A VIRTUAL MANUFACTURING ENVIRONMENT FOR INTEROPERABILITY TESTING

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ABSTRACT

Studies have documented the high cost of the lack of software interoperability on manufacturing. New interface standards are being developed by various organizations to address interoperability issues. Unfortunately these standards often overlap and conflict with each other. Adequate testing facilities are not available for evaluating the suitability and effectiveness of existing and candidate standards for application to specific manufacturing domain areas. The Virtual Manufacturing Environment (VME) Project of the NIST Manufacturing Interoperability Program is focused on developing integrated manufacturing simulations that can be used to support future industry interoperability testing needs. This paper presents a summary of interoperability testing opportunities and needs, an overview of a project to develop a virtual manufacturing environment to support interoperability testing, and the current status of simulation development efforts.

INTRODUCTION

Manufacturing systems often tend to be large, complex, and expensive to construct, operate, and maintain. Studies have documented the high cost and other impacts of the lack of software interoperability on manufacturing; see (NIST 1999). Software will continue to evolve and interoperability is expected to remain a problem area for manufacturers. New interface standards are being developed by various organizations to address interoperability issues. Unfortunately standards often overlap and conflict with each other.

The U.S. National Institute of Standards and Technology (NIST) has invested considerable effort in the development of test methods and tools that address manufacturing interoperability issues, see (Kulvatunyou 2004). To date, these methods and tools have largely focused on static testing, e.g., correctness of schemas and message formats. Adequate testing facilities are not available for evaluating the suitability and effectiveness of existing and candidate standards for application to specific manufacturing domain areas. New, dynamic, manufacturing domain-specific testing capabilities will also be needed to evaluate the suitability of suites of standards for selected applications, identify and resolve conflicts between standards, and evaluate compliance of vendor implementations with standards. Dynamic testing capabilities would enable the live testing of multiple manufacturing subsystems working together using various interface standards and protocols that have been developed by different standards organizations.

Software developers, research institutions, universities, and testing facilities cannot afford to duplicate real manufacturing systems in their laboratories due to the high costs of manufacturing hardware and software, system maintenance, and required space. Researcher hands-on experiences with manufacturing systems are often limited to individual or small groups of machine tools in laboratory shops, prototype work cells, or tabletop manufacturing systems. Manufacturing software development activities, training programs, research experiments, and testing activities could be significantly enhanced if manufacturing systems could somehow be brought into the laboratories of research institutions, universities, and software developers. Computer simulation technology now allows us to construct large, realistic virtual worlds in software. The military has made extensive use of this technology for a number of years. Virtual manufacturing environments could be used by a variety of organizations involved in manufacturing for training, experimentation, and testing purposes.

The Virtual Manufacturing Environment (VME) Project of the NIST Manufacturing Interoperability Program is focused on developing integrated manufacturing simulations that can be used to support future industry interoperability testing needs. The rationale for this project is that it is impractical to use real industrial systems to support manufacturing interoperability research and testing due to:

- *Access issues* – Manufacturing facilities are normally not open to outsiders because businesses are concerned that proprietary data and processes may be compromised.
- *Technical issues* – Existing operational manufacturing and support systems are not likely to be properly instrumented to support testing needs.
- *Cost issues* – Manufacturers lose productivity when systems are taken offline to support testing.

No publicly available facility with open interfaces currently exists to support interoperability testing for a broad range of manufacturing interface standards and software applications. Prohibitive development costs and other priorities prevent most software vendors, research, and standards organizations from developing systems to support interoperability testing. Non-proprietary systems and neutral test case data sets are needed to support fair and open competition and accelerate the systems integration process.

TESTING OPPORTUNITIES AND NEEDS

Simulations can be used to model the behavior of and take the place of real manufacturing systems. What types of simulation applications are needed to support testing? A number of different clusters of manufacturing simulators are envisioned. Each possible cluster and its associated simulation applications are briefly introduced below:

- *Supply chain simulators* can be used to model the organization and management of supply chains. Organizations that may be simulated include supply chain headquarters, manufacturing primes, suppliers, transportation networks, warehouses, distribution centers, retailers, and customers. Some of the issues that may be addressed include lead times, inventory levels, production capacity, operations under surge conditions, and information flows.
- *Enterprise organizational simulators* can be used to model the internal business processes of various departments within the manufacturing organization, such as customer order servicing, design, engineering, production, and inventory management. Business process modeling techniques may be used to analyze order flow and processing times in order to streamline operations and minimize non value-added functions.
- *Manufacturing system and equipment simulators* can be used to model the normal operations, failure modes, and maintenance of various manufacturing equipment, such as fabrication, assembly, material handling, quality, and packaging systems. Examples of some of the equipment making up these systems includes machine tools, coordinate measuring machines, robots, storage and retrieval systems, and conveyors. Discrete event simulation techniques may be used to analyze operation times, capacity, queue lengths, bottlenecks, buffer storage requirements, inventory levels, etc.
- *Physical process simulators* can be used to create accurate models of the physical transformations that products and tooling undergo in various manufacturing industries. Industries that will have unique process simulations include metalworking, electronics, food, textiles, plastics, and chemicals/refining. For example, a physical process simulator for metalworking may model processes associated with a machine tool's operation. Information obtained from the simulation may include changes to work piece geometry, chip formation, tool wear, chatter, thermal and mechanical variations to the machine.

How might manufacturing simulations be used to support interoperability testing? Some examples of possible simulation-based testing applications include:

- Evaluate effectiveness of new interface standards and protocols to meet manufacturing industry needs.
- Evaluate conflicts and inconsistencies between standards developed by different organizations.
- Perform interoperability testing with models of systems being integrated. For example a model of a robot controller may be integrated with a model of the robot for testing purposes to ensure interoperability.
- Perform interoperability testing with emulated physical equipment. For example, a physical programmable logic controller may be tested with an emulated conveyor system before the physical conveyor system is installed or even delivered.
- Evaluate the capability of the delivered process, system or design to meet interface specifications.
- Perform conformance and acceptance tests using simulations to create the specified range of inputs for a delivered system or process.
- Evaluate whether new systems, processes or designs meet performance specifications. For example, test programs for robots and other machinery using simulations.
- Develop metrics to allow the comparison of predicted performance against "best in class" benchmarks to support continuous improvement of manufacturing operations.

Testing applications will also require that simulations be technically correct, i.e., accurately reflect the interfaces and behavior of real manufacturing systems. Models will need to be carefully validated; however, the procedures used may be more focused on functional and deterministic validation rather than statistical validation used for system-level research applications that use stochastic factors. The validation procedures should be defined to ensure common practices. Supporting applications that exercise the models through the range of parameters defined in the specifications should be provided to facilitate the process. The development of test cases would help manufacturers by providing a baseline that could be used for the initial screening of vendors. If a vendor's software passed initial tests, customers could proceed with testing candidate applications using company-specific data.

A number of different testing and support tools will be needed that may not normally be required in an actual production environment. What types of testing and support tools are needed? Some examples of interoperability testing instrumentation is briefly described below:

- *Module integration infrastructure* – This software is needed to allow simulation modules and other applications to be interconnected in such a way as to enable time synchronization and data sharing.
- *Communications channel monitors* – Mechanisms are needed which will allow test personnel to observe communications traffic between modules.
- *System and module status displays* – Displays are needed that will allow testers to track the health and status of applications under test.
- *Logging and reporting tools* – Various diagnostic tools are needed for recording traces of the execution sequence of modules being tested.
- *Message and file syntax checkers* – Syntax checkers are needed to validate that messages and data structures written to files are properly formatted according to standards.
- *System initialization, control, and rollback utilities* – Functions are needed to initialize tests, place systems in proper modes, set checkpoints, and rollback tests and data sets to these checkpoints to avoid restarting entire systems unnecessarily during testing.
- *Configuration management and build software* – Support tools are needed to provide configuration

management and system build functions for testing tools and test case data sets.
- *Testing policies, procedures, and checklists* – Testing procedures must be consistent and repeatable, standard policies and procedures must be established and documented to ensure that systems are evaluated fairly.

PROJECT OVERVIEW

The goal of the VME Project is to: 1) establish a virtual manufacturing environment based upon simulation technology that enables dynamic interoperability testing for manufacturing software applications, candidate interface specifications, protocols, and standards, and 2) provide interoperability testing support to software developers, manufacturers, research institutions, consortia, and standards organizations for selected manufacturing product domains, facilities, systems, operations, and processes.

The objectives that have been identified as steps to achieving these goals include:

- Identify and select high priority manufacturing product domains for implementation within the virtual manufacturing environment.
- Identify system functions and test case data for selected supply chain, facilities, systems and processes.
- Develop simulation models of manufacturing supply chains, facilities, and process lines.
- Identify and implement relevant neutral interfaces and standards to enable integration and data transactions between simulations and with external systems.
- Instrument simulations with monitoring, testing, and diagnostic tools to support interoperability testing.
- Establish interoperability testing services, procedures, and reports for internal and external customers.

What benefits may be expected from this project? The creation of a virtual manufacturing environment for interoperability testing:

- Establishes a baseline reference model for targeting interface standardization needs and helps minimize redundant specification efforts.
- Provides open, neutral test-based evaluations of interface standards and conforming software applications.
- Enables collaboration and cost sharing between competing organizations (e.g., manufacturers and software vendors) that have difficulty cooperating or sharing information in other venues.
- Provides neutral models, test case data, and support tools that can be used by software developers for self-testing and academic institutions for research purposes.
- Shortens development time for new standards and improves the interoperability of commercially developed manufacturing software applications.

The major components of the VME test bed are:

- Simulations of manufacturing systems at various hierarchical levels, e.g., supply chain, manufacturing plant, and shop floor.
- Design, engineering, and analysis systems for creating manufacturing data and populating life cycle databases,
- Instrumentation and testing tools for conducting interoperability tests.
- Test case data and databases in neutral format for conducting interoperability tests on real manufacturing systems.
- Interface standards, protocols, and communications mechanisms for connecting simulation modules and modules under test.
- Policies and procedures for providing interoperability testing services.

See Figure 1 for an illustration of the conceptual architecture of the VME test bed.

A phased approach is underway for the development of the VME test bed. The focus of Phase I was to develop test case data and stand-alone simulation models of an automotive supply chain, vehicle final assembly facility, and paint process line. This phase has been completed. Phase II, currently underway, is focusing on extending the simulations using selected interface specifications and standards to integrate the simulations with each other and other manufacturing software applications. In Phase III, monitoring, testing, and diagnostic tools to enable interoperability research and testing will be incorporated into the test bed and integrated with test bed systems. These will be designed to support the testing opportunities and described in the first section of this paper. Phase IV will open interoperability testing facilities and services for use by software developers, manufacturers, research institutions, consortia, and standards organizations.
Phases V and later will expand the VME test bed to include simulations of other manufacturing supply chains, facilities, systems, operations, and processes as well as additional interface specifications, testing tools, and data sets.

CURRENT STATUS

In this section, a summary of the current status of the simulation development is provided. Work on a standard manufacturing simulation data model is also highlighted.

Supply Chain Simulation

The purpose of the supply chain simulation is to provide a representation that generates dynamic information exchanges that would be created in a real life supply chain in order to test standards and supply chain applications' compliance to standards. The simulation executes a model of interactions and material and information flows through a defined supply chain network extending from suppliers to customers.

The scope of the supply chain model includes manufacturing facilities with multiple stages of suppliers on the input side and multiple stages of distribution on the network side. Each of the supplier facilities is modeled at an abstract level based on the capacity of bottleneck and the lead-time through the facility. The flow of material is tracked at the supplier at three major stages: raw materials, work in process, and finished goods. Suppliers can send their outputs to multiple consuming facilities. For example, a tier II supplier can send its products to a tier I supplier and to the manufacturing facility directly.

The manufacturing facility itself is modeled in a bit more detail, with major sections (lines or departments) of the facility modeled with their individual bottlenecks. The flow of product is tracked through the stages of raw material (components), work in process within the major sections and in-between the sections, and finished goods. The production activity is modeled at shift level.

The distribution network can be modeled to include flow of product to distribution centers, retailers and customers either linearly through these stages or directly to any of them. Customer purchase activity through the retailers can be modeled by specifying appropriate distributions. The logistics is modeled at an abstract level with travel times defined in integer days based on a from-to matrix.

The current implementation of the model is based on a generic automotive supply chain data set with the final assembly plant at the center as the manufacturing facility, tier I and tier II automotive suppliers on the supply side, and distribution centers, car dealers and customers on the consumption end.

The model mimics the dynamics of the supply chain and associated interactions between the supply chain nodes. These interactions can be executed through transactional messages between the nodes consistent with a standard that may be under evaluation. With the current implementation of an automotive supply chain, the interaction messages use data fields consistent with those defined in OAGIS/AIAG Business Object Documents (BODs) for Inventory Visibility and Interoperability (IV&I) (OAGi, 2007). For example, the orders for vehicles from dealers to assembly plants are defined using XML fields defined in the “order” BOD of the OAGIS IV&I standard. Similarly, the shipment notifications that are sent from the assembly plant to dealers use XML messages that are formed using the corresponding shipment notice BOD specification.

The supply chain simulation has been developed using Rockwell Automation’s ARENA discrete event simulator. The simulation is data driven with all the supply chain parameters defined in variable structures. Figure 2 shows a screenshot of the model with the generic logic modules identified. The data for the automotive supply chain has been defined in an Excel file and brought into ARENA to create the model. A graphical user interface (GUI) module has been developed using C## for flexibility in accessing and presenting information beyond that offered by ARENA. The GUI module communicates with the simulation model through an MS-Access database using .NET framework.

The input data for the automotive supply chain has been developed as a neutral data set. It is representative of industrial data based on discussions with automotive manufacturers and examples in the open literature, see (Schmenner 1981). It does not include any proprietary information and can be shared freely among researchers. The data includes a high level description of automotive bill of material, the suppliers for the major components, the assembly plant, the dealers and the logistics network connecting all the nodes. A more detailed, external simulation model of a manufacturing plant, described in the next section, can replace the assembly plant node in the supply chain model.

Manufacturing Plant Simulation

The purpose of the manufacturing plant simulation model is to generate dynamic information representative of a real life assembly plant to enable testing of standards and applications for plant level information and decision-making systems. The simulation mimics the flow of product and associated information in a manufacturing plant. The interfaces to the model can be built using selected standards. Similar to the supply chain simulation, the current plant simulation implementation uses interactions messages defined in OAGIS BODs for IV&I.

The scope of the manufacturing plant simulation model includes all the major sections of the plant with the key workstations represented. In the current implementation of an automotive assembly plant, its three major sections namely, body shop, paint shop and general assembly are modeled with a number of workstations for each connected by the appropriate material handling system. The body shop representation includes body assembly stations, conveyors and various kinds of buffers allowing stacking of auto body panels. As the car bodies move through the stations, the processing is modeled through passage of cycle time. The movement of equipment at each workstation such as robots is not modeled. The paint shop and general assembly area are modeled similarly except that the conveyance mechanism is different. A power and free conveyor is modeled with car carriers appropriate for moving the assembled car body through the stations.

The plant model includes tracking of component inventories in storage areas and on the assembly line. The inventories are used as the components are assembled on to the cars. Completely assembled cars move on their own power through test stations and any required rework to a shipping area. The shipment from the plant to distribution centers and/or car dealers is modeled in the supply chain simulation described above.

The manufacturing plant simulation model can also be developed using a data-driven approach. It can thus test the standards that provide for describing a manufacturing plant. The current implementation utilizes an automotive assembly plant description defined using the Core Manufacturing Simulation Standard (CMSD) currently under development by the Simulation Interoperability Standards Organization (SISO. Another overlapping standard that may be considered in the future for modeling control systems in future is the ISA-95 (ANSI 2000, 2001, 2005).

The automotive assembly plant simulation model was developed using the Delmia QUEST discrete event simulation system, based on an internally generated neutral data set. The model includes high-level representations of body shop, paint shop and the general assembly area of an automotive plant.

Figure 3 shows a screenshot of the 3-D view of the modeled plant. The neutral data set for the assembly plant includes a more detailed bill of material than used for the supply chain simulation, definitions of stations on the line, and policies controlling the scheduling and flow of vehicles through the facility. In the future, the simulation will include a capability to replace line segments with an external detailed model briefly described next.

Line and Work Cell Simulations

The purpose of detailed simulations of parts of the manufacturing plant is to generate dynamic control messages representative of real life manufacturing lines and work cells to enable development and testing of standards and applications at that level. The current line level implementation uses CMSD based data files for reading in a description of a more detailed system. The paint process line of an automotive plant has been incorporated that uses Enterprise Dynamics software. The model is based on proprietary data and hence its details and screen images are not included. The experience will be useful for developing a publicly accessible model in the future.

Standards Development

If software applications including simulations are going to share data, they should have a common understanding of the meaning and structure of that data. The primary objective of the Core Manufacturing Simulation Data model (CMSD) is to develop a structure for exchanging shop data between various manufacturing software applications, including simulation. The idea is to use the same data structures for managing actual production operations and simulating the machine shop. The rationale is that if one structure can serve both purposes, the need for translation and abstraction of the real data would be minimized when simulations are constructed. The machine shop data model contains twenty major elements. The data elements are called: *Organizations, Calendars, Resources, Skill-definitions, Setup-definitions, Operation-definitions, Maintenance-definitions, Layout, Parts, Bills-of-materials, Inventory, Procurements, Process-Plans, Work, Schedules, Time-Sheets, References, Revisions, Units-of-measurement,* and *Probability-distributions*

Maintaining data integrity and minimizing the duplication of data is an important requirement. For this reason, each unique piece of information appears in only one place in the model. Cross-reference links are used to avoid the creation of redundant copies of data. The mapping of real world data into simulation abstractions is not, for the most part, addressed in the current data model. Due to space limitations, the entire model is not shown or discussed in detail.

This information model and associated data formats are undergoing standardization under the Simulation Interoperability Standards Organization (SISO 2005). For a more detailed discussion of the CMSD model, see (Lee 2003) or (McLean 2005a).

CONCLUSIONS

The implementation of the Virtual Manufacturing Environment provides a test bed industry, government, and academic researchers to evaluate manufacturing interface standards. The VME can be used to test the interoperability of manufacturing applications including enterprise resource planning, scheduling, manufacturing execution systems, machine and material handling equipment control programs, and machine and robot programs. It can also be used to test proposed standard interfaces for such applications.

The test bed will be highly effective if supported with additional test case data that is based upon real industrial scenarios and problems. The repository of test case data can also serve as a benchmark for comparison of alternate approaches for similar applications and thus further spur development. Test cases may also be used by industry to establish baselines for evaluating vendor offerings. It will also eventually provide a new set of capabilities not previously available to standards development organizations.

NIST researchers have prepared draft specifications for shop floor data and are working with the Simulation Interoperability Standards Organization for their formal acceptance. Work on the CMSD and implementation of the VME is expected to help identify the need for other manufacturing data standards including data models, interfaces, distribution and synchronization mechanisms.

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DISCLAIMER

Software architecture, models and languages are identified in context in this paper. This does not imply a recommendation or endorsement of the associated commercial software products by the authors or NIST, nor does it imply that such software products are necessarily the best available for the purpose.

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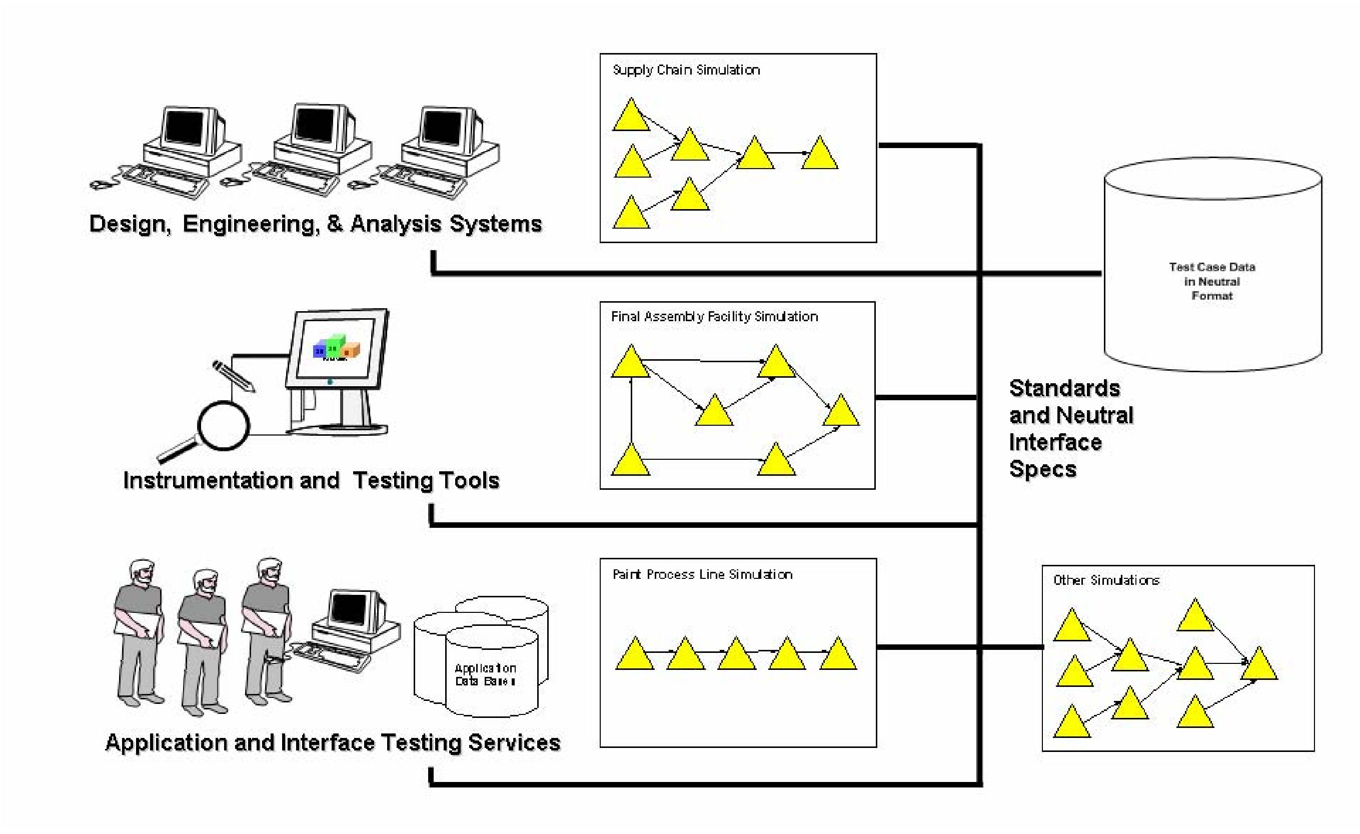

Figure 1: Conceptual architecture of Virtual Manufacturing Environment for interoperability testing

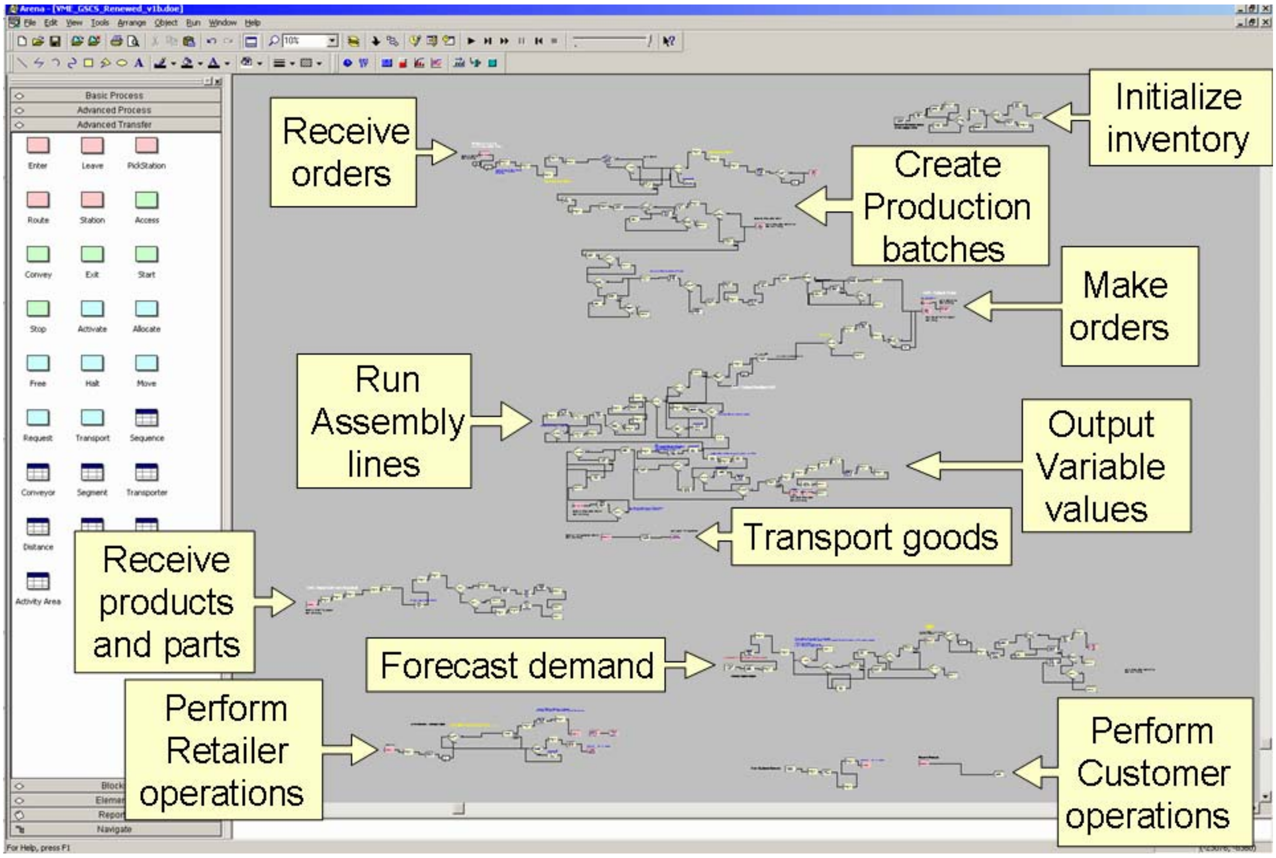

Figure 2: Screen image of supply chain simulation model logic in ARENA with annotations

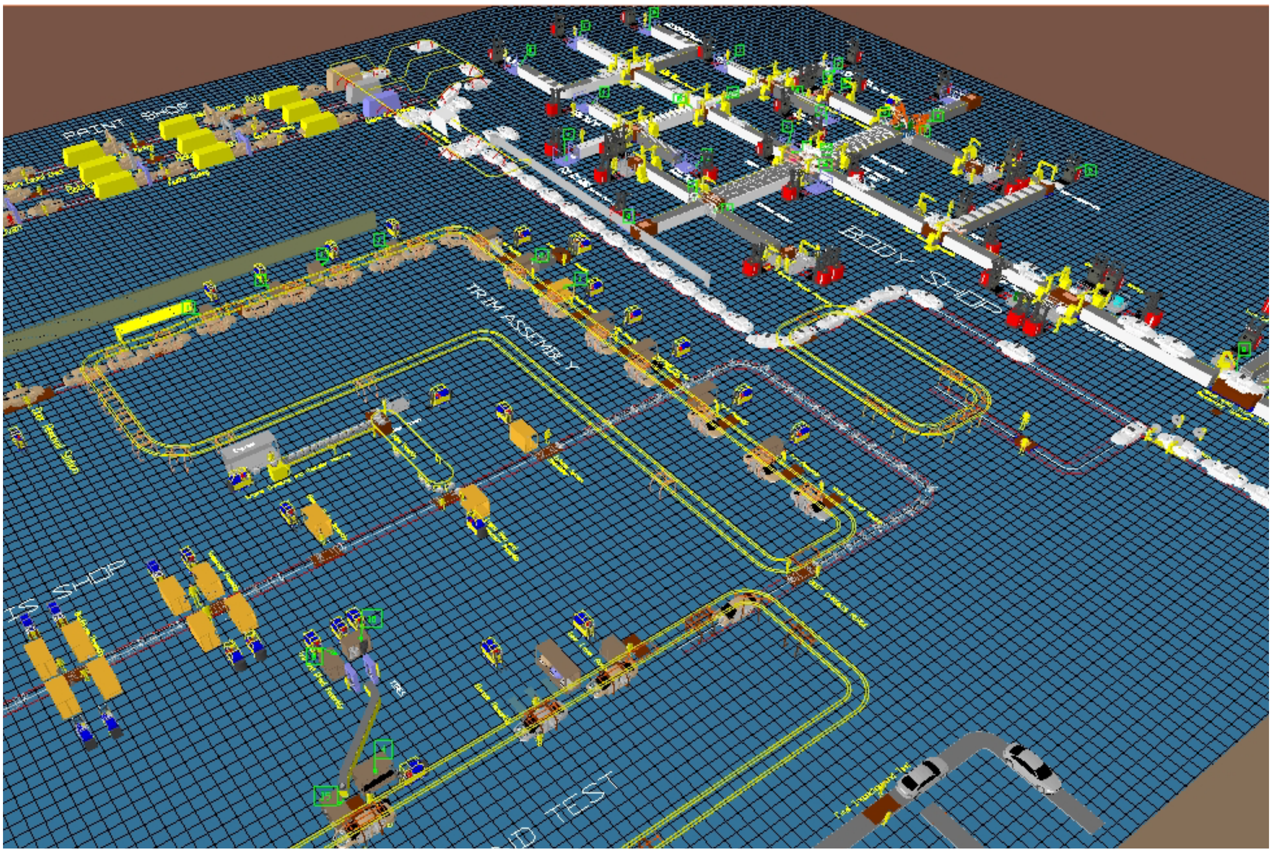

Figure 3: Screen image of the automotive manufacturing assembly plant simulation in QUEST