, England: Addison-Wesley.

Scheer, A. 1998. *Business Process Engineering Study Edition: Reference Models for Industrial Enterprises*. Berlin: Springer.

Shapiro, J. 2001. *Modeling the Supply Chain*. Pacific Grove, CA: Duxbury.

Storch, R., Hammon, C., Bunch, H., Moore, R. 1995. *Ship Production.* Centreville, MD: Cornell Maritime Press.

Todd, R., Allen, D., Alting, L. 1994. *Manufacturing Processes Reference Guide*. New York, NY: Industrial Press.

Williams, T. (ed.). 1989. *Reference Model for Computer Integrated Manufacturing (CIM): A Description from the Viewpoint of Industrial Automation*. Research Triangle Park, NC: Instrument Society of America.

ACKNOWLEDGMENTS

This project is funded [in part] by NIST's SIMA Program. SIMA supports NIST projects applying information technologies and standards-based approaches to manufacturing software integration problems. The work described was funded by the United States Government and is not subject to copyright.

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