CHAPTER 15

Simulation in the Automobile Industry

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15.1 INTRODUCTION

In this chapter we discuss the use of computer simulation in design and operation of car and truck assembly plants as well as automotive components manufacturing plants. Most of the automotive manufacturers worldwide and, in particular, the big three U.S.-based companies (General Motors Corporation, Ford Motor Company, and Chrysler Corporation) currently require that all new and modified manufacturing system designs be verified by simulation analysis before they are approved for final equipment purchases. In fact, there is a general push in the big three automotive companies that any new equipment purchase or manufacturing line modification costing more than several million dollars should be verified by simulation modeling before approval. Studies performed in the past are indicators of how useful simulation could be in the design and operation of production systems of all kinds, including vehicle manufacturing. Examples can be found in refs. 1 to 8.

In what follows, we discuss mainly the applications of discrete-event simulation in the automotive industry, with some discussion of the emerging role of robotics simulation. Applications of discrete-event simulation in the design and operation of vehicle manufacturing systems can be categorized in two different ways. The first classification is based on the stage of the development of the design of the system. Four categories are observed in this classification: conceptual design phase, detailed design phase, launching phase, and fully operational phase. The *conceptual phase* refers to the initial stage where new methods of manufacturing and material handling are tested by the engineers. Discrete-event simulation packages with three-dimensional animation capabilities are the popular simulation tools at this phase. The *detailed design phase* refers to the stage where

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detailed layout plans and equipment specifications are verified for the system. The principal factors considered here include equipment justifications (e.g., the number of hold tables, power and free carriers, the size of buffers), cycle-time verifications (e.g., conveyor speeds, line throughput), and line operational and scheduling issues (e.g., logic for evacuating ovens and paint booths, repairs, and product mix decisions). Discrete-event simulation packages with built-in detailed equipment features and three-dimensional animation features appear to be the most popular packages used at this stage. The *launching phase* refers to the stage where the plant operates below the designed operational conditions. In some cases it may take up to 6 months for the plant to operate under maximum-capacity conditions. Simulation studies performed at this stage are generally used to test operational policies (e.g., operate one of the two paint booths at a time, run each shop for one-half of the total available time, use different product mixes). Discrete-event simulation packages used at this stage do not typically require the detailed equipment features or the three-dimensional animation features. The simulation program generators with user-friendly features are the most popular packages used at this phase, as models tend to be at a macro level rather than a micro level. An explanation of macro and micro models, and an example of their interactions, appears in ref. 9. The *fully operational* phase refers to the stage where the plant is operating at its anticipated capacity. The simulation studies done at this phase consider product mix decisions, new product introductions, new operational policies, and line modifications. Simulation software used at this phase generally require the same capabilities as those used at the launching phase.

The second classification of the use of discrete-event simulation in automotive manufacturing plants is based on the nature of the problem to be investigated. Four major categories can also be identified in this classification: equipment and layout design issues, issues related to variation management, product-mix sequencing issues, and other operational issues. The equipment and layout design issues include typical problems such as number of machines required, cycle-time verification, identification of buffer storage locations, buffer size (strip conveyors and buffers for sequencing) analysis, and conveyor length and speed determination. Examples of typical problems in the variation management area are repair and scrap policy analysis, order-size variation, and paint booth scheduling. The *product-mix sequencing issues* typically include trim line and body shop sequencing, shift scheduling, and trim and final assembly line balancing. In the *other operational issues* area, typical applications involve priority assignment at traffic intersections, assembly-line sequencing, and shift and break scheduling. Table 15.1 summarizes various uses of simulation in vehicle assembly plants. The x-marks indicate typical phases(s) where simulation can play an essential role for the application area listed and where certain types of problems are more likely to be attacked by the designers or managers. For example, cycle-time verification problems are more likely to arise at earlier stages of the design and operation cycle. However, shift-scheduling problems are likely to be solved once all equipment and layout design issues are finalized. It should be noted, however, that the table constitutes only a broad framework since, in reality, each type of problem area can be attacked in any phase of the design cycle.

In the following sections of this chapter, we discuss applications of discrete-event simulation in assembly plants, major-component plants, and small-components plants. Then we consider the nonmanufacturing applications of discrete-event simulation. In the following section we discuss the role that corporate groups, simulation service vendors, and equipment suppliers play in applying simulation in the automotive industry.

TABLE 15.1 Classification of the Applications of Simulation in the Automotive Industry

Application Category	Example Application	Phase			
		Conceptual Design	Detailed Design	Launch	Full Operation
Equipment and layout	Buffer size analysis	x ◀	x	x	
	Surge bank locations	x	x	x	
	Cycle time verification	x	x	x	x
	Conveyor length and speed	x	x	x	
Variation management	Test-repair loop analysis		x	x	x
	Scrap analysis		x	x	x
	Paint gun spray purge scheduling		x	x	x
Product mix sequencing	Trim line sequencing		x	x	x
	Body shop sequencing	x	x	x	x
	Shift overlap	x	x	x	x
Detailed operational issues	Traffic priority management		x	x	x
	Assembly sequencing		x	x	x
	Shift and break scheduling		x	x	x

Simulation model life-cycle approaches are discussed next. In the final two sections of the chapter we review the emerging role of robotics simulation and discuss trends in the future of simulation in the automotive industry.

15.2 APPLICATIONS IN ASSEMBLY PLANTS

An automotive assembly plant typically has three major sections with respect to the stages of the assembly process: body shop, paint shop, and trim and final assembly (Figure 15.1). Each of these areas has different types of processes with unique features. There are many issues in an assembly plant that are addressed effectively through simulation. Following is a discussion of the typical issues.

The major components of a vehicle body are assembled in the body shop. The major components typically come from stamping plants. The inner and outer faces of doors, the inner and outer faces of body sides, the hood, and the trunk lid are some of those parts that go into body shop operations. The process to assemble body parts includes stations to bring components loosely together, stations to weld the components, and stations to inspect the structural integrity of the welded components. In the body shop, the emphasis is on the process more than on material movement. The operation times are very dependent on the model of the vehicle being made. Most operations require subassemblies to stop at a station for processing. The reliability of process machinery is the critical part of many problems that can be observed in a typical body shop. Consequently, adequate representation of the machine breakdowns and cycle times is an important part of a body shop simulation. Additional discussion of downtime modeling appears in ref. 10.

Once all major body parts are assembled, the body is sent to the paint shop as the second major phase in the assembly process. A typical paint shop will consist of several painting processes. In rough order, those processes include electrocoating, sealing, prime painting, main color painting, inspection, and auxiliary

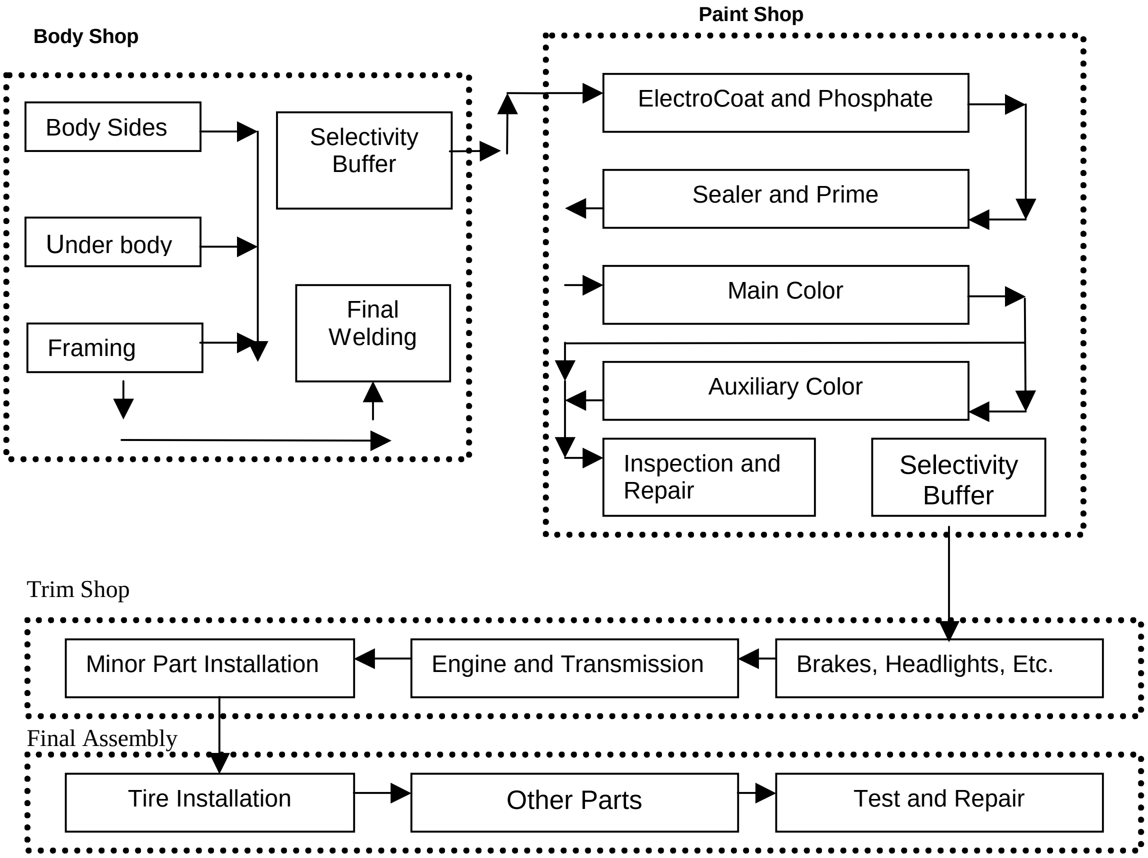

Figure 15.1 Parts of and job flow in a typical automotive assembly plant

painting operations. The paint shop processes are such that many of the operations can be performed without stopping the vehicle at a station. Therefore, the capability and the reliability of the material handling equipment (conveyors in almost all cases) is important in a paint shop.

One of the typical problems in a paint shop is to sort the incoming sequence of vehicles to minimize the color changes in paint booths. Since changing colors involves a setup time, it is desired to sequence same color vehicles back to back. To achieve such *color blocking,* however, there is a need for a temporary storage place. Once a sufficient number of units are accumulated, vehicles of the same color can be pulled from this bank in order of color. Similar temporary storage banks are required to have the ability to empty the ovens that are used for baking different coats of paint, If for some reason, the processes ahead of a paint oven are blocked, there must be sufficient space to unload the units once they come out of an oven.

Another source of variation in a paint shop is the yield of the painting processes. Since the yield of processes is relatively low (in a typical paint shop, the first pass rate could be as low as 65%), the chances of rework are high. Because of the randomness in the process, it is always a challenge to keep vehicles in the same order as they arrived in the paint shop. Vehicles requiring rework would need additional passes through the paint booths. Keeping vehicles in a certain order is one of the critical problems in a typical assembly plant. The movement of material to stations is dependent on the type of vehicles to be assembled next. Consequently, there is a need to schedule a certain order of vehicles ahead of time. Once a schedule is made and issued to all workstations, changing the sequence may cause loss of production by creating material shortages at various points in the plant. Therefore, it is a common practice to accumulate the vehicle bodies in temporary storage areas after the paint process. Such temporary areas allow sufficient time for the late units to catch up to their position in the assembly sequence.

Once vehicles come out of a paint shop, they go into the trim and final assembly area. This area is where all the major and minor components of a vehicle are put together. In a typical setup, some of the minor components are assembled to the vehicle body in the trim shop. The brake system, headlights, and taillights

taillights are examples of those minor components. Then the major components are assembled: the engine, power train, and chassis. Finally, the vehicle is put on a final assembly line. Most of the operations in those areas are done by manual labor. Usually, vehicle bodies are not stopped for an operation except for major component assemblies. Consequently, the capability of the material handling equipment (almost all cases involve conveyors) is an important issue. Another issue is the ability to make available the required parts at the time they are needed at every operation.

15.2.1 Case Study: Body Shop Material Handling System Analysis

This simulation study was performed during the conceptual design phase of a new vehicle program for a major U.S. car manufacturer. The system studied consisted of the following components: (1) a car track system with several sections, (2) 90° turn tables between various sections of the car track system, (3) several robotic spot welding stations, (4) two load/unload stations for two different car models, and (5) a variable number of carriers for each car model. Figure 15.2 depicts a snapshot of a part of the model that shows the car track system. The objectives of the study were threefold:

1. Determine the best equipment configuration and the corresponding line throughput under a given set of operating parameters.
2. Determine the maximum allowable cycle time at the loading stations for either car model.
3. Determine the best number of carriers for each car model.

Some of the model assumptions were as follows:

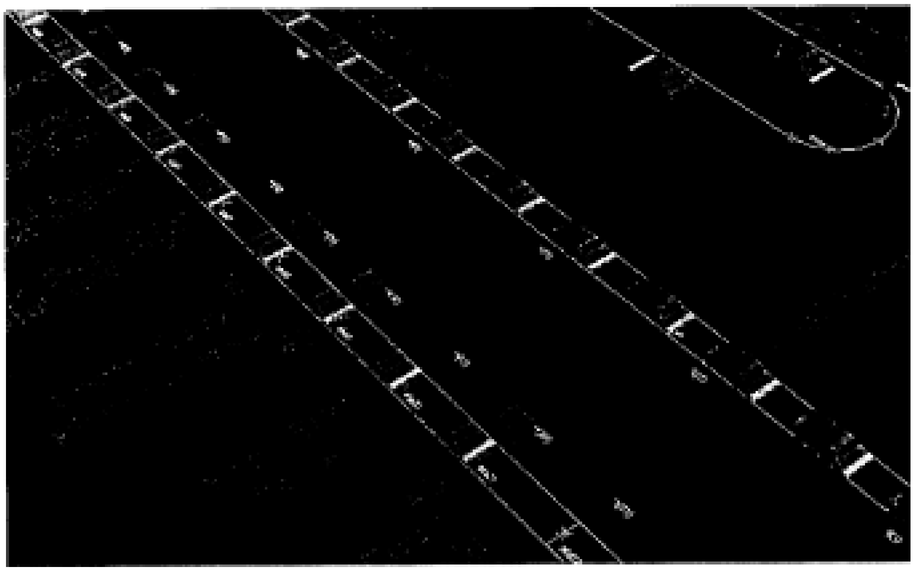

Figure 15.2 Snapshot of a section of a body shop simulation model.

TABLE 15.2 Results of Four Scenarios

	SCENARIO			
	1	2	3	4
Parameters				
RA station type	I	II	I	II
Main welding station type	Manual	Robotic	Robotic	Robotic
Flexible station configuration?	No	No	Yes	Yes
Results summary				
Number of model A completed/hour	32.47	33.29	33.44	33.57
Number of model B completed/hour	15.64	16.33	16.48	16.59
Average production rate/hour	48.11	49.62	49.92	50.16

- Target production rate is 38 model A and 18 model B cars.
- There will always be a vehicle waiting for loading at either load station.
- Each station has a randomly distributed downtime and a random repair time. The mean values and distributions of those random variables were known based on historical data from similar systems.
- The transfer time between two stations on the line is 6 seconds if the carriers do not stop at a station. If the vehicle stops at a station, the transfer time would be 8 seconds, taking acceleration and deceleration into account.
- A station is assumed to break down only after a full cycle of operation, not during a cycle.

The following parameters and variables (evaluated in the what-if scenarios) were used in the simulation model: (1) two different equipment configurations distinguished by cycle times and downtime data, (2) number of carriers allocated to each of two job types, (3) loading/ unloading station cycles times. The performance statistics from the model included the line throughput for each type of car and the utilization of each station.

The system was modeled using the AutoMod software such that most operating parameters could be input from data files rather than by modifying the model. The system capacity was evaluated under equipment downtimes with different equipment configurations, ranging from labor-intensive to robotic processes. In particular, the type of equipment for the robotic alignment (RA) station was considered in detail. Table 15.2 summarizes the results from some of the scenarios investigated during the course of the study.

The results in the table indicate that the last alternative, with a flexible line configuration and a type II RA station, would provide the most output from the line. Other scenarios that are not displayed in the table also showed that the system performance was not highly sensitive to the number of carriers. In addition to those results, it was also found that the loading operation could be done manually for model A cars without affecting the throughput, although a longer cycle time was needed. Consequently, a line configuration with a best mixture of robotic and manual operations was determined and submitted to the project team.

15.2.2 Case Study: Paint Shop Material Handling and Model Mix Scheduling

This study involved simulation modeling and analysis of a paint shop and an adjoining automated storage and retrieval system (AS/RS) during the conceptual and detailed design phases. In addition to evaluating the design, the animation of the model was used as a visual tool to facilitate the brainstorming sessions of the design team. The objectives of this study were as follows:

During the Conceptual Design Phase:

- Evaluate the conceptual design at each iteration of the design cycle to determine the potential bottlenecks and identify alternative solution strategies.

During the Detailed Design Phase:

- Determine the throughput capability of the system.
- Assess the feasibility of the proposed shift schedules and paint booth strip sequences.
- Investigate the best stock levels of various products in the AS/RS.
- Analyze the impact of different trim line operation schedules on the number of out-of-sequence conditions.

The system consisted of the following subsystems in sequence: (1) electrocoat and phosphate, (2) sealer lines and sealer gel oven, (3) prime booth and prime oven, (4) main enamel booth and enamel oven, (5) inspection lines, (6) spot repair area, (7) second-coat paint booth and oven, (8) paper masking and repair lines, and (9) the AS/RS (see Figure 15.3). The material handling equipment in the system consisted of many two- and three-strand chain conveyors, lift tables, turntables, and power roll beds.

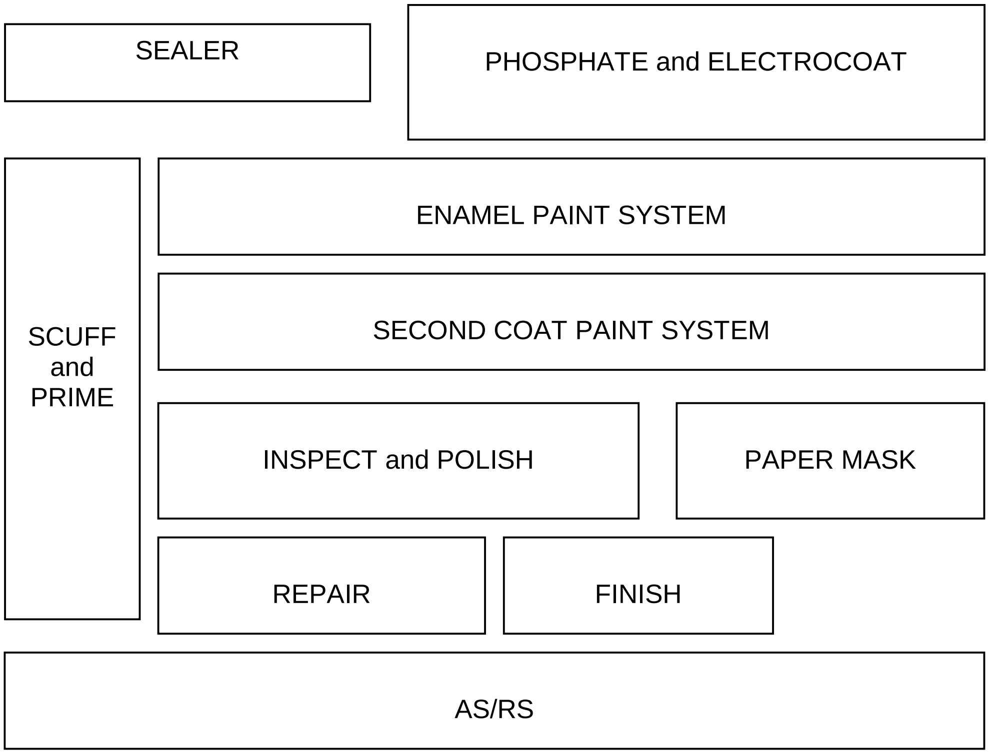

Figure 15.3 Rough layout of a paint shop.

The following parameters and variables (evaluated in what-if scenarios) were used in the simulation model: (1) conveyor speeds, spacing, and speed-up section data; (2) cycle times at repair and mask lines; (3) cycle times at spot repair area; (4) product and paint mixes; and (5) major and minor repair percentages.

The model also required a front-end scheduling routine that was customized using a programming language (e.g., FORTRAN and C). Because some of the units required several passes through paint booths, they took a longer time to be ready for delivery to the trim lines. However, since the product mix showed significant differences between shifts, and since the trim lines operated on a different shift pattern, the jobs that required long processing times were pulled ahead of their original sequence. Thus even though they would be taking more time than the other jobs, by the time they were completed, they would be able to catch their original position in the assembly sequence. Because of the randomness of the defect rate, there would be a good chance that some units would miss their sequence if they were not moved sufficiently ahead in the paint sequence. On the contrary, if they were moved too much ahead of their sequence, they would finish the paint process much earlier than the rest of the units. Therefore, to protect against such random variations in the makespan of different job types, a buffer storage bank was held in the adjoining AS/RS. This buffer would be sized to allow sufficient time for all units to catch their original sequence. The following are some of the original rules of resequencing the jobs:

- Jobs with two colors were moved ahead by 100 jobs for two product types.
- Jobs with three colors were moved ahead by 200 jobs for only one of the models.
- Pattern color jobs were moved ahead by 200 jobs.
- A job with more than one matching criterion is moved ahead by the sum of the jobs required by each criterion (e.g., a two-color job with patterns would be moved ahead by 400 jobs).

Some of the model assumptions were as follows:

- The two vehicle models, A and B, are considered. Model A vehicles have up to two coats of paint, whereas model B vehicles have up to three coats of paint.
- The model mix was known and assumed constant within a day.
- The major repair percentage is 22% and the minor repair percentage is 9% on average with random occurrences.
- Minor repair times are randomly distributed between 30 and 120 minutes and are performed at a dedicated area. Major repairs go through the second paint loop as necessary.
- Shift patterns are known and constant. The first shift is dedicated to model B and the second shift is dedicated to model A at the paint shop. The trim shop runs only one shift and makes both products.
- All conveyors run at full speed with negligible downtimes.

Analysis of the model involved an evaluation of the alternative job sequencing policies to choose one that will eliminate late jobs at the trim lines for all job types. In addition to sequencing concerns, the model was used to investigate the selectivity system (AS/RS) utilization. The runs of the model indicated that there was no reason to

TABLE 15.3 Results of Investigation

	Total Missed Jobs in a Week			
	With Resequencing		Without Resequencing	
Model A Buffer	Single Coat	Double Coat	Single Coat	Double Coat
135	120.32	16.29	0	115.76
160	14.75	4.43		56.45
170	1.09	4.21	0	40.32
180	0	0	0	30.20
200	0	0	0	12.29

resequence model B vehicles since the plant was planning to store a full day's worth of buffer in the AS/RS for this type. The model showed that during the second shift in the paint shop all of the longest paint jobs would be completed for the next day's production at the trim lines. Results from some of the scenarios investigated are summarized in Table 15.3 for model A only. The table depicts the results with and without resequencing. In either case, different levels of model A buffer in AS/RS were tested to find a level that will balance the buffer size and the number of missed jobs.

The results in the table indicate that a buffer size of 180 vehicles would be sufficient to avoid the missing jobs for the vehicle model A. It was also determined that with chosen buffer sizes, the utilization of the AS/RS was at a feasible level. The plant would make substantial cost savings by avoiding the reprogramming of their production monitoring system for vehicle model B.

15.2.3 Case Study: Trim and Final Assembly Lines

This simulation study was performed during the detailed design phase of a new conveyor system. An assembly plant would be making several different models of cars on one trim line. The process and flow of jobs in the system showed differences with respect to the model of cars. The conceptual design of the new system was completed following the previous version of the system. However, to accommodate the variety of the product assembly sequence, many new hardware pieces were needed. To ensure that the system could move the desired product quantities between various parts of the system, a detailed simulation model was built. An important parameter of the design was the mix of models in the target production rate. The objectives of the simulation study were:

- Verify the capability of the conveyor system to move the target number of vehicles through the trim system by considering various product mixes.
- Investigate various scenarios of assigning the size and location of empty carrier buffers by considering different product mixes.
- Analyze the impact of building a new buffer area to hold additional empty carriers.
- Determine the maximum allowable cycle times at several transfer stations by considering different product mixes.

Some of the important assumptions of the study were as follows:

- All manual operations can be completed within the given cycle time.
- All materials are always present.
- The line speed would be set up higher than the required rate so that occasional downtimes could be tolerated.
- There are three models of cars and eight possible mixes of those models.

The system consisted of a chassis buildup system, an engine delivery system, a frame buildup system, and a final trim line. All material movement were made by using power and free conveyors except for the frame buildup area where a chain conveyor was used to move the units continuously. The transfer of units and subassemblies between major areas required complicated equipment that was prone to mechanical failure. Since there was limited room for buffers, an additional storage space was designed at the mezzanine level. The size of the buffer was being questioned since there were random downtimes at major transfer points. Since there were no detailed data, the system was designed to run at a speed 12% higher than the speed required, to allow time for breakdowns and shift breaks. However, the designers wanted to confirm that the system would be capable of delivering an average number of vehicles to meet the weekly production target at a 5 to 10% downtime rate. Based on past data, only an average recovery time of 5 minutes was specified. Also, the newly designed engine assembly area required the proper number of pallets in the system to support the production of all different types of jobs. Since there could be a variety of job mixes to be produced in the system, it was necessary to determine a number of pallets that would work with all possible product mixes.

During the simulation study, first an evaluation of possible product mixes were made by using a baseline layout. This portion of the study helped to determine the maximum allowable cycle times at critical stations to accommodate a variety of product mixes. Then the study focused on evaluation of the size of the empty carrier buffer. Three different layout alternatives were investigated. The simulation runs indicated that there would be no difference between layouts with respect to the average throughput capability. However, the utilization of various subsystems would be greatly affected by allocation of the empty carriers. Table 15.4 depicts, for all three layout alternatives, the time it takes to starve various subsystems after a catastrophic breakdown at one of the critical stations. The table clearly demonstrates that the first layout alternative is significantly better than the latter two in protecting the chassis buildup system against long periods of breakdowns.

The model (see Figure 15.4 for a snapshot of a section) showed that at the transfer point from the engine build line to the engine deck area, the control logic and buffer size originally proposed would not support the cycle-

TABLE 15.4 Time to Starve Subsystems After Breakdown

Subsystem	Layout 1	Layout 2	Layout 3
Chassis buildup 1 and 2	20.0	7.0	7.5
Chassis buildup 3	12.0	4.5	5.0
Chassis buildup 4	4.5	2.0	2.5
Engine load	37.0	37.0	37.0
Final line	2.0	2.0	2.0

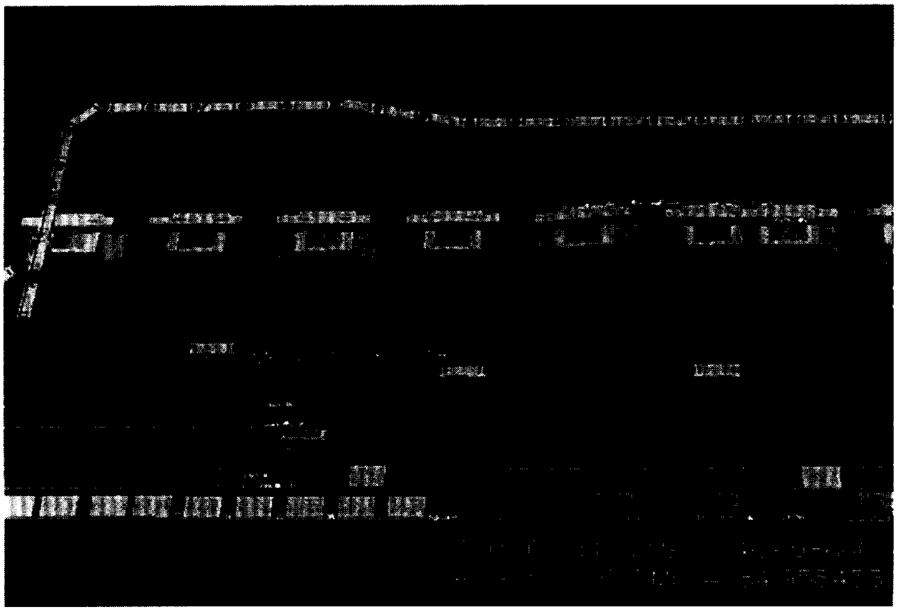

Figure 15.4 Snapshot of a section of a trim shop simulation model.

-time requirement of the engine assembly area. Also, the simulation showed that the final assembly line would be starved immediately if the downtime at the body assembly area were longer than 3 minutes. It was also determined that the buffer storage space placed in the mezzanine level would be sufficient only for breakdowns of relatively short duration. An evaluation of an alternative design showed that additional empty carrier lanes were required to support the system for a longer time should downtime occur at a body assembly point.

15.3 APPLICATIONS IN MAJOR COMPONENT PLANTS

Two of the major components in a vehicle include the sheet metal portions of the body, such as the frame, body sides, doors, roof, and hood, and the cast iron parts used to build the engine and transmission components. A typical automotive manufacturer would have a different plant for each major component. These manufacturing processes, however, could have a higher rate of production than that of cars built at an assembly plant. Consequently, it is usual that a single component plant feeds several assembly plants for several different car models. Due to the unique nature of each type of process, the nature of design problems shows variations among those component plants. In an engine plant, for example, the emphasis is on the reliability of the manufacturing machinery rather than the material handling equipment. In a stamping plant, on the contrary, the problems might be around production schedules and material movement within the plant. Two case studies are given in the following sections. Each case study is related to one type of component plant.

15.3.1 Case Study: Stamping Plant Material Handling Study

The stamping plant involved in this study had several stamping lines that made the sheet metal parts and several subassembly lines that built subassemblies to be used in the assembly plant. For a new vehicle program, a new panel assembly line was going to be put in operation. However, due to the required production volumes and complicated material flow patterns, choosing an efficient method for racking excess panels at the front end of the panel assembly line was going to be an integral part of the solution. The dynamism of the system could be captured only in a simulation model. Consequently, the study involved developing a model of the material handling system supporting the new assembly line. The main objective of the study was to find the best combination of material handling system parameters and operating rules, with an emphasis on the racking methods for excess panels.

The material handling system modeled was divided into the following four areas: (1) monorail delivery system, (2) panel assembly line, (3) empty racks load area with excess panels, and (4) full racks storage area. The simulation model also included material handling processes, job routing logic, and the operating procedures/policies. Through simulation, the system's capabilities were evaluated, resulting in improvements and modifications to the proposed system. More specifically, the study allowed plant engineers to understand product flow, identify bottlenecks, evaluate buffer space requirements, and analyze staffing, equipment, and operating plans. The results from simulation showed that one of the racking methods provided sufficient capacity to handle the racking of excess panels in a relatively inexpensive setting. Furthermore, by varying the number of forklift trucks in simulation, the best number that yielded the required throughput and minimum traffic congestion was determined.

15.3.2 Case Study: Die-Casting Cell Cycle-Time Study

In this study, a model of a die-cast cell was built to investigate the cycle time. The model included two die-cast machines, an operator, and a press machine. Parts were cast in one of the two die-cast machines that fed a single press machine to trim the cast parts. The die-cast machines were automatic needing no operator. However, an operator was required at the press. The operator was responsible for loading and unloading the parts from the press. After the parts were trimmed, they moved on to a series of operations that were not investigated in this study. The specification of a press was the decision to be made. More expensive machines had shorter cycle times. A short cycle time at the press allowed the operator a wider time window for loading and unloading.

Because of the variable nature of the manual operations and the randomness in the rate of scrap parts, a simulation model was needed to analyze the problem in more detail. The objective of the investigation was to determine the operating conditions for the system to achieve maximum throughput. To facilitate a detailed investigation, a model of the system was built to determine the press cycle time for a given range of operator utilization. The model was built so that it could be used to address the impact of the following issues on the system throughput: (1) operator utilization, (2) equipment downtimes, (3) material handling equipment cycle times, (4) individual job processing times, and (5) scrap rates.

The results from simulation analyses indicated that the two die-cast- machine approach will meet production at an acceptable rate of utilization for the operator. The study also concluded that the throughput of the system would be increased if three die-cast machines were used. The latter configuration would also improve the operator and press machine utilization if some of the flexibility issues could be resolved.

15.4 APPLICATIONS IN SMALL COMPONENTS PLANTS

All components of a vehicle other than the major components (stamped sheet metal parts, cast metal parts, and the power-train parts) can be viewed as small components for the purposes of this chapter. Manufacturing of small components is typically done in much smaller areas. However, a small-components manufacturing plant could be as big as an assembly plant, due to the variety of the components and the required production volumes. A small-components plant typically feeds many assembly plants, thus requiring a high volume of production. Many of the problems associated with such plants are due to the high volume of production. The cycle times are much smaller and the parts are smaller in size.

Many small components, such as alternators, starters, and fuel injectors, are made in separate assembly areas in a typical small-components plant. The material handling within such assembly areas is done by small but efficient and reliable conveyors. Consequently, many of the problems that constitute good opportunities for the use of simulation arise in the analysis of the part-making and assembly manufacturing processes. Reliability of machinery, scrap rates, machine setup requirements, product mix decisions, scheduling conflicts, and the efficiency of interdepartmental material handling equipment are some of the common problems with which simulation models can efficiently be of help. The following three case studies provide good examples of typical problems and their solutions using simulation.

15.4.1 Case Study: Machining Cell Design Study in an Electrical Components Assembly Plant

This study involved the study of a coil winding cell. The purpose of the study was to determine a combination of the machine configuration and operating parameters that provided the maximum possible throughput. The coil winding area consisted of robotic winding cells which (1) receive bobbins on trays, (2) insert two terminals, (3) wind bobbins, (4) trim excess wire, (5) crimp the terminals, (6) flux and solder terminals, (7) test and reject assemblies electrically, and (8) place finished coils back into the trays. Each of these operations was performed in a separate cell. An accumulating conveyor system transported trays between operations.

Numerous system parameters needed to be evaluated to determine the best configuration that would yield both satisfactory resource utilization and overall system throughput. Since the study was being performed in the very early stages of the design cycle, many of the line configuration parameters, such as the size and location of buffers and the number of machines, were variables. In addition to such higher-level variables, the length and speed of conveyors and the number of operators were lower-level variables that could be fine tuned to obtain the maximum throughput from the system.

Random downtimes and random changes in the product mix were the main contributors to the variation of the system. To represent such variation adequately and obtain meaningful performance predictions, a simulation model was needed. The model would be built to determine the operating conditions for the system to achieve maximum possible throughput. The model was built to enable a detailed study of the proposed coil winding process by analyzing the impact of the operating issues on throughput: (1) buffer sizes and locations, (2) unscheduled equipment downtimes, (3) individual part processing times, (4) conveyor parameters, (5) scrap generated, and (6) labor involved in maintaining and repairing the equipment.

By analyzing the performance of the system under various operating conditions, the best combination of the system parameters (among those tested) was determined. The simulation showed that some of the originally proposed buffer sizes would have to be modified to improve system performance. Some other buffers, however, could be much smaller than proposed. Consequently, simulation played an important role in the design of this assembly line.

15.4.2 Case Study: Car Seat Assembly Material Handling System Study

The plant involved in this study manufactured most of the upholstered components that were put inside a vehicle. For a new vehicle program, the plant was undergoing a revamping process by installing new lines to support the production targets and cost reduction goals. The proposed seat assembly process depended on an automated guided vehicle (AGV) system for material movements within the assembly area. At distinct assembly islands within the system, front and rear seats are assembled, then joined. The general flow of the assembly process is to transport car seat parts on AGVs through the following sequence of operations: (1) pallet loading; (2) front seat parts kitting; (3) assembly islands 1, 2, and 3 (front seat assembly); (4) front seat oven heating; (5) assembly island 4 (front seat fit, finish, and inspection); (6) front seat repair; (7) rear seat parts kitting; (8) assembly islands 6 and 7 (rear seat assembly); (9) rear seat oven heating; (10) rear seat inspection and repair; (It) stretch wrapping; and (12) pallet unloading.

For a cost-effective design, several issues would have to be addressed. First, the best number of AGVs should be determined. Adding more vehicles to the system can help increase the capability of the system, but congestion might prevent an increase in the throughput. Second, the number of assembly lanes must be decided. Also, the impact of various lane assignment rules on the system performance should be evaluated. Instead of the current rule, which is relatively complicated, it was desired to simplify the operating policy for the new system. In addition, an assessment of the impact of the productivity of manual operations on overall system throughput was needed. Finally, the possibility of increasing the pace of manual operations would be weighed against more work-in-process and congestion in the system. Considering the complexity of the traffic control system, the randomness of operation cycle times, and availability of the vehicles, the simulation approach was found to be an effective analysis tool for the problem. The main objective of the study was to determine the operating parameters that would enable the seat assembly area to achieve maximum hourly throughput.

The results from simulation indicated that adding more AGVs to the current fleet, originally contemplated by the design team, would not significantly increase overall system throughput. Thus unnecessary expenditure on capital equipment was avoided. Overall system throughput increased with higher operator efficiency levels but was limited by the stretch wrapper. The throughput did not increase with further increases in worker efficiency once the bottleneck shifted to that operation. Different sequences of assigning available lanes to AGVs arriving at assembly islands did not affect overall system throughput. Opening more lanes in one assembly island did not necessarily translate to higher throughput, because of the interdependencies between consecutive assembly islands.

In this study, simulation provided a detailed picture of the behavior of the system under the assumptions of increased efficiency at various operations. Analyses clearly showed that unless some of the existing processes were improved, adding more capacity to the material handling system could not be justified. The plant engineers were able to determine the root causes of the problems, which were not evident by observation of the system or by statistical analysis of data.

15.4.3 Case Study: Instrument Panel Assembly Line

In a small-components plant, prior to installing a new instrument panel assembly line, the engineering and management teams wanted to detect potential bottlenecks that may limit capacity and to assess the utilization of resources. The new design included a conveyor system unfamiliar to the plant management and line personnel. In addition, there was a need to determine the best scheduling and loading patterns for the new system.

The system consists of a closed-loop powered roller assembly line. Each 10-ft section of conveyor has a variable-speed driver and a mechanical stop. One of two part types is loaded onto a pallet at the start of the system. The pallet enters several manual assembly stations and operations are performed on both part types. After the pallets pass through these stations, they are separated according to part type. Part A pallets are transferred across to the top of the line, where they are unloaded. Part B pallets continue on the lower line through more assembly stations and are then transferred up to the top section of the line. Then part B pallets enter one of four test cells. Following this operation, empty pallets are sent to a buffer in front of the loading station, while part B pallets merge back into the main line with part A for unloading.

The goals of this study were to (1) evaluate different line configurations identifying and correcting any problems (blockages, bottlenecks, etc.), (2) evaluate the throughput of the system using different loading patterns, and (3) determine the number of required pallets. Using the simulation model, process engineers were able to determine the buffer capacity required for empty pallets, line speeds, and control logic required at transfer and intersection points. The final system was robust enough to handle any type of product mix that could enter the system. Results showed the number of pallets required to achieve maximum system throughput to be 28, whereas the original estimate was 48, resulting in 42% savings.

15.5 NONMANUFACTURING APPLICATIONS

15.5.1 Case Study: Distribution Chain Management

A European car manufacturer was reengineering its vehicle distribution system over its North American dealership network and required a detailed study of the existing and proposed systems and recommendations on improvements to the system. Vehicles are manufactured abroad, and the distribution system uses several U.S. ports to satisfy North American demand. Dealerships in metropolitan markets get their shipments from port inventories.

The company feels that building distribution centers closer to metro markets should reduce costs and improve customer service metrics in terms of first-choice deliveries (i.e., ability to deliver to the customer immediately what she or he is asking for). There was a need for flexible analysis tools to generate and evaluate various alternatives. The objective of the study was to develop a set of models for predicting the performance of a given distribution system configuration. The performance criteria were the rate of matching customers' first choice and the total cost of installing and operating a given configuration of the distribution network.

In this study, a mathematical optimization model was developed to generate distribution center alternatives that minimize transportation-related costs per year. Once a solution is generated, the configuration was input into a simulation model that explicitly considered the probabilistic and dynamic elements in the system, and hence estimated the overall performance of the given alternative more realistically. Using an algorithm that iterated between the optimization and simulation models, a configuration was found that satisfied most of the evaluation criteria. The new design showed that it was possible to reduce transportation costs by about 25% while improving customer service.

15.5.2 Case Study: Warehousing Study

This project studied the proposed changes to a warehouse and the proposed material handling equipment. The modifications to the system were needed as a result of increased storage, shipping, and receiving volumes anticipated due to packaging changes in existing products and introduction of new product lines. It was desired to determine alternative ways of increasing both cubic storage space and material handling (shipping and receiving) capabilities. The challenge was to optimize the layout of the warehouse and select the most suitable material handling equipment to provide adequate service based on planned future volumes.

The goals of the study were to identify system constraints that could limit future space and handling requirements and to suggest potential improvements and modifications to the system design. The design alternatives were based on the following system parameters: (1) dedicated versus random storage rules, (2) original rack orientation versus rotated (perpendicular to the docks) orientation, (3) aisle width and overall storage space utilization, and (4) capacity of material handling equipment, most notably the number of lift trucks.

The results from the simulation model demonstrated that (1) randomized storage was better suited to this situation than dedicated storage, (2) the rotated orientation with the corresponding narrower aisle configuration resulted in an 85.96% increase in overall unit load storage capacity, (3) the rotated orientation also resulted in an increase from 23.57% to 41.95% in total storage space utilization, and (4) the existing number of lift trucks was sufficient to service the increased volumes.

15.6 ROLE PLAYERS AND STANDARDS

15.6.1 Role Players

Interest in determining the best use of simulation in building efficient manufacturing systems (see refs. 11 to 13) in the automotive industry continues to increase. Advances in computer hardware and software and an increasing awareness of the capabilities of simulation have helped to achieve this higher level of interest. There are several groups of people with close interests in using simulation as a productivity enhancement tool. First, almost all major manufacturers have their own consulting groups providing simulation modeling and analysis services within

within the corporation. These groups act as internal consultants and are closely tied to industrial engineering departments. An important function of these groups is to increase the awareness of simulation across the corporation. Working closely with process and material handling engineers, these groups help establish simulation technology as an indispensable computer-aided engineering tool. For further discussion, see ref. 14. In addition to corporate wide groups, some of the divisions of the corporation and most of the plants have access to internal personnel as simulation analysts. Another important function of these internal resources is to coordinate the acquisition of modeling services when needed. By ensuring that the models delivered are accurate and are in usable form, these internal resources also act as liaisons between simulation modeling vendors and the corporation [15].

Simulation service providers are a second group dedicated to enabling simulation technology to be used properly and to achieve its maximum benefits. Smaller companies show a high degree of variation in size and the breadth of services offered. Many simulation service providers would typically use only a few of the commercially available simulation software packages. There is only a very small number of vendors that provide expertise in all simulation software. An important contribution of simulation service providers is the expertise and focus to turn projects around at a faster rate than with the typical internal resources of a corporation. Also, simulation services providers have the ability to play a mentorship role in use of the methodology. Such mentorship programs offer an opportunity for speeding up the learning of the proper methodology. Guiding relatively novice users of the technology through complicated modeling and analysis situations is a very critical task in establishing simulation as a powerful tool in designing and operating a manufacturing system.

As indicated previously, each of the major automotive manufacturers has made it a practice to simulate new systems prior to their installation in a plant. Consequently, more and more machine tool sellers are increasing their use of simulation. Besides concurring with the requirements of the automotive companies, simulation is being used by some machine tool sellers and material handling equipment suppliers in designing, specifying, and planning the production line.

Machine tool sellers and material handling suppliers have different needs when they use simulation. From a machine tool seller's viewpoint, the objective is to evaluate the capability of the equipment to deliver the required throughput. Consequently, individual machine downtimes, machine cycle times, scrap rates, and buffer sizes become the most typical inputs to a simulation model. The typical results from a study of the machinery include the location and size of each buffer, an assessment of the line throughput, and identification of potential bottlenecks should the product mix change. A material handling equipment supplier is, however, concerned with providing the right material at the right time and at the right place. Consequently, the speed, routing and traffic logic, and capacity of the material handling equipment become predominant inputs to a simulation. Identification of congestion problems, evaluation of the speed and capacity of material handlers, and an assessment of the throughput capability of the material handling system are the typical results from a simulation study.

An examination of models built for a material handling supplier and for a machine tool seller would reveal that the simulations on each side have ignored the other even though they are ultimately for the same production line. A machine tool seller assumes that material handlers would always be present and that they would have sufficient capacity. The material handling supplier would assume that the process would always yield the target throughput. Obviously, the interactions between the two systems are seldom captured in simulation models. It is the responsibility of the buyer of the system to ensure that a complete model of the production system is built by considering both components of the manufacturing hardware. However, in a typical organization, the material handling group and the process engineers work in separate areas and, perhaps, use different simulation models. Therefore, it is seldom the case that the members of one group would gain an insight from the simulations performed by the other group. Consequently, inefficiencies, redundant effort, and even misleading conclusions are possible. Thus the management of simulation modeling for large-scale integrated design projects has some room for improvement.

15.6.2 Standards

Standardization of simulation models could have many benefits for an automotive company. A typical automotive company would have many geographically dispersed plants that are likely to be very similar in nature. For example, many of the assembly plants of the same vehicle manufacturer would look very similar. The designers of the same type of facility tend to be the same across different car programs. By keeping the same design teams on similar car programs, a vehicle manufacturer attempts to maintain and utilize the know-how generated among other programs. By the same token, building simulation models by adhering to a well-defined set of standards can reduce the costs of development. In addition, standardized animation, source codes, and reports can all help to minimize communication problems between analysts and the users of simulation results.

As discussed previously in this chapter, simulation models are being built for many reasons at many different points in a vehicle program by many different parties. Since it is spread across many functions and departments within an automotive company, the use of simulation shows a significant degree of variation.

Considering the multiplicity of users of simulation among the vendors, internal and external simulation consultants, and many facilities of a large company, structuring a set of standards for simulation modeling is a very challenging task. Furthermore, developing standards on model building, animation, analysis, and report generation has not been recognized as a problem.

Modeling tools that allow building of application templates have been an attempt at standardization on the software side of the technology. However, an important roadblock in standardization is the fact that simulation modeling is a cognitive task. Models are developed by people with different levels of education, skills, and experience. The perception of problems and understanding of the capabilities of the software tools are highly dependent on the individual. Consequently, there are differences between models of similar systems developed by different people. Furthermore, as there is a learning process and different timing requirements on different projects, even the models developed by the same person show significant differences over time.

There have been efforts toward standardizing a methodology for application of the simulation methodology. For example, refs. 16 to 20 report significant benefits from applying such methodologies. Those studies indicate that the success of a simulation study is determined primarily by how well certain guidelines on project management and model building are followed and communicated to the project team. However, at the date of this writing, there have been no published common standards of modeling and model building techniques, particularly for the automotive industry.

15.7 SIMULATION MODEL LIFE-CYCLE CONSIDERATIONS

Simulation models may have a short or long life cycle based on the use of the model through the life of the system. Short-life-cycle simulation models are developed for a single decision-making purpose at a certain point during the life of the system (e.g., conceptual design issues, detailed design issues), and once the decision is made, the model is discarded. On the other hand, long-life-cycle simulation models are built to be used at multiple points in time during the life of the system and are maintained and revalidated as conditions change in the system. Currently, about 70 to 80% of the simulation models built can be categorized as short-term models, while the rest are longer term in that they will be reused after the initial simulation study has been completed. Long-term simulation models require long-term ownership (i.e., use, control, and maintenance) of the model by a modeler and/or engineer. Long-life-cycle models are generally built for the purposes of (1) training, (2) reuse at the launch phase, and (3) reuse at the fully operational phase for changes in design and operation of the system. Training-focused long-life-cycle models are used to train engineers on the stochastic nature of the system that they are controlling and/or teaching simulation to them. Models built at the detailed design phase of a system may be used for partial personnel allocations and line segment operations in the launching phase of a new manufacturing system. The reuse of models at the fully operational phase of a system are generally for product-mix decisions as the demand for products change or as new products are introduced into the system. The successful use of long-life-cycle simulation models may require the following tasks to be accomplished in addition to the traditional steps of simulation model building [16]:

1. Construct user-friendly model input and output interfaces.
2. Determine model maintenance and training responsibility.
3. Establish data integrity and collection procedures.
4. Perform field data validation tests.

It is important that the long-life-cycle nature of the model be specified as part of the original objectives of the study because the model design is highly influenced by it. For the long-life simulation model to be effective, the simulation project team should include at least one person who is a long-term user of the model.

15.8 ROBOTICS SIMULATION

15.8.1 Overview of Robotics Simulation Technology

Robot applications are becoming more and more widely used in industries from manufacturing to health care. The most common utilization of robots is in manufacturing. In the automotive industry, primary areas of robotics applications include arc and spot welding, painting, material handling, assembly, and testing and inspection. There are many automotive assembly plants in the United States that use robots, for example, for all welding operations in body shops. Similarly, almost all new paint shops utilize robots for most paint applications. Also, many small -components manufacturing plants have robots for a significant portion of the assembly operations. In addition, in electronic component assembly lines, robots are very common. Consequently, there is a strong need for effective analysis and design tools for applying the technology successfully. With its flexibility to address a wide range of design and operational problems in robotics applications, simulation technology proves to be such a tool. Some commonly used software includes IGRIP from Deneb Robotics, ROBCAD from Technomatrix Technologies, CimStation from SILMA, and Workspace from RWT. All of these software can display a work cell in three-dimensional graphics. They also provide inversive kinematics calculations to facilitate a wide range of analyses on robotic systems, such as robot selection, robot placement, reaching capability assessment, and interference checking.

Robotics simulation applications can be categorized into four areas: (1) conceptual design and presentation applications, (2) robotics work cell design applications, (3) offline programming, and (4) integrated simulation with ergonomics and discrete-event simulation. The first category includes applications where a proposed or existing system is modeled for demonstrating a concept, marketing, training, or documentation of different designs. A typical simulation in this category consists of machines, robots, robot tools, jigs and fixtures, material handling devices, and human operators. The main objective of these types of models is communicating the ideas and concepts through a realistic graphical representation of system operation,

The second category of robotics applications involves mostly engineering applications. Designing and evaluating the layout of a work cell, selection of robots, designing tools and fixtures, eliminating colliding motion paths, optimizing robot movements, and cycle-time assessment and task allocation are among the typical uses of robotics simulation models. Clearly, those models require a high degree of accuracy in the geometric representation of cell components.

All of the software tools mentioned above provide the capability to create robot programs in their native language (i.e., ARLA for ABB robots and KAREL for FANUC robots). Once an accurate model of a work cell is created, it is possible to develop programs for the robots. Those programs can then be downloaded to the robot controllers on the floor, eliminating the need for teaching by using a pendant. For some applications, however, there might be a need to calibrate the off-line program since there are always differences between a simulation model and real-life implementation of the work cell, due to installation errors and manufacturing tolerances. Off-line programming using robotics simulation software is explained in more detail in the following section.

Integrating a robotics simulation study with a discrete-event simulation study benefits both in various ways. The most important interaction, however, is the cycle-time determination. An assembly-line simulation can determine a time window for the cycle time, which can then be fed to a robotics simulation model for determining feasibility. On the other hand, a robotics simulation model can help determine the best and worst estimates of the cycle time in a robotics work cell. Those estimates can then constitute a basis for what-if scenarios by using a discrete-event simulation of the entire production line.

15.8.2 Off-Line Programming Using Robotics Simulation Software

The traditional "teach" method is by far the most common method of programming a robot. This method is usually satisfactory if the complexity of an application allows a relatively short programming time. With this technique, the robot program is generated by using the robot itself in its production environment. The off-line approach makes it possible to develop robot programs using a computer model. ROBCAD and IGRIP are commonly used robotics modeling and simulation software programs used for off-line programming (OLP) purposes. As exciting as it can be, be, off-line programming through such software could be an inefficient, expensive, and frustrating experience if precautions are not taken.

The process of generating robot programs using kinematics simulation software has three major phases: (1) preparation, (2) calibration, and (3) program development. The preparation phase is involved primarily with the generation of solid models of the related work-cell components. This phase is completed when a model of the work cell is put together using those component models. In the calibration phase, the differences between the simulated and actual environments are measured and a mathematical approximation of the actual system is constructed using techniques mostly external to the simulation software. In the third phase the actual robot programs are developed using the simulated environment. Clearly, the third phase can start immediately after the preparation phase is completed. However, the calibration phase can help determine special programming requirements that should be considered in developing final robot programs (e.g., additional work locations to compensate for deflections under heavy payloads). Consequently, those three phases follow each other in a typical OLP project.

15.8.3 Case Study: Gear Machining Cell Design

In this study, a simulation model of a proposed robotic operation that interfaced two CNC machines was developed. The operation was part of the gear-making process in an engine and transmission assembly plant. By replacing manual operations with a robotic system, it was expected that the reliability of the system would increase as the cycle time is reduced. A proposal for a robotic work cell was developed and investigated through the models built during the study.

The present process to load parts on machines was labor intensive. By using robots it would be possible to increase the efficiency and reliability of the entire operation. However, the feasibility of a robotic operation should be investigated thoroughly before taking any serious action. Among the issues that must be addressed were:

- What type of robot was required to accomplish the tasks involved in the operation?
- Where should the gantry robot and its supporting facility be placed?
- How should the robots and the existing machinery be interfaced?
- How can the robot movements be optimized to ensure that cycle-time constraints are satisfied?
- What type of gripper is required to handle both parts and containers?

To answer those questions, a model of the work cell was developed (see Figure 15.5 for a snapshot of part of the model) using a robotic simulation software tool with the following objectives:

- To develop a cell layout based on geometrical constraints, work locations, and robot work envelope.
- To develop a conceptual gripper design.
- To determine whether the robot can perform the tasks within the allowed cycle time.
- To demonstrate the initial feasibility of the robotic operation.

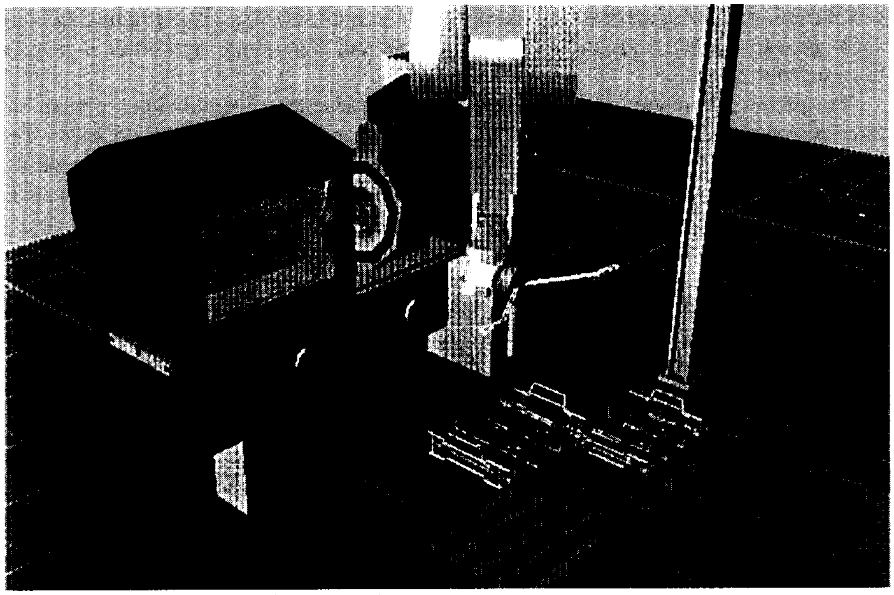

Figure 15.5 Snapshot of a section of the gear loading cell simulation model.

The work cell consisted of one gantry robot, a part container, two CNC machines, and conveyors for inbound and outbound containers. The model allowed experimentation with several parameters, including various gripper designs, and robot movement parameters, such as speed and acceleration. An arrangement for the work cell was developed by considering geometrical constraints and cycle-time limitations. The gripper design was tested and interference were eliminated. Cycle-time analysis showed that the robot could easily load two machines within the allowable cycle time. Consequently, a second gantry requiring a significant investment was avoided. The monetary savings from using simulation were much more than the cost of simulation. Also, by testing the system in a virtual environment, an efficient design was developed by testing many design alternatives in a very short amount of time. Such comparisons would take months if traditional tools of design were to be used. Finally, a videotape of the three-dimensional animation was used to demonstrate the proposed system to plant personnel.

15.9 FUTURE OF SIMULATION IN THE AUTOMOTIVE INDUSTRY

In many ways, the automotive industry was a leader in the application of discrete-event and robotics simulation in the last 35 years. Some of the earliest manufacturing simulators were developed by automotive companies in the 1970s [21] and a number of new applications of simulation are currently being tested in this industry for the first time (e.g., multiple computers running multiple manufacturing simulations in an integrated fashion, combining layout optimization with layout simulation, off-line programming of welding robots). In looking at the next 5 years, one may see the following trends in simulation in the automotive industry: (1) development of more rigorous model-building and validation procedures, (2) creation of model databases for effective model archiving and reuse, (3) development of databases for plant machinery and equipment for model input, (4) development of megamodels incorporating supply chain models with final assembly plant models, (5) use of models at various detail levels by different levels of management in a plant environment concurrently, (6) integration of kinematics models-robot, ergonomic worker with discrete-event models, (7) integration of realtime scheduling with simulation models for more effective shop floor control, and (8) expanding the virtual reality applications in simulation of manufacturing systems.

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