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GENERIC SIMULATION OF AUTOMOTIVE ASSEMBLY FOR INTEROPERABILITY TESTING

Deogratias Kibira
Charles R. McLean

Manufacturing Systems Integration Division,
National Institute of Standards and Technology
100 Bureau Drive, MS 8260
Gaithersburg, M.D. 20899, U.S.A.

ABSTRACT

Computer simulation is effective in improving the efficiency of manufacturing system design, operation, and maintenance. Most simulation models are usually tailored to address a narrow set of industrial issues, e.g., the introduction of a new product. If generic data-driven simulations could be developed they would be reusable for wider application including interoperability testing of standards for exchange of data across the supply chain in manufacturing. To facilitate future interoperability testing and training, scientists at the National Institute of Standards and Technology are currently developing distributed, integrated manufacturing simulations for automotive manufacturing. These simulations are being developed at four different levels: the supply chain, the assembly plant, the engineering systems, and the shop floor level. This paper describes the development of a simulation model of the final assembly plant. Future efforts will increase the versatility of the model, run it on neutral data and extend integration with supply chain simulation.

1 INTRODUCTION

Automotive manufacturing is complex and includes the coordination of design and manufacturing activities between many companies. The process involves a number of operations, which require assembling together thousands of fabricated, and purchased components, subassemblies, and systems. Purchased components are outsourced from many supplying companies who generally use different data formats, which are not always compatible. Yet this product data must be shared among many companies involved in the production activities. This lack of software interoperability among different companies along the supply chain causes major cost increases in the manufacturing industry (NIST, 1999). Researchers would need to test and evaluate the suitability and effectiveness of existing and candidate standards for application to specific manufacturing areas. It is impossible for researchers in institutions and universities to duplicate real life manufacturing systems due to the high costs of manufacturing hardware and software. Additionally, they do not have unlimited access to real manufacturing systems since this would interfere with production activities. Companies are also reluctant to supply much detail about plant operations since some of the information is confidential.

To circumvent this difficulty, researchers are constructing generic, data-driven simulation models of manufacturing systems to facilitate current and future, training, experimentation, and testing of interoperability of software. By generic simulation the model can be reconfigured for many situations in automotive assembly. Generic simulation identifies common model input and output data interfaces that could be standardized for particular modeling level and simulation case studies (McLean and Shao, 2003). Case study templates can be developed that are generic for a specific domain such as scheduling, plant layout, materials handling, new equipment. This paper is not based on any specific automotive final assembly plant but is a step in that direction. By being data-driven, it will have information relating to part-subcomponent association, process definition, part routing, and initial inventory levels defined and specified outside the model. Such information would then be read into the simulation at initialization time during a run. This enables modification of production operations of the final assembly plant with minimal changes to the simulation model.

Previously, the general application of simulation in automotive manufacturing centers on investigation of operational options of different shops used in the process. For example Lohrer (1997) identifies that simulation is usually applied to investigate body, paint, and trim/chassis/final assembly shops. There is also literature on plant traffic design (Hugan, 2001). The focus of investigation on engine block casting, machining, and assembly is often to investigate the effect on new tooling, materials delivery systems, and the impact of failures. A dynamic operating algorithm for the painted body storage in an automotive manufacturing plant is presented in Moon et al. (2005). It investigates grouping cars of the same color together to reduce changeover costs. Simulation has also been used to determine the cycle time of the robots and buffer sizes between sub-lines of body shop Moon et al. (2006). Some applications also focus on the supply chain such as Tan et al. (2003) and Jain et al. (2005).

Currently, there are no dynamic, manufacturing oriented testing facilities to evaluate the suitability of standards for selected applications. There also lacks ways to identify and resolve conflicts between standards, and evaluate compliance of vendor implementations with standards. Dynamic testing capability would enable the live testing of multiple independently operating manufacturing subsystems. The linkage between subsystems would be various interface standards and protocols developed by different standards organizations. As such, virtual manufacturing environments with data-driven simulation could be used by manufacturing companies for training, experimentation, and testing purposes. The simulation of the assembly plant will include such issues as facility layouts, materials handling, and system schematics for major production shops. It will also be concerned with the exchange of data such as bills of materials, configuration, lot sizing.

While the overall goal of the Virtual Manufacturing Environment (VME) project is to provide interoperability testing support to software developers, manufacturers, researchers, and standards organizations using a virtual reality simulation environment, the objectives of the work presented here are:

- Identify facilities, systems, operations, parts, and processes in automotive manufacturing assembly to develop the model.
- Develop the simulation model of the final assembly plant.
- Integrate the assembly simulation model with other simulations using High Level Architecture.
- Carry out interoperability testing using test case data.

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 testing using simulations to create the specified range of inputs for a delivered system or process.
- Evaluate whether new systems, processes, or designs meet performance requirements and specifications. For example, test programs for robots and materials handling systems using simulations.
- Develop metrics to allow the comparison of predicted performance against “best in class” benchmarks to support continuous improvement of manufacturing operations

2 MOTOR VEHICLE ASSEMBLY PROCESS

This section describes the manufacturing process and the development of the assembly simulation model. Information about motor vehicle manufacturing was obtained from published literature and reports of visits to the Volvo motor vehicle plant in Gothenburg (Sweden) and the General Motors plant for Cadillac/Buick vehicles in Detroit, Michigan. However, the simulation model does not represent the production system of either plant. A typical automotive assembly plant has more than one thousand stations. But because of the desire to simulate the entire plant rather than part of the process, it became necessary to consolidate processes to reduce this number.

The automotive production process consists of three major sections: the body shop, the paint shop, and the trim assembly shop. Other sections are the power train assembly (consisting of the engine, gearbox, clutch, and transmission), and the press shop if body parts are stamped at the plant. There is also a final testing process where vehicles are checked for water tightness and a stationary road test.

2.1 The Body Shop

The first stage in the production of a motor vehicle is the fabrication and assembly of what is called the “white body” or “body in white” of the car. The major components of the automotive body are the underbody (or sometimes called the floor pan), body sides, framing, hood, trunk lid, doors, and roof. These are produced by separate robotic cells. The underbody is in turn made up of the front, middle, and rear sections. The front section is made up of the engine compartment and mounting for instrument panel. The middle section is the under floor of the passenger compartment while the rear section comprises the trunk. The sections are produced from stamped parts. The underbodies are usually bar-coded at this stage to indicate body type. Then they are transported to another section where the sides are attached to the underbody. There is usually a storage space for underbodies at the start of the following section.

The framing and body structures are further welded to the underbody, and after which the roof attached by welding. The car body then begins taking shape. The body sides consisting of the entire side from the trunk to the hood, except the doors are assembled at separate stations and transported to the body side assembly area. Cross roof supports are also welded on the side panels. The roofs are sometimes bought or stamped and assembled at the shop. Some roofs are the "open roof" type, some are closed roofs. At another station the doors, hood, and trunk lid are also assembled to the body.

2.2 The Paint Shop

This is the shop where the body in white is painted and given the final color and texture required in the final saleable vehicle. There are often a number of parallel paint lines. Typically many processes are involved here. The stages in the paint sequence are invariably as follows:

- Degrease – clean any grease on vehicle bodies that stuck as a result of the body forming process.
- Phosphate wash – wash any oil on the body so that the paint can stick to the body.
- Dry – bake the body in an oven to dry.
- Electro paint – dip the body into a tank containing the paint and apply an electric charge so that the paint can stick to the body.
- Clean – clean the body of any dirt.
- Dry – bake the body in an oven to dry.
- Pre-seal – seal off or plug any hole left in the body and perform some touch up grinding work.
- Undercoat paint – apply a second coat of paint which determines the final color of the vehicle.
- Dry – automobile body is again in an oven.
- Light application of sand – remove any dust and manual cleaning or using a feather duster machine.
- Primer manual paint – manually paint the inside of the vehicle where robots may not easily reach.
- Outside coat painting using robots – apply the undercoat paint.
- Dry – bake the body once again dried in an oven.
- Quality control check – ensure work is done well so far. The bodies that do not satisfy required specifications are re-done.
- Top coat paint application – apply the final color paint.
- Dry – final baking of the body in an oven to dry.

Most of the above processes are done by robots except where human intervention is required. In general, air flow and water reservoirs are used to carry away excess paint. Small defects in the paint finishes are generally corrected manually. After painting the body is sent to the final trim assembly shop. One of the typical problems encountered is the sorting of the incoming vehicles to minimize color changes. Although robots can change colors very quickly, flushing the entire shop to change from painting one color to another takes a setup time. Therefore, it is desirable to sequence same color vehicles one after the other – a concept called *color blocking.* This necessitates a temporary storage for white bodies before the paint process. While changing colors, it is usual that white or lighter colors precede darker colors rather that the other way round. Another point, according to Ulgen et al. (1998), is the percentage of painted cars passing the quality control check. It is called the *yield* of the painting process. Yield can be as low as 65% and the chances of rework are high. This can be a major source of process variation. The process ahead of the paint process should have sufficient storage to prevent blockage.

2.3 The Trim Assembly Shop

Trim assembly is where all parts and assemblies needed for a vehicle to move as well as other conveniences are assembled into the body. There is usually a separate shop for fabrication and assembly of the chassis and power system of the vehicle. The engine is first fit with various features according to required specifications (engine dressing) and assembled together with the transmission system (clutch, gear box, propeller shaft, etc). The power system is attached to the chassis onto which axles, suspension, exhaust, steering, and brake system have already been assembled. Some parts are usually assembled into the body before it is merged with the power system; the process is called "body drop" since it is the body that is usually lowered onto the chassis/power system. In many cases the doors are removed at the beginning of the trim assembly. After various parts are assembled at a separate station into the doors, they are re-attached to the car at a later stage. Removing doors before trim assembly allows easy access to the inside of the vehicle and to reduce possible damage to doors. In some plants the doors are not removed from the body during trim assembly. In this case they have to be left open through most of trim assembly, requiring larger assembly space.

Many older vehicles had separate underlying stiffening structures and bodies, the body housing the passengers. This design requires more materials and results in a heavier car, thus raising costs. Today most cars are manufactured with a unibody spaceframe chassis. This means that the body itself is constructed such that it provides the stiffness required by the vehicle. In this case the body is dropped to the axles onto which the power, suspension, steering, brake, and fuel delivery systems are already assembled. In some cases the hood is removed before the power system is merged with the body. This allows easier access to the engine compartment and reduces possible damage. Most trim assembly operations are carried out manually. Typically, there is a worker or two on either side of the line at a station. There is sufficient space on which to work, equipment and tools specific to the station, and there are racks or bins on which the parts are stored for assembly. This is where a variety of configuration options can be made by the customer.

It is in the trim assembly shop that electrical wiring is added into the body and engine compartments, weather proofing, carpets and floor mats, dashboard and instrument panel, steering wheel, gear lever, handbrake, and pedals, vinyl top, bumpers, inside lighting, outside lighting, indicator lamps, mirrors, windshield, wipers, seats, etc. are inserted The underside of the body is also assembled at trim assembly. The fuel delivery, exhaust systems, etc. are firmly clamped to the body. There is also where various parts not directly attached to the engine are finally inserted. The tires are finally bolted onto the vehicle.

Door assemblies with windows, switches, and systems for closing and opening windows, electrical work, side mirrors, arm rest, etc. and hood are re-attached in the last stages. Fluids (brake fluid, engine oil, transmission system fluid, water, gas) are added to the reservoirs. The vehicle is then tested for water tightness. The final stationary road test, carried out inside the plant, ensures the vehicle and metering systems are working correctly.

Figure 1 summarizes the description of the automotive fabrication and assembly process. This formed the basis for the simulation model development of the next section.

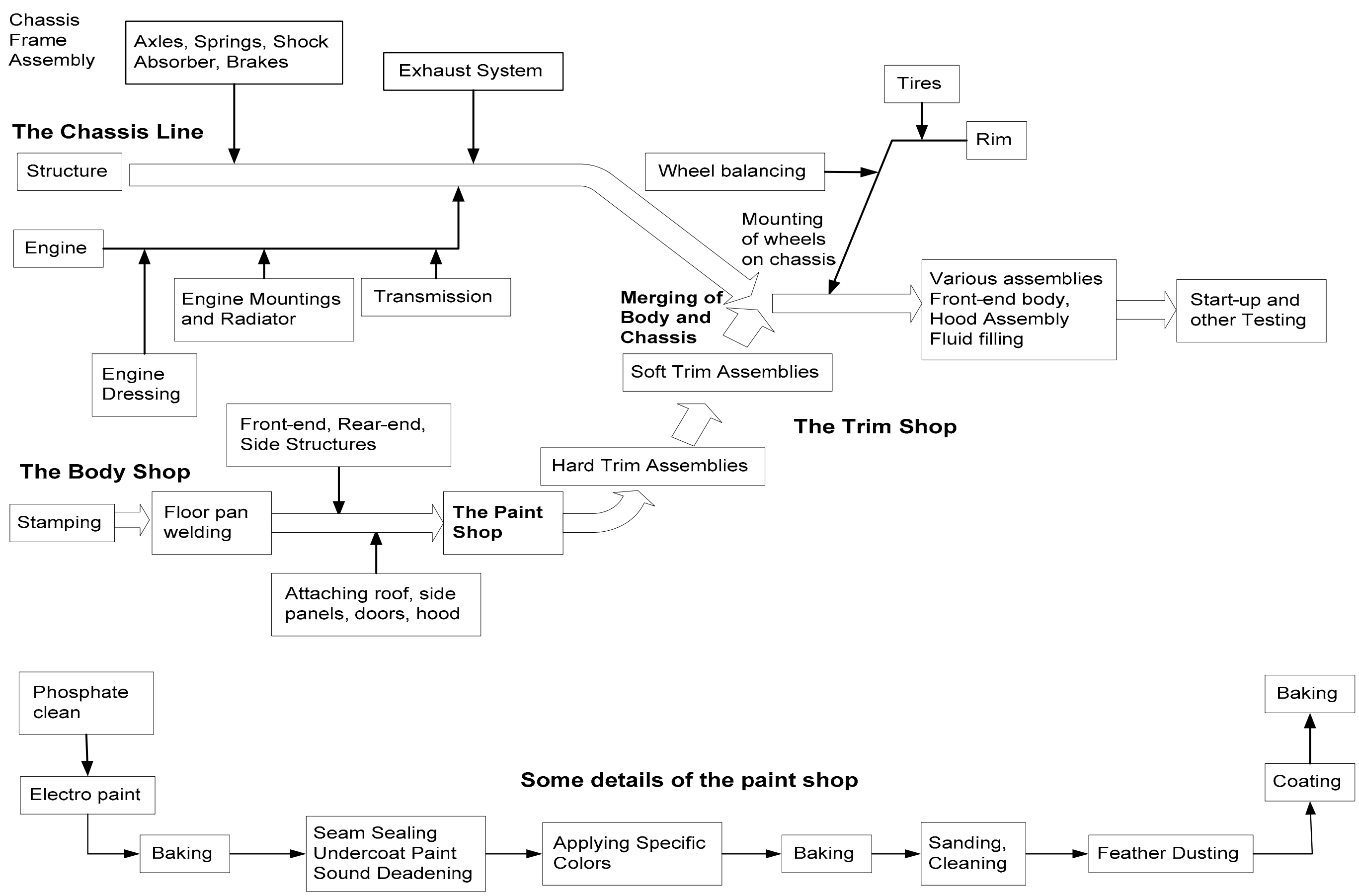

Figure 1. Basic processes in an automotive final assembly plant

3 AUTOMOTIVE ASSEMBLY SIMULATION

3.1 Product Options

There is one model of car to be manufactured but can have many options. The options on the car are that it can be either two door or four door. A two-door car will require a different body side panel from a four-door car. Additionally, the car can be either open roof or ordinary roof (closed). Either a two or four door car can have open or ordinary roof. Thus, there are four options at the "body in white" car stage. There are three color options available at the paint shop. This totals to twelve options as shown in Figure 2.

Type of car	Type of roof	Color		
		Blue	Grey	Tan
4- door car	Closed roof	**1**	**2**	**3**
	Open roof	**4**	**5**	**6**
2- door car	Closed roof	**7**	**8**	**9**
	Open roof	**10**	**11**	**12**

Figure 2. Description of options modeled in the assembly line simulation

3.2 Production Data

The simulation model receives data about required production in terms of type of car and quantities from the supply chain simulation. This information about what is to be made and in what quantities is not known before the start of a simulation run but rather this information is received dynamically during the course of a simulation run as would be the case in a real world operation. The orders are sequenced for processing on a first-come first-serve basis. In future enhancements more sophisticated sequencing procedures will be developed at the beginning of the body, the paint, and the trim assembly shops.

Variability of process time is included in the model. A probability distribution is also used to model failures at test stations. In automotive manufacturing production rates are usually described in terms of cars per hour. The production rate of the assembly plant is set at approximately 60 cars/hour. The production line is assumed to be balanced such that the sum of cycle time and transfer time between stations is approximately one minute. Considering a 10 hour shift and 2 shifts per day the production rate of the plant should be set at 1200 cars per day. Considering 5 working days a week, the weekly production level is 6000 cars. Once a car is fully assembled and has exited through the last stage on the line it is compared with the first order in the sequence. The total number of cars required to complete that order is decremented by one if the current order of car options is the same as those of the exiting car. If not, the next order in the sequence is considered. When the total number of units in an order are produced a message is sent to the supply chain simulation. In the current version of the simulation model, an order comprises only one type of product.

3.3 Delivery of Parts

When production data is received the model creates the parts required using a bill-of-materials for the required configuration of car. The parts which differ for either two-doors or four-doors or open roof and closed roof options are the underbody parts, side panels, doors, roofs, and trunk lids. When there are no orders to process the model does not have parts. The components created are joined into sub assemblies and transported by the materials handling system to stations where they are assembled to the main body of the automobile.

3.4 The Simulation Model

The simulation model of the assembly line operations was developed in Delmia QUEST. QUEST is a discrete event simulation tool with three dimensional visualization, import, and export of data capabilities. A section of the simulation model is shown in Figure 3. In addition to external interface mechanisms i.e. files and user-defined popups, QUEST uses 'sockets' as a bridge to communicate and exchange data with other simulations systems.

The workstations are arranged and connected with an appropriate materials handling system using features available in the simulation tool. Workstations are modeled as QUEST machines. In the body shop the conveyor is used as the materials handling system to move materials between stations. All components were originally modeled as separate entities that are joined to form a new part which is conveyed to the next workstation. In the paint shop the power and free system and conveyors are used for materials handling. The stations are modeled as either machines or conveyor decision points. In the trim shop, conveyors and power and free conveying systems are likewise used. Simulation control language (SCL), encoded in the process logic of workstations, is used to select the appropriate process to execute when a part arrives. Different displays, based on appearance of motor vehicles during subassembly, are used for each subassembly and component. Probability distributions of failure are used at test quality control check stations after the body and paint shops.

The CAD feature of QUEST is used to model parts and workstations in the simulation model. Others which have complex shapes, such as the car body, are obtained by importing bought models of cars. The number of units contained in buffers at stations is displayed. The number of stations has been reduced from 1200 for a typical automotive assembly plant to about 60 in the simulation model. For painting, it is assumed that there are three parallel painting lines all carrying out the same set of operations and the materials handling system is made up of conveyors and power and free systems. Cars are transported between stations in the paint and the final trim assembly shops using power-and-free and ordinary conveyor systems. The automotive final simulation model has been integrated with the supply chain using the High Level Architecture (HLA) as the Run Time Infrastructure (RTI) (McLean et. al., 2005). A demonstration of this integration has been carried out.

The simulation includes associations and interactions between the supply chain nodes. Production order requirements and other messages encoded in eXtensible Markup Language (XML) (Goldfarb, 2000) are passed from the supply chain simulation to the assembly simulation. These are the messages exchanged via sockets since QUEST does not communicate directly with other systems. Order completion and shipping messages from the assembly simulation to the supply chain components are likewise transmitted. The interaction messages use data fields consistent with those defined in Open Applications Group's Integration Specification /Automotive Industry Action Group (OAGIS/AIAG) Business Object Documents (BODs) for Inventory Visibility and Interoperability (IV&I). For example, shipment notifications that are sent from the assembly plant to dealers use XML messages that are formed using the SyncShipmentSchedule BOD specification (OAGi, 2007).

The QUEST simulation reads and sends XML messages as a single continuous string of characters. The string has to be searched for the appropriate information it contains. For example, car order data on specifications and quantities are extracted from the XML message and stored in a dynamic SCL list structure. This list is updated with the arrival of a new order when a new one arrives. When a particular order is completed it is deleted from the list. An example XML shipment message is indicated in the exhibit in Figure 4. Since orders are received and executed dynamically we will refer to a current order (CurOrder). The CurOrder->orderId refers to the current order identification. MyFactory and MyDealer refer to the plant and dealer identification. The CurOrder->shippingInfo in the shipping information. Other information are the CurOrder->CarType and CurOrder->Quantity, which refer to the type of car and the quantity that has been shipped.


```
<?xml version="1.0" encoding="utf-8" ?>
- <AcknowledgeShipment xmlns =
"http://www.openapplications.org/oagis/9"
xmlns:xsi=http://www.w3.org/2001/XMLSchema-instance
xsi:schemaLocation="http://www.openapplications.org/oagis/9
../../BODs/Developer/AcknowledgeShipment.xsd">
- <ApplicationArea>
- <Sender>
 <LogicalID>123</LogicalID>
 </Sender>
 <CreationDateTime>2006-08-13</CreationDateTime>
 <BODID>CurOrder->orderId</BODID>
 </ApplicationArea>
- <DataArea>
- <Shipment>
- <ShipmentHeader>
 <ActualDeliveryDateTime>2006-08-13
 </ActualDeliveryDateTime>
- <ShipFromParty category="Organization">
- <PartyIDs>
 <ID>123</ID>
 </PartyIDs>
 <Name>MyCarFactory</Name>
- <Location>
 <ID>123</ID>
 </Location>
 </ShipFromParty>
- <ShipToParty category="Organization">
- <PartyIDs>
 <ID>123</ID>
 </PartyIDs>
 <Name>MyDealer</Name>
- <Location>
 <ID>123</ID>
 </Location> CurOrder->shippingInfo
 </ShipToParty>
 </ShipmentHeader>
- <ShipmentItem>
- <ItemID>
 <ID>CurOrder->CarType</ID>
 </ItemID>
 <Description>MyFirstCar</Description>
- <PurchaseOrderReference>
- <DocumentID>
 <ID>123</ID>
 </DocumentID>
 </PurchaseOrderReference>
- <ItemSubLine>
 <Quantity>CurOrder->Quantity</Quantity>
 </ItemSubLine>
 </ShipmentItem>
 </Shipment>
 </DataArea>
 </AcknowledgeShipment>
```


Figure 4: XML Message notifying headquarters of the completion of a production order.

4 THE WAY FORWARD

The project has gone through the first phase of developing the simulations and integrating with the HLA so that the simulations can exchange messages. Future plans in the development of the generic simulation will increase the sophistication of the model to make it more reflective of real production systems, and to handle a wider range of exchanged messages. The following are planned to be incorporated:

- The number of workstations will be increased.
- A system using a set of rules to be written in QUEST simulation control language (SCL) will be incorporated to sequence orders. This could also be implemented by an external application. Orders that are completed will be deleted while new ones will be dynamically added to the sequence. The information to consider in sequencing will be the customer, estimated lead time of the parts and components, due-date customer requirements, capacity of the plant, estimated start time for the order, etc. Similar sequencing logic will be used before beginning paint and final assembly processes.
- The delivery of raw materials and parts for assembly will depend on a forecast of expected production. In this case, lead time of the acquisition of parts will be taken into account. We will also consider the lot sizing of parts during ordering.
- Initial inventory in the model will either be read into the model or carried over from a previous simulation run. At the start of the simulation the model need not be empty of parts.
- Additional information will be exchanged between the supply chain and assembly plant simulations rather than just the orders.
- The customer order will comprise of more than one product by increasing sophistication in the exchange and interpretation of messages.
- In addition to showing the quantities of parts at the stations, the buffer storage will be made to change color if the quantities of parts at a station falls below a pre-defined level.
- The logic should allow the plant to stop if the quantities of given parts at a station are used up or if the quantities have fallen below a predetermined level.
- There will be a dynamically updated inventory file to allow sending a message when a replenishment is required.
- The model to include taking care of contingencies such as breakdowns, downtime, and time to repair.
- Final assembly plant information such as process times, part routing, and process definition. will be defined outside the model using XML and read into the simulation at initialization. The plan is to utilize automotive assembly using the Core Manufacturing Simulation Data (CMSD) specification (CMSD Product Development Group, 2006) currently under development. Such data can be applicable to other simulation systems and can also be changed with minimal or no change to the simulation model.
- The animation of operations of some workstations using Delmia IGRIP and incorporate them into the QUEST model.

5 CONCLUSION

This paper has described the development of an automotive final assembly simulation model to enable interoperability testing of data exchanged across a supply chain from headquarters to shipping. The model has been integrated with the supply chain simulation developed in another system (ARENA) using the High Level Architecture. Production orders and completed order information has been exchanged across simulations. Further improvements in sophistication of the simulation model will enable it to handle a wider range of products and exchange a wider range of messages. It will also largely be run on neutral data, which will be defined outside the model and read in at initialization time. This will reduce the model modification effort. The simulation model will also facilitate the development and testing of a hierarchical planning system approach where a central Enterprise Requirements Planning (ERP) system controls all operations including inventory management, products, and scheduling. It will also enable the testing for exchange of data from the highest level of simulation (supply chain) to the lowest level (machine operation) including Programmable Logic Controllers (PLC) systems since generally these would be modeled using different software.

As standards for interoperability of information systems continue to develop, the need for such generic models to test these standards will increase. The current project at NIST is aimed at enabling testing of manufacturing engineering processes including design data, engineering, and production planning. When this is facilitated it will help reduce costs associated with lack of interoperability of data exchange not only in automotive, but also in other manufacturing environments.

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DISCLAIMER

A number of software products are identified in context in this paper. This does not imply a recommendation or endorsement of the 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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AUTHOR BIOGRAPHIES

DEOGRATIAS KIBIRA is a Senior Lecturer in the Department of Mechanical Engineering at Makerere University in Uganda where he teaches Manufacturing and Quality systems. He has wide research experience in manufacturing simulation and production scheduling. He is currently a Guest Researcher at the National Institute of Standards and Technology where he is part of the research team involved in the development of a Virtual Manufacturing Environment (VME) for automotive manufacturing. He has a first class honors degree in Mechanical Engineering from Makerere University and Masters and PhD degrees in Manufacturing Engineering from the University of New South Wales, Australia. His e-mail addresses are <dkibira@tech.mak.ac.ug> and <kibira@cme.nist.gov>.

CHARLES R. MCLEAN is a computer scientist and Group Leader of the Manufacturing Simulation and Modeling Group at the National Institute of Standards and Technology. He has managed research programs in manufacturing simulation, engineering tool integration, product data standards, and manufacturing automation at NIST since 1982. He has authored more than 50 technical papers on topics in these areas. He is on the Executive Board of the Winter Simulation Conference and the Editorial Board of the International Journal of Production, Planning, and Control. He is formerly the Vice Chairman of the International Federation of Information Processing (IFIP) Working Group on Production Management Systems (WG 5.7). He holds an M.S. in Information Engineering from University of Illinois at Chicago and a B.A. from Cornell University. His e-mail address is <charles.mclean@nist.gov.>

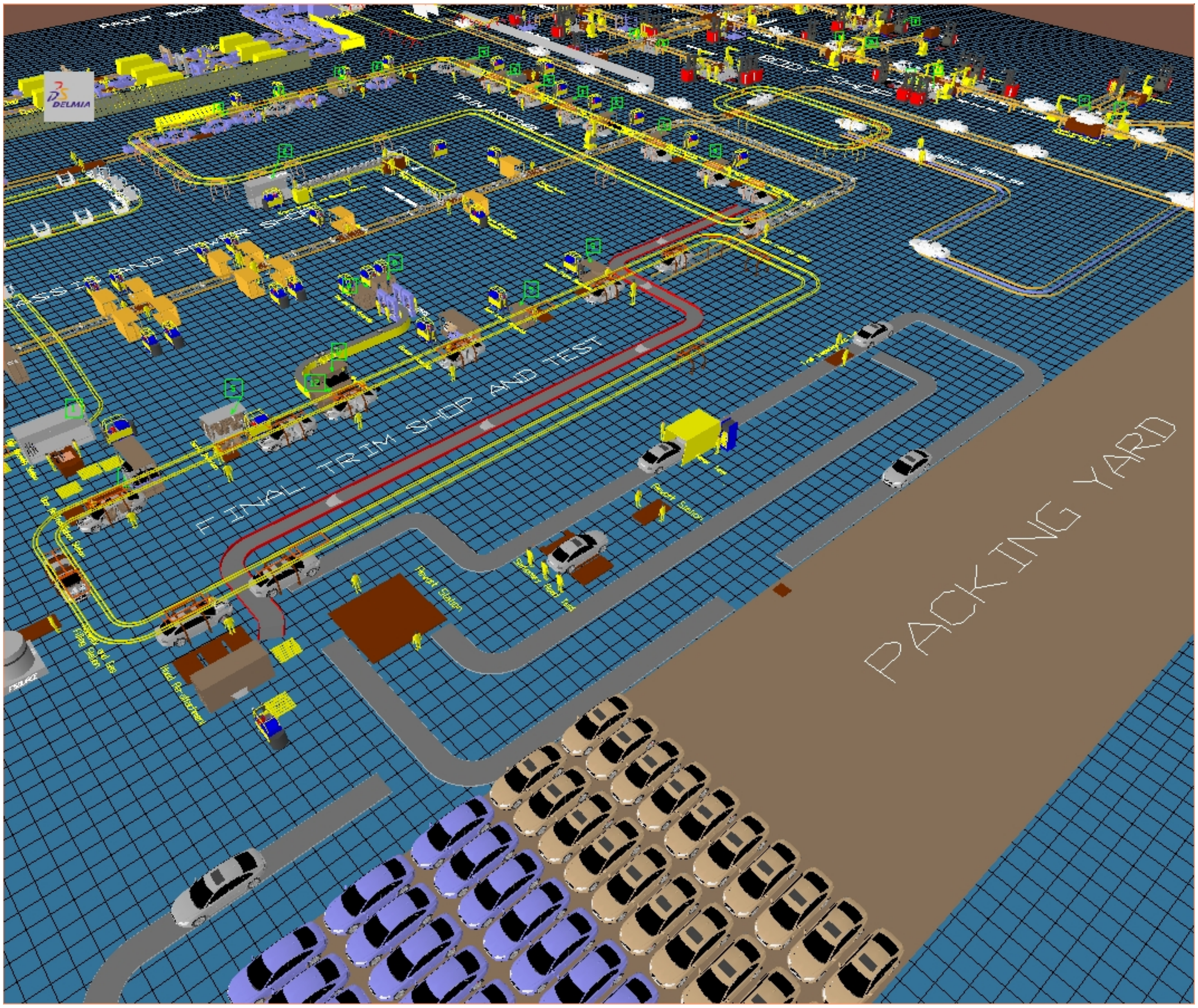

Figure 3: Screen shot of the automotive manufacturing assembly plant simulation.