Proceedings of the 1992 Winter Simulation Conference
ed. J. J. Swain, D. Goldsman, R. C. Crain, and J. R. Wilson

INSIGHTS INTO CARRIER CONTROL: A SIMULATION OF A POWER AND FREE CONVEYOR THROUGH AN AUTOMOTIVE PAINT SHOP

DAVID W. GRAEHL

Ann Arbor Computer
A Division of Jervis B. Webb
1201 East Ellsworth
Ann Arbor, Michigan 48108, U.S.A.

ABSTRACT

An existing auto body paint shop uses power and free conveyors to transport auto bodies through the plant. Discrete event simulation is used to model portions of the system in order to determine whether the system can operate sufficiently when a second body style is introduced and to study the effects of making modifications to some of the conveyors. The new body style requires production lines in the work booths to be dedicated to only one of the body styles in the system. This paper describes the simulation study that was conducted to evaluate the modified system and provides some details about the methods used to model the system.

1 INTRODUCTION

Two years after operations began, managers of an auto body paint shop are using discrete event simulation to study some aspects of their power and free conveyor system.

In general, power and free conveyor systems are made up of four types of components: carriers, free track, power track and chain in the power track. Figure 1 is a diagram of how these components interact. Carriers are used to transport products from one point in the system to another. Each carrier in this system is able to carry one body at a time. The combined weight of the carrier and its load rests on the carrier trolleys which move along the free track. When carriers are allowed to move, the pusher dog on the chain engages the carrier trolley.

This system has two groups of power and free conveyors: high speed transport conveyors and low speed production conveyors. High speed transport conveyors move carriers between the work booths. Low speed production conveyors move carriers through the work booths. (Additional differences between and within these two categories will be noted later in this paper.) Prior to transferring to production rate conveyors, high speed conveyors divide into two routes. This is done because there are two low speed conveyors in each of the work booths. Carriers alternate from side to side as they proceed through these diverge points. This method of routing to production conveyors requires little or no accumulation for carriers going through the diverges.

The proposed system however, will have two body types to transport through the shop. Furthermore, each of the two production conveyors within most of the work booths will be dedicated to a single body type, making route selection into the booths a matter of determining the type of body on the carrier. Carriers moving through diverge points will no longer be able to simply alternate between conveyor lines.

The purpose of conducting the simulation study is two fold: 1) to evaluate the feasibility of adding a new body style to the production line, and, 2) to estimate the advantages of several proposed changes to the system layout. The layout changes are not complicated and by themselves, may not be significant enough to justify a study. (These changes, though included in the model, are not specifically addressed in this paper.) Because of complexities in routing throughout the extensive conveyor system however, addition of the new body style generates questions which are more difficult to answer.

The simulation software used is Wolverine Software's GPSS/H on an IBM mainframe. Experience has shown that the level of detail desired for modeling and the size and complexity of this and other models developed make GPSS/H our choice. For animations we use Proof, also from Wolverine Software. Proof is a postprocessed animator that runs on a PC.

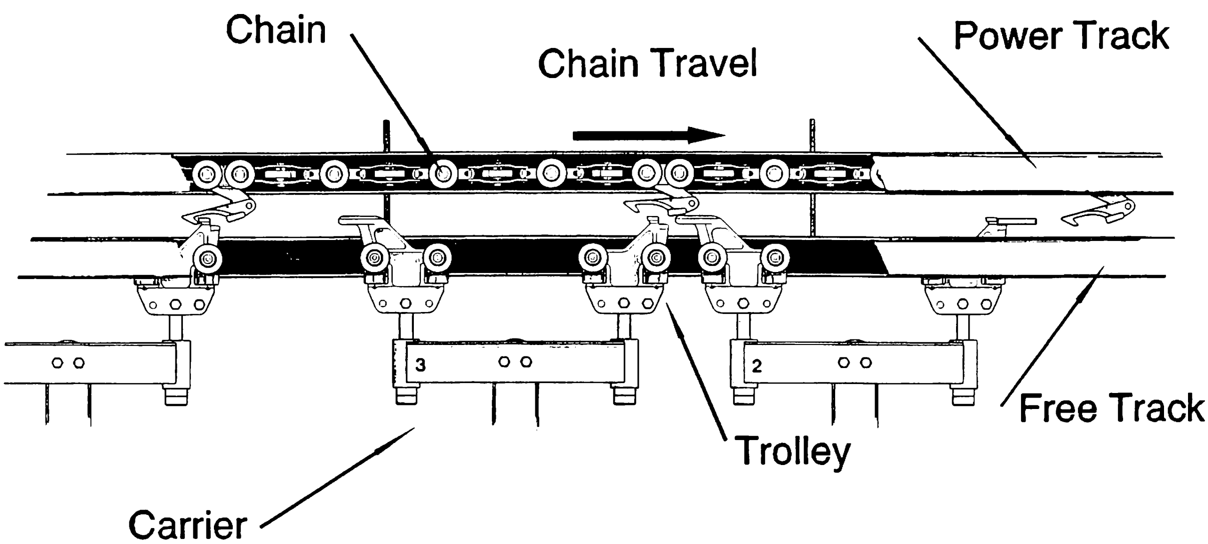

Figure 1: Power and Free Components

2 BEGINNING THE PROJECT

The first step in this simulation project was an internal meeting, during which another simulation analyst and I were introduced to the current layout, carrier flow and some concerns about carrier routing logic. In addition, the meeting was attended by representatives from sales, estimating and engineering. From the meeting we wanted to acquire as much information about the system as possible. We also wanted to have a clear understanding of the concerns that the simulation would be expected to address. We left the meeting with conveyor layout drawings, descriptions of the conveyor modifications, as well as sets of electrical and mechanical drawings and extensive notes. The electrical drawings included detailed stop and limit switch location and logic information.

The next meeting had three purposes. The first was to get the client involved in the study. Those in attendance included the individuals who were at the first meeting as well as a materials handling engineer from the client. The second reason was to further clarify the carrier paths and determine production rates that the simulation study would use. The third reason was to agree on the scope of the simulation model, and determine the areas on which the model would concentrate.

3 SCOPE AND LEVEL OF DETAIL OF THIS STUDY AND THE ASSUMPTIONS

Typically, simulation studies of large material handling systems include only a portion of the entire system. One reason for this is that large systems tend to require equally large and time-consuming simulation efforts. Another reason is that oftentimes only certain areas of a system need to be studied.

3.1 SCOPE OF THE STUDY

The size of this system and its complexity make this study no different. The entire system is prohibitively large while the effects of the additional body style are only seen in the work booths located between the scuff decks and final inspection. Thus, the beginning and ending points are easily determined: where loaded carriers appear (enter the simulation) just before the diverge located prior to the scuff decks (at this point the carriers go from a non-dedicated inbound line to dedicated lines going into the scuff deck lines) and the carriers disappear (leave the simulation) at the diverge point prior to the dedicated wax booths. The work booths that the carriers go through are: prime scuff, masking, interior paint, the main enamel booths and ovens, inspection, spot repair, two-tone and major repair. Figure 2 shows the possible routes carriers can take.

Not included in the simulation are the strip lanes. Strip lanes are storage lanes that are used when

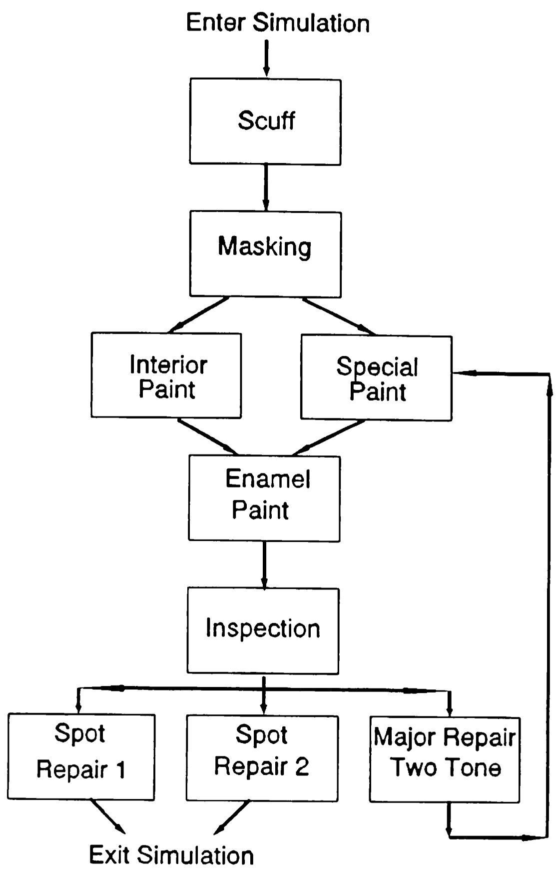

Figure 2: Carrier Routing

carriers need to continue through some portions of the paint system but are unable to proceed down the regular path. These stoppages may occur when the ovens need to be emptied for the weekend or at a shift change. Other stoppages are unplanned, for instance, when emergencies require some production chains to stop. The objective of this study is to see how the system functions under standard operating conditions at full production without the use of the strip lanes.

3.2 LEVEL OF DETAIL

The level of detail for a model is usually determined by the kind of information that one expects to obtain from the study. Other factors include the complexity of the system being modeled, and the level of detail that the modeling software can address.

Some examples of the details included in this model are: carrier banking lengths for both normal and diagonal banking, chain speeds, dog spacing, job centers, stop and limit switch locations, locations for chain to chain transfers and maximum bank counts. The importance of the carrier lengths, for example, can be seen by considering the two different carriers. The old body style has a carrier that is over 21 feet long while the new body style is just under 18 feet long. This becomes important when the carriers are out on the transportation chains since the dog spacing for these chains is 5 feet. Another example is that the portion of the system within the scope of this simulation includes conveyors which have 20 different chain speeds and 6 different dog spacings.

Within the scope of this model, some limit switches and other control points do not appear in this simulation. Some examples of the hardware not included are the limit switches used to determine which carrier type is at a stop and some of the bank count capabilities used for carrier safety. Since this study is examining traffic control, the stops and limit switches that govern the release of carriers from those stops are the only ones needed.

4 BUILDING THE MODEL

Taking into account the features of GPSS/H and Proof, we determined that the most efficient way to model the conveyors is to divide them into segments. The endpoints of the segments are usually at points like chain to chain transfers where carriers transfer from one chain to another or at a stop. If limit switches are present in the segment, they are represented in the GPSS/H code but do not require an individual segment. Therefore, when a carrier leaves a stop it enters a new segment and whenever a chain transfer takes place the carrier also enters a new segment. These segments correspond to the "paths" used in the Proof animation.

4.1 GPSS/H MACROS

The code for the conveyor segments is made up of sets of 2 or 3 GPSS/H macros. The use of macros not only simplifies the code for model creation but contributes substantially to the readability while debugging. For this model there are only 5 types of macros that are needed. These macros perform functions which include: passing a limit switch, entering a stop, leaving a stop that has 0, 1 or 2 controlling limit switches and/or a carrier count in the next bank, changing conveyor segments (chain to chain transfers), and moving carriers from point to point along the conveyor.

The code is set up so that each carrier is modeled by a GPSS/H transaction. Carrier attributes, such as body type and carrier ID (used in the animation), are assigned to the transaction parameters.

Each point on the conveyor, whether it is a stop, clearing limit switch, chain to chain transfer, or other point, is represented by a GPSS/H Facility. Facilities are used since GPSS/H automatically collects performance and utilization statistics that are useful in studying model behavior.

In addition to a Facility, each point has GPSS/H blocks that model the functions performed on the carrier as it passes through the point. An example of this is illustrated by code that represents a clearing limit switch. Clearing limit switches are modeled using GPSS/H Logic Switches. When a carrier leaves a stop which has one or more clearing limit switches controlling carrier movement, the Logic Switches for those clearing limit switches are placed in the "set" mode. As the carrier passes the clearing limit switch, the Logic Switch is placed in the "reset" mode. Therefore, code for clearing limit switches includes a macro that resets the Logic Switch as well as the chain move macro that moves the carrier from the current point to the next.

Another example of the additional code at conveyor points is found in the accumulation banks. Accumulation banks are represented by Storages. Prior to carriers entering the simulation, these Storages are initialized to the appropriate maximum number of carriers. When a carrier enters an accumulation bank, the Storage is incremented by one. When it leaves the bank, the Storage is decremented by one. In order to limit the number of carriers between two stops to the total number of carriers that can accumulate in the accumulation bank, a carrier enters a bank when it leaves the last stop prior to the bank. If a carrier can enter an accumulation bank then it is assured a position somewhere in the bank even if no more carriers are allowed to leave the bank.

To model carriers accumulating in and leaving accumulation banks, the GPSS/H code needs information about only the first two carriers in queue. The next carrier to leave a bank must first wait for permission to proceed and for a pusher dog on the power chain to reach the carrier trolley. When both conditions are met, the carrier proceeds out of the stop at the head of the bank. At that point the second carrier is free to catch the next available pusher dog and proceed to the stop. The time that the carrier will arrive at the stop is determined by the formula found in equation (1).

$$t = \frac{CL+PDS-(CL \bmod PDS)}{CS} \quad (1)$$

In equation (1) t is the time the next carrier arrives at the stop at the end of the accumulation bank, CL is the carrier length, PDS is the pusher dog spacing length and CS is the chain speed. "mod" refers to modulo division. To depict the image on the animation screen, the mechanisms of Proof provide the logistics for accumulating carriers in the bank.

The concluding logic needed to model power and free conveyor is determining the time when pusher dogs arrive at stops and chain to chain transfers. This is accomplished in two steps. The first step is to identify the initial distance that the next pusher dog must travel to reach each stop and each chain to chain transfer. Equation (2) is used to calculate the initial distance.

$$d = (DL+LCS) \bmod PDS \quad (2)$$

In equation (2), d is the distance that the next pusher dog is away from the point at the <u>end</u> of the conveyor segment, DL is the distance of the next dog away from the <u>beginning</u> of the segment, LCS is the length of the conveyor segment and PDS is the pusher dog spacing for the chain.

The second step is to determine the time until the next pusher dog arrives at a location. This value is derived by equation (3).

$$td = \frac{(d+(CS \times ST)) \bmod PDS}{CS} \quad (3)$$

In equation (3), td is the time that the next dog will arrive at the end of the conveyor, d is the initial value derived by equation (2), CS is the chain speed, ST is the time since the simulation began, PDS is the pusher dog spacing and "mod" indicates modulo division.

4.2 CARRIER MOVEMENT

A carrier at a stop waits for either or both of the following conditions before the next pusher dog is allowed to move it:

- If the bank count is used in the conveyor segment into which the carrier is moving, then the carrier waits for space available.
- If the clearing limit switches are used for this stop then the carrier waits for the appropriate ones to be cleared. (See section 5)

If both of these conditions are used in the logic then they are examined in the order given above. Once the carrier is cleared to move, it waits for the next pusher dog on the power chain. The move time is calculated and the GPSS/H transaction representing the carrier goes to an Advance block. On its way to the Advance block, the transaction passes through an animation macro and the appropriate code is written out to the Proof animation trace file. The appropriate code in this case places the carrier out onto the next Proof path.

To calculate the time it takes a carrier to move from one point to the next, the precise distance between the two points is divided by the speed of the conveyor. For visual purposes, the precise distance should match the distance used in the animation layout, which can be obtained from Proof's linkage file. If, at the scheduled arrival time, another carrier is at the next point, then the moving carrier "accumulates" on a GPSS/H User Chain, where it waits in a FIFO queue before proceeding. This adds some complexity to the calculations of the true arrival time since now the carrier must not only wait for the preceding carrier(s) to leave the desired point but the carrier must also wait for the next available dog on the chain before it can even move in to the position. (Refer to Section 4.1)

At the diverge intersections, route selections must be made to determine where the carrier is going. If the route selection determines the lane of a work booth, the decision is based on body style. For major repair and two-tone, the selection uses an alternating scheme between the two lanes. Other route selections are made at several conveyor intersections which are more stochastic in nature. They are based on expected production rates down stream. These selections govern:

- mix of carriers entering the system
- routing to interior paint or to regular enamel paint
- routing to special interior paint or regular interior paint
- routing to exit the simulation or to continue to the spot repair or two-tone/major repair
- routing carriers from two-tone/major repair according to the first two criteria above.

In the case of these latter types of selections, Bernoulli random trials are used to determine the route. The probabilities for the Bernoulli trials are calculated to meet the desired production rates.

5 SIMULATION TEST RUNS

During the latter portions of the model building phase, the model output indicated that carriers entering the model were not able to make it through the initial diverge point fast enough to keep up with the production rates. Using GPSS/H's debug mode, combined with the animation, an examination of the model revealed that oftentimes carriers were not able to leave the stop due to no space available ahead of the diverge.

Figure 3 shows the conveyor path and the location of the chain transfers, stops and limit switches for the initial diverge. Carriers enter the simulation from the right and accumulate at the stop labeled S1. Production Chain A moves at 13.0 feet per minute and has dogs spaced at 13.0 feet. Production Chain B moves at 25.48 feet per minute and also has dogs spaced at 13.0 feet. All others are transport conveyors which move at 60.0 feet per minute and have dogs spaced every 5.0 feet.

Carriers headed for Production Chain A wait at S1 until both limit switches LS1 and LS3 are cleared. Once they are cleared, the carrier sets limit switches

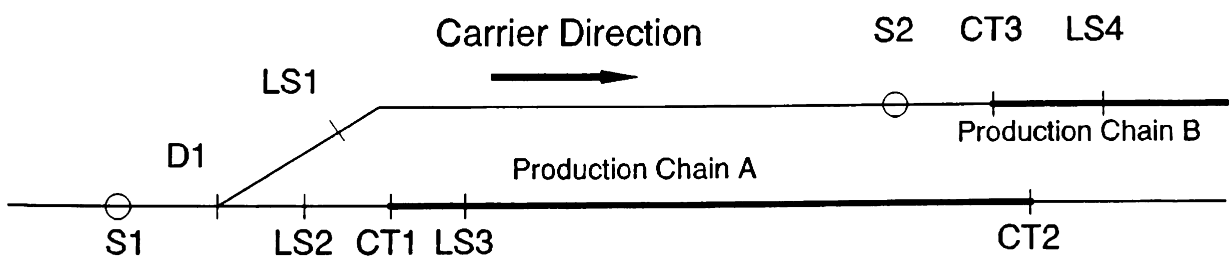

Figure 3: Conveyor Diverge

LS2 and LS3, waits for a pusher dog then leaves S1. When it passes limit switch LS2 it clears it and proceeds to the chain-to-chain transfer CT1. It waits there for the next pusher dog on the new chain then proceeds through limit switch LS3 to chain-to-chain transfer CT2.

Carriers headed for Production Chain B wait at S1 until limit switch LS2 has been cleared and there is room ahead to accumulate at stop S2. Once these two conditions have been met, the carrier sets limit switch LS1, waits for a pusher dog then leaves S1. When it arrives at diverge D1 it dedogs (i.e. disengages) from the power chain and waits for a dog on the chain that will take it to limit switch LS1. When the carrier passes limit switch LS1 it clears it and proceeds to stop S2 or accumulates behind any carriers already at S2. Once at stop S2 it waits until limit switch LS4 is cleared before it moves on. When LS4 is cleared the carrier waits for the next pusher dog on the transportation chain before it moves toward the chain-to-chain transfer CT3.

Note that limit switch LS1 has been placed so that carriers leaving S1, headed for Production Chain A, will not hit the back end of the last carrier to go toward Production Chain B. Limit switch LS1 ensures that carriers going to Production Chain B will have completely cleared diverge D1 by the time the next carrier leaves S1 and gets to D1. The limit switch LS2 has been placed to be certain that carriers going to Production Chain A will have completely cleared diverge intersection D1 before releasing the next carrier from stop S1.

Note as well that limit switch LS3 has been placed so that carriers ready to leave stop S1, proceeding toward Production Chain A, are not allowed to leave until the carrier at LS3 has completely cleared chain-to-chain transfer CT1. The same is true for limit switch LS4, stop S2 and chain-to-chain transfer CT3.

Recall that since the system was designed to let the carriers alternate at this diverge point, one carrier going to Production Chain A, the next to Production Chain B, the next to Production Chain A, and so on, there was no need for accumulation going into the chain-to-chain transfer CT1. But when running this area in dedicated production mode, two carriers in a row can arrive at S1 headed for Production Chain A. When this happens, the second one waits at stop S1 until the first one has cleared limit switch LS3. This blocks any carriers attempting to go toward Production Chain B as well. If there are insufficient carriers accumulated at stop S2 then Production Chain B will be starved and a gap will occur in the production.

A similar gap is produced on Production Chain A if three or more carriers in a row, headed for Production Chain B, go through stop S1. Since there is no bank from which to pull carriers to feed the chain-to-chain transfer CT1, the transfer is starved while the carriers are going up toward Production Chain B.

6 MODEL VALIDATION AND REFINEMENTS

As model development progressed, it became increasingly apparent that the model showed high sensitivity to the stochastic route selection algorithms, i.e. the distributions used for the model inputs. In fact, the use of a Bernoulli random variable to determine the order in which carriers arrive often results in one scuff deck or the other being starved for carriers. Despite the ability of the randomly generated Bernoulli trials to average out to the desired probability over time, in the short run (say for 3 or 4 carriers) the probabilities could be very skewed. The model shows that the order in which the carriers enter the system must be very close to the right proportions, virtually carrier by carrier, as opposed to averaged out over longer periods of simulated operation.

This problem did not surprise the engineers and sales staff. After discussions with the client, it was agreed that we could assume that the carriers would be properly ordered as they leave the preceding work booths and that the simulation needed to be adjusted to provide a more even distribution of the two body styles.

7 ADDITIONAL RUNS AND VALIDATION

After the changes were made allowing carriers to enter the system at the target production rate, another bottleneck was discovered where one of the body styles exits the masking booth. Again the Bernoulli random variable used to determine carrier routing (in this case either through interior paint then to an enamel booth or directly to an enamel booth) allows too many carriers in a row to attempt to go in the same direction. This also caused blockage where no accumulation had been provided. Additional discussions with the client showed that this too, is corrected by the plant since current operations expect carriers to be scheduled in such a way that carriers arriving at this first major decision point will not arrive in large groups all going to the same place.

With a more even carrier distribution going through the system, test runs were made to look at the rate at which carriers leave the system. Figure 4 is a graph showing the number of carriers by type, to exit the system per simulated hour. The top line represents the number of the original type carriers to leave the system while the lower line represents the number of new type carriers to leave the system each hour. The graph shows some wide fluctuations from hour to hour. The fluctuations are the result of the use of Bernoulli random variables to determine the routes. In this graph the valleys represent times when gaps occurred in the production.

These gaps are reflected as well in the overall average number of carriers to leave the system. To meet the average, carrier availability has to be fairly consistent over time. This is the case since the conveyor speeds are set at the average production rate, making it the maximum as well. Since the loss of production due to gaps can not be made up, no gaps can occur if the production rate is to be met. If in another hour more carriers than the average arrive to be processed, they must accumulate or cause blockage.

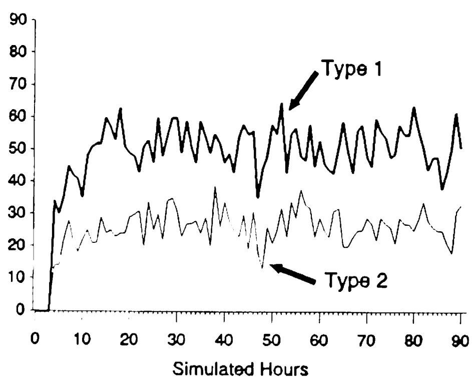

Figure 4: Number of Carriers to Exit Per Hour with Bernoulli Trials

At this point it was determined that if we wanted to study the behavior of the intersections in question, the model would need to duplicate the system at a steady level of performance, the instantaneous rates that the client had first proposed.

One reason for this approach that the independent trials are not usually used for route selection. An example of this lack of independence is often seen in the number of carriers going to major repair. If some significant problem occurs and is not caught for 20 or 30 minutes then for those 20 or 30 minutes all of the carriers may need to be routed to the Major Repair.

With these details in mind, adjustments were made to provide an even carrier flow through the 4 major decision points. This flow represented a 70% first run rate at the decision point governing whether carriers leave the system or proceed to Major Repair. Figure 5, like figure 4, is a graph showing the number of carriers, by body style, to exit the system when the route selection is made using proportional carrier rates going to Major Repair. As expected, the graph is much smoother. The output data shows that virtually no gaps are seen in the production and that the average number of carriers leaving the system is in line with the expected amount.

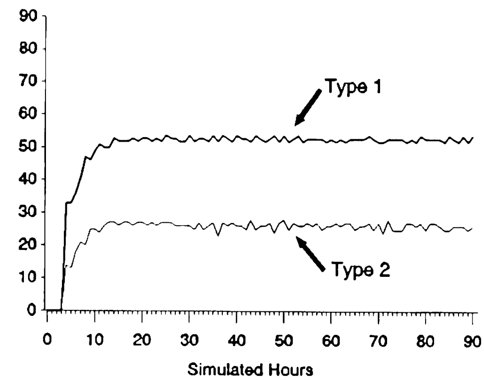

Figure 5: Number of Carriers to Exit Per Hour with Even Carrier Flow

8 MODEL OUTPUTS

From the analysis of the test runs it was determined that a 40 hour warm up period would put the system in a steady state. This is critical to the analysis of the model output for several reasons. The first reason is apparent by examining either figure 4 or figure 5. Notice that carriers do not begin to exit the system until the fourth simulated hour. If these values were left in the collected data, results would be dramatically skewed. The second reason is that empirical calculations show that the first carriers must pass through some of the decision points three to five times before the effects of first run rate selection have leveled off. This means that 35 to 40 simulated hours are required until the model is filled with enough carriers to achieve at full production. After this warm up period, with all statistics cleared, the model ran for an additional 200 simulated hours.

GPSS/H blocks are strategically placed in the model to provide statistics about critical intersections and track segments. Statistics are also collected for production rates through selected points of the system. After 200 simulated hours, the statistics show that the model is able to maintain the target throughput, that there are no intersections where blocking occurs (bottlenecks) and that carrier accumulation occurs only at those conveyor segments where it is planned.

9 PRESENTATION TO CLIENT

With the model complete and validation steps performed, the animation was presented to the client and the simulation output discussed. Included in this presentation were our sales team, the client's engineers and the client's upper management. The model was used as part of the sales process to assure the client that the system would perform the required functions and to help the client understand the changes and their impact on the system.

The question that the client ultimately needed to answer was whether the system could operate to their satisfaction with the suggested changes. The simulation, with its animation, was only one portion of the overall decision making process but it seemed to be one of the major criteria on which the decision rested. It also provided a convenient place to study the system without a great deal of expense or interruption to the present operations of the paint system.

10 CONCLUSIONS

The simulation verified that, with some modifications to the track, the system could handle the addition of the new body style. This conclusion is valid for a 70% first run rate (70% of the vehicles need no repair) and holds for first run rates higher than that. Additional simulations could be done which would show how the system would react to different first run rates, especially rates which are lower, i.e., more carriers going to major repairs. Another subject that could be addressed by additional use of the simulation model is the interaction of the system and the strip banks. This would allow the performance of the system to be studied more thoroughly when portions of or entire work stations are shut down while carriers continue to move through other areas of the plant.

AUTHOR BIOGRAPHY

DAVID W. GRAEHL is a senior simulation analyst at Ann Arbor Computer. He received his B.A. degree in mathematics from the University of Utah in 1983 and M.S. degree in industrial engineering from the University of Utah in 1988. He is a member of SCS, ORSA and Alpha Pi Mu.