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# VIRTUAL REALITY SIMULATION OF A MECHANICAL ASSEMBLY PRODUCTION LINE

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## ABSTRACT

This paper presents our work on the application of virtual-reality simulation to the design of a production line for a mechanically-assembled product. The development of this simulation was undertaken as a part of the Manufacturing Simulation and Visualization Program at the National Institute of Standards and Technology in Gaithersburg, MD. The major research problem is the partitioning and analysis of the assembly operation of the prototype product into different tasks and allocation of these tasks to different assembly workstations. Issues such as cycle times, material handling and assembly line balancing complicate the problem. This paper demonstrates the difficulties of using simulation modeling for concurrent graphical simulation of assembly operations and discrete event analysis of a production process in the same model. It also points out the need to speed up the modeling process and reduce the level of effort required in the construction of a simulation model.

## 1 INTRODUCTION

Computer simulation shows great promise for raising productivity, improving product quality, shortening lead times, and reducing costs in the future. However, today the application of this technology is not very widespread in the manufacturing industry. One of the major reasons for this fact is that simulation modeling and analysis is a labor-intensive and time-consuming activity. Today, the trend in manufacturing industry is to be more responsive to changes in product design and market conditions. Simulation modeling would tend to delay that process. Reducing time and the high level of effort will require the development of new simulation capabilities that automate the input of simulation parameters and data to speed up the model-building process (Umeda 1999).

The mainstream research in the application of simulation for solving manufacturing problems has focused on investigation of the dynamics of the current system and how it can be improved by additional equipment or better scheduling and a resources allocation system (Williams *et al.* 2001). Simulation research and application has also dealt with development of visual interactive simulation systems to act as a common mode of communication between experts from different domains. Such a simulation could be the best aid in decision making during design and improvement of a manufacturing system (Albastro *et al.* 1995, West *et al.* 2000). Considerable research has also recently focused on the application of simulation in enterprise design and enterprise integration such as reported in Harding and Popplewell (2000).

This paper investigates and demonstrates the application of computer simulation for the design of a manufacturing process for a manually-assembled mechanical product in a virtual-reality environment. It also discusses the difficulties as well as solutions that can be devised to speed up the process of model building for this type of application.

### 1.1 Research Program Background

The assembly-line system design and simulation modeling is being undertaken as part of the NIST Manufacturing Simulation and Visualization Program and the Intelligent Manufacturing Systems (IMS) Project officially called "Modeling and Simulation Environments for Designing, Planning and Operation of Globally Distributed Enterprises" or MISSION. The goal of the NIST Manufacturing Simulation and Visualization Program is to establish standard interfaces and develop conformance tests for:

- manufacturing simulation to support the rapid construction of distributed manufacturing simulation systems based upon a High Level Architecture (HLA) foundation and
- discrete-event simulation models based upon a neutral library of simulation components that will be adopted by simulation software vendors in future product offerings.

The MISSION project seeks to integrate and utilize data modeling and management technologies to meet the needs of globally distributed enterprise modeling and simulation. Members of the MISSION Consortium include manufacturers, software vendors, government agencies, and academic research organizations in the United States, Japan, and Europe. Black and Decker is one of the members of the U.S. MISSION team. The parts described in this paper and our simulation are characteristic of those manufactured by Black and Decker.

### 1.2 Taxonomy of Simulation Study Types

A major objective of the NIST Manufacturing Simulation and Visualization Program is to develop a classification system of simulation study types, i.e., a taxonomy. One of the major purposes of the taxonomy is to provide a framework for the identification of interface data requirements for future simulation standards.

The proposed simulation taxonomy organizes simulation studies along three axes or dimensions. The first dimension is industrial domain. Standard industrial codes provide one possible framework for organizing industrial domains. The second dimension identifies study requirements by manufacturing system, their function, and hierarchical level. The third dimension identifies input, output data elements, and algorithms needed to support the simulation studies.

The long-term objective of the taxonomy is to identify and exploit commonalities among industries, manufacturing systems, and their component elements in the development of models and interfaces. Many manufacturing systems and studies will be common across industries, e.g., machine shops and materials handling systems. The required standards for data structures (inputs, outputs, internal) and algorithms are determined by simulation study type, system level, and industrial domain. Simulation study areas should provide building blocks or templates that can be assembled to solve a specific set of industrial problems.

### 1.3 Simulation Study of a Small Assembly Line

One of our major objectives is to identify the data requirements and issues associated with a simulation study of a small assembly line. As such, the simulation model of the production line may be used to:

- support the definition, design, and actualization of the overall system
- evaluate different decision options for the design or reconfiguration of the production line, for example:
    - loading options, part mix
    - number of stations, layout
    - allocation of operations to stations, cycle times for operations, tooling requirements
    - equipment selection, process and support equipment
    - staffing options
    - workstation space requirements
    - buffer storage requirements
    - materials handling requirements, etc.
- generate cost and performance data for the operation that cannot be calculated in a straightforward manner
    - throughput
    - resource utilization, idle times
    - identify bottlenecks
    - effects of breakdowns, rejects, and rework
    - service and material replenishment requirements
    - effect of shift scheduling on throughput and cost
- demonstrate and/or visualize the operation of the line.

Data requirements for simulation study include:

- product design, bill of materials, assembly constraints
- assembly process specification including operation sequences, process times, and testing requirements
- expected product demand
- failure and repair data for production line systems
- system configuration and layout options
- unit cost of labor, tooling, and materials

## 2 MANUFACTURING PROCESS DESIGN

The research focused on three manufactured products: a handheld power drill, a palm-grip finishing sander, and a jigsaw. Due to the limited space available in this paper, only full procedure for the drill is described. QUEST$^R$ and IGRIP$^R$ were the simulation application tools used to develop the models. IGRIP$^R$ provides the graphical ergonomic modeling of workstation operations. QUEST$^R$ provides the discrete-event modeling of the overall production line. These tools complemented each other in the determination of process times, assembly line balancing and discrete analysis of the process. Other issues that were addressed included buffer storage spaces, production scheduling issues, and material handling requirements. This paper explains our procedure for simulation modeling, difficulties encountered, and how they were resolved.

## 2.1 Design Process Overview

Our approach was to assume that we had to develop the manufacturing process design for a prototype product for which the assembly line had yet to be realized. As such, the procedure is as follows:

- (i) A prototype of the product is disassembled to determine the components parts list and quantity. Table 1 shows some of the components that make up the product.
- (ii) An assembly tree is constructed showing the different stages of assembly of the product and the sequence of the various assembly processes.
- (iii) Using precedence relations between assembly operations and time associated to perform each operation, a number of operations are aggregated into tasks that can be performed at a single workstation.
- (iv) The arrangement of workstations on the production line was determined.
- (v) Material handling requirements were also specified.

Table 1: Component Parts

| Item No. | Description | Quantity |
|---|---|---|
| 1a | Housing | 1 |
| 1b | Housing Cover | 1 |
| 2 | Spindle & Pin | 1 |
| 3 | Spindle Gear | 1 |
| . | . | . |
| . | . | . |
| . | . | . |
| 23 | Nameplate | 1 |
| 24 | Identification Label | 1 |
| 25 | Brush Assembly | 2 |

## 2.2 Description and Analysis of Assembly Operations

The manufacturing process, which is essentially manual assembly, was partitioned into a number of assembly operations. The duration of each operation and the precedence relationships between the operations were estimated based on what an average person might do. Rigorous time studies were not performed. Figure 1 shows the assembly tree for the product. Table 2 illustrates a breakdown of operations, their descriptions, and the assembly precedence relationships between the operations.

## 2.3 Workstation Assembly Operations Assignments

The process of determining which operations were to be assigned to a workstation is an assembly-line balancing problem. The problem is one of optimally partitioning, or balancing, the assembly work among the stations with respect to some objective. Assembly lines are special flow-line production systems, which are typical in the industrial production of high-quantity standardized products. They have advantages in that flow of materials is regular and can be controlled. Flow lines generally need less material handling than job shop production since work pieces are transferred between stations using mechanical handling equipment such as belt conveyors. Usually there is storage space for components and incoming subassemblies at each workstation. More than one product may be handled by one assembly line in which case it is called a mixed model production line. Analysis of assembly line systems has been given considerable treatment in industrial engineering literature. See Scholl (1999) and Bard (1989).

An iterative approach was used without mathematical formulations. The next sections will describe this approach. The production-line simulation was originally developed in the discrete-event simulation application to determine a time window for the cycle time of each station. The time window was then fed to the human simulation of station operation for determining feasibility. Also, a number of operations would be assigned to a workstation and simulated to determine the estimates of the cycle time in the ergonomics work cell of the station. In case of a significant difference between these two cycle times for each station, some operations could be moved to a precedence station or to a succeeding station. Alternatively, operations from either of these two stations would be added to the current station. The process repeated until a balanced production line is obtained. Table 3 shows the grouping of manufacturing operations at each workstation.

After the assembly of the product, three additional stations- Inspection and Test, Repair, and Packing were added to complete the power drill manufacturing process. The descriptions of operations for these stations are described in the next section.

## 2.4 Additional Workstation Operations

*Inspection and Test Station*

1. Pick completed unit and inspect it visually.
2. Use chuck key to insert a drill.
3. Connect the cord to the power supply.
4. Test its performance taking not of power output and speed of rotation while listening for any vibrations.
5. Decide to accept or reject the unit.
6. If the unit is accepted place it in outbound bin or belt conveyor.
7. If the unit is not faulty and needs repair put in bin designated for repair.
8. If unit is faulty beyond repair send to scrap.

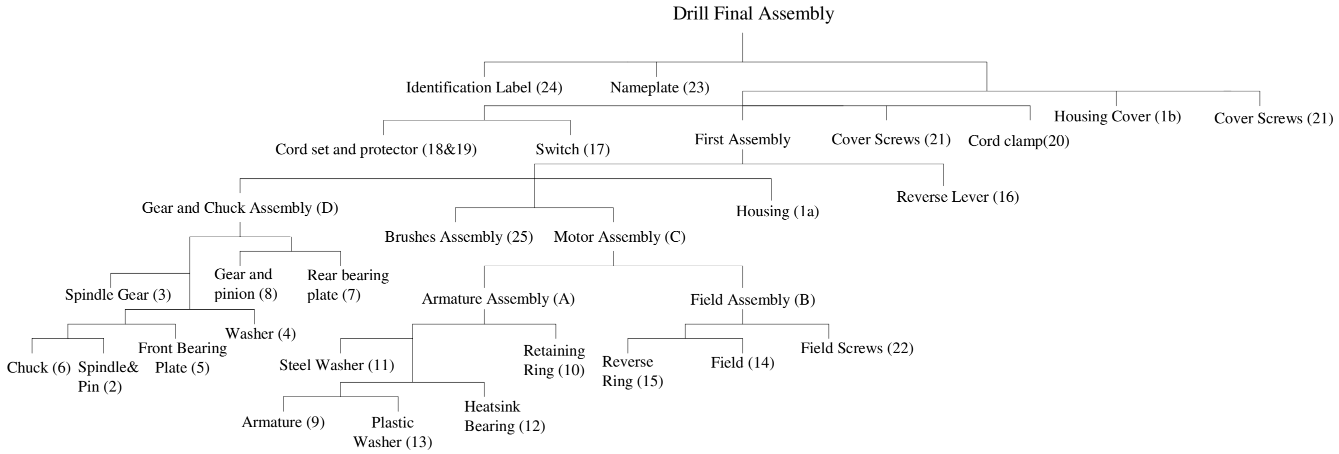

Figure 1: Assembly Tree

Table 2: Assembly Plan

| Operation No. | Precedence Activity | DESCRIPTION | Duration (Sec) |
|---|---|---|---|
| 1 | - | Insert *Plastic Washer* (13) into *Spindle* of the *Armature* (9) | 5 |
| 2 | 1 | Insert *Heatsink Bearing* (12) into the spindle on the same side as the *Washer* (13) | 5 |
| 3 | 2 | Insert *Steel Washer* (11) into spindle after the *Heatsink Bearing* (12) | 5 |
| 4 | 3 | Insert *Retaining Ring* (10) into spindle to lock bearing in place. Place the subassembly onto worktable | 15 |
| 5 | - | Attach *Reverse Ring* (15) onto the *Field* (14) manually | 15 |
| 6 | 5 | Use 2 *Field Screws* (22) to fix *Reverse Ring* (15) onto the *Field* (14) | 20 |
| 7 | 3,5 | Insert the *armature subassembly* (obtained in operation 4) into the *Field Subassembly* (obtained in operation 6) | 5 |
| 8 | - | Push and fit *Chuck* (6) onto *Spindle and Pin* (2) | 15 |
| 9 | 8 | Press fit the *Front Bearing Plate* (5) onto the *Spindle* (2) | 10 |
| 10 | 9 | Insert the *Washer* (4) | 5 |
| 11 | 10 | Press fit the *Spindle Gear* (3) | 15 |
| 12 | - | Insert the *Gear and Pinion* (8) onto the *Rear Bearing Plate* (7) | 10 |
| 13 | 9,10 | Attach the *Chuck Assembly* (obtained in 9) to the *Gear Assembly* (obtained in 10) | 10 |
| 14 | - | Attach the *Brush Assemblies* (25) and bearing onto the armature connections. | 20 |
| 15 | 4 | Insert the *Motor* (obtained in 4) into the *Housing (1a)*. | 15 |
| 16 | 13,15 | Place *Chuck Assembly* and *Gear Assembly* into the *Housing (1a)*. | 10 |
| 17 | 16 | Insert the *Reverse Lever* (16) into the *Housing* and connect to the *Reverse Ring* (15). | 15 |
| 18 | 17 | Attach *Cord set and Protector*(18&19) to *Switch* (17) and insert assembly into *Housing (1a)*. | 20 |
| 19 | 18 | Attach end of *Cord set and Protector* (18&19) to *Armature* (9) connections. | 10 |
| 20 | 19 | Use *cord Clamp* (20) and 2 *Cover Screws* (21) to attach *Cord set and Protector*(18&19) to *Housing (1a)*. | 15 |
| 21 | 20 | Screw *cover* (1) to housing to complete the assembly using eight *Cover Screws* (21). | 20 |
| 22 | 20 | Attach *Nameplate* (23) and *Identification label* (24) to the completed assembly. | 10 |

Table 3: Workstation Operation Assignment

| WORKSTATION NAME | OPERATIONS NO. |
|---|---|
| Motor Assembly | 1,2,3,4,5,6,7 |
| Chuck and Gear Assembly | 8,9,10,11,12,13 |
| First Final Assembly Stage | 14,15,16,17 |
| Final Assembly Stage | 18,19,20,21 |

*Repair Station*

1. Pick completed unit and open cover using a screwdriver.
2. Do the necessary repairs and tests.
3. Carry back to Inspection and Test.

*Packing Station*

1. Attach the identification label and nameplate to the completed unit.
2. Get a packing box.
3. Fold cord and insert unit in cellophane bag and then in the packing box.
4. Close and seal the box.
5. Place the box on the conveyor.

### 2.5 Production Line Design Description

The production resources are organized as a flow line consisting of a series of workstations that execute different operations. The components are received at staging areas and carried to the first stage in the assembly process in bins by operators responsible for the process. A repair station is added for assemblies that fail inspection and testing. Assemblies that cannot be repaired are scrapped. An accumulating-belt conveyor links most workstations. Figure 2 shows the sequence of assembly operations that define the drill-assembly process.

The purchased components are packed into bins and picked by operators who transport them to their workstations for assembly. They are then assembled into subassemblies and carried to the next station by the same operator after a given number of parts have accumulated in the output bin. The operator empties subassemblies at the next station and returns with the empty bin to his/her station.

## 3 SIMULATION MODELING OVERVIEW

### 3.1 Software and methods

The simulation model was constructed using three software applications. A CAD package was used for modeling the geometry of components. The two simulation tools were used to model individual station operations and the overall flow of the line, as schematically represented in Figure 2. The synergistic effect of different software applications provided a platform upon which the simulation model of the manufacturing system was built. The applications that were used are:

(i) QUEST$^R$, for discrete event modeling.
(ii) IGRIP$^R$ and the ERGO Option for script development and animation of work cell operations.
(iii) AutoCAD$^R$, a computer-aided design application for object modeling.

### 3.2 Object Modeling

The CAD system used for modeling objects is both a two- and a three-dimensional (2D-3D) design and drafting plat-

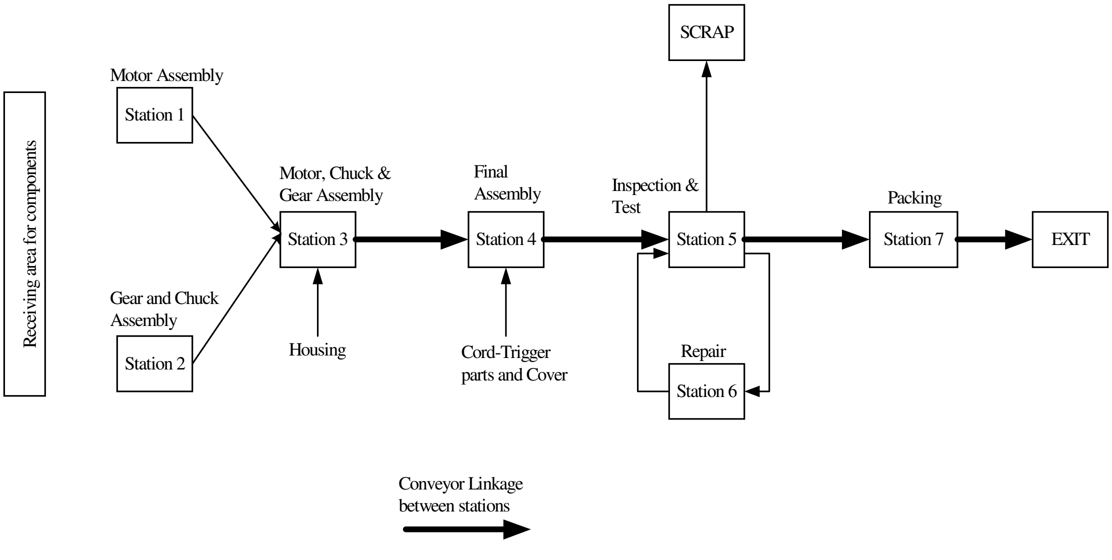

Figure 2: Schematic Representation of the Assembly Process

form that automates design tasks. Various professionals such as architects, engineers, drafters, and design-related professionals use it to create, view, manage, plot, share, and reuse accurate, information-rich drawings.

The components and subassemblies of the product and tools, input and output bins, subassemblies and fixtures were modeled manually using the CAD tool. The models of the components and parts were exported into the simulation applications using the stereolithography (STL) file export feature.

### 3.3 Modeling Workstation Motion Scripts

IGRIP$^R$ was used for 3D graphical modeling and visual representation. It has an ergonomics-analysis option (ERGO) that can be used to model assembly and materials handling operations between workstations. This option is basically used to design safe working environments that accommodate a wide range of workers and for ergonomic assessment and task analysis. It was used to address the human interface issue that impacts the ability of a wide range of humans to assemble the prototype product and the process times needed for each task. Libraries of whole body and hand postures were used. The software also provided point and click routines to generate walking, climbing, lifting and carrying sequences.

Figure 3 shows an example of a workstation and operator modeled in IGRIP$^R$. To model a workstation operation, the worktable, parts and bins and human operator were imported as "devices" and placed at appropriate locations in the workstation. Using the ergonomics option, the human device was "taught" to perform the assembly process by creating a series of positions of the human hands while holding and assembling the product. Other features that were used provided functions for "grabbing" and "releasing" objects, orienting operator limbs in various positions, walking, bending and rotating fingers. The successive positions of operator and part during operation of a station were stored and later played like a video recording. Interpolation between consecutive positions produced the appearance of smoothly connected operations.

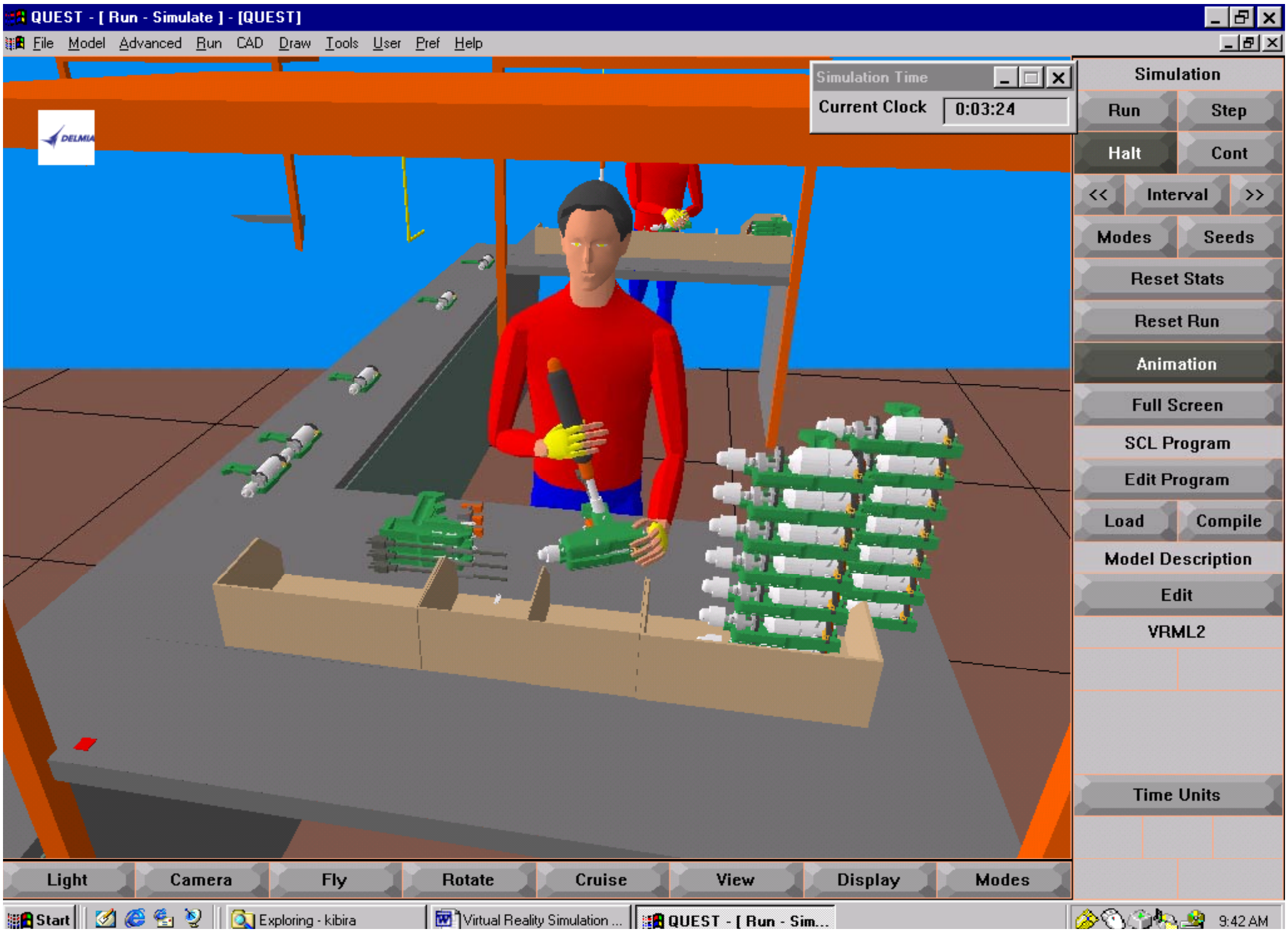

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Figure 3: An Operator Finalizes the Assembly of a Hand-Held Power Drill

### 3.4 Virtual Reality-Based Discrete Event Model

The simulation model of the production line operation representing workstations and materials handling systems as described in the preceding sections was developed in QUEST$^R$. QUEST$^R$ is an object-based, discrete event simulation tool. It was used to model, experiment with, and analyze facility layout and process flow. It provided visualization and data import/export capabilities.

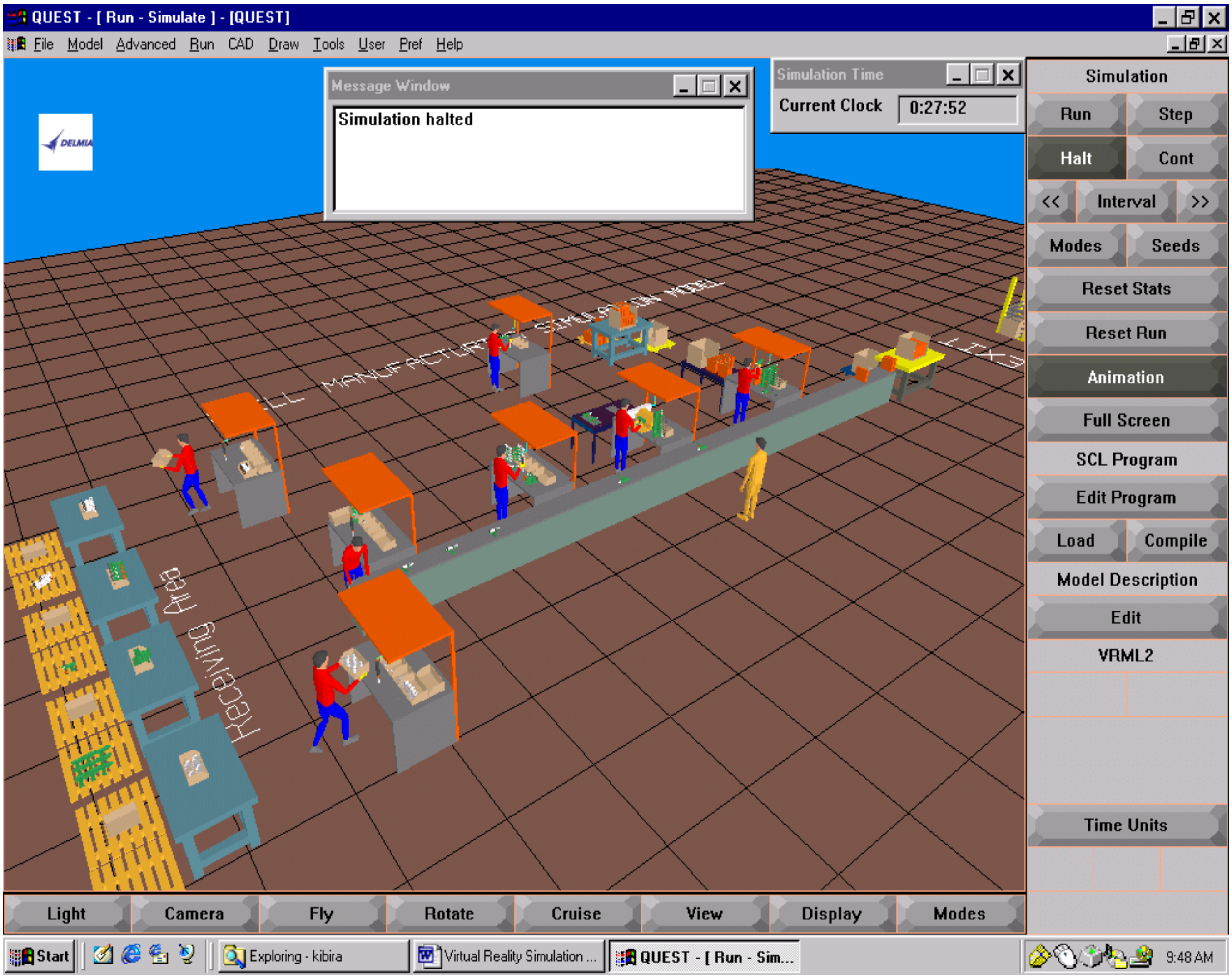
This simulation application was used to construct the simulation model of the production line which was then populated with pre-built sub-models that were generated as described in the proceeding sections. The process of incorporating workstation sub-models into the discrete-event-simulation model was basically simple. Initially, the workstation operation was played and recorded in the graphical modeling application. It was then exported as a QUESTCELL file.

Using the display option provided in the discrete-event-simulation tool each station was displayed as the imported workstation sub-model. Similarly, the scripts associated with a human carrying a bin of components or sub-assemblies between stations were determined and imported. Figure 4 shows what the QUEST$^R$ simulation model looks like after importing and integrating the workstation models that were developed in IGRIP$^R$.

The DELMIA Simulation Control Language (SCL) was used to more accurately program the display of the actions of material handling and workstation operations by the same operator.

## 4 DISCUSSION AND CONCLUSIONS

This paper has demonstrated a method of designing a manufacturing process from a prototype of the product us



Simulation halted

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Figure 4: Snapshot of the Simulation During a Run

ing virtual-reality simulation modeling. The simulation model has been constructed using both graphical modeling of detailed manual operations and discrete event simulation of overall process flow. The discrete event modeling was a relatively easy process. However, the construction of animated workstation sub-models was found to be time-consuming and tedious. This problem was especially true for the development of operator kinematics scripts required for determination of workstation cycle time and illustration of the assembly process. An approach that can speed up the modeling process and simplify this process would be desirable.

Current simulation systems do not provide standard formats for reading product attributes, processing times, and material quantity requirements from data files or other data sources. In the same way, we would like to be able to read and write external, process-specification data files that would drive the simulation of the assembly of the product. Neutral formats for reading these types of data would be very useful.

One can also imagine a situation where an operator at a station can not only read assembly instructions from a file but also be able to intelligently learn and adapt to different situations and products. As such, it should be possible that the logic that controls the simulation and directs interaction between various elements of the model is read from outside of the model. This would make it easier to investigate different scenarios and interaction rules between elements during the experimental phase. It would be useful to create an environment that integrates and facilitates planning, visualization, validation, documentation, and training production workers on the manufacturing process.

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