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ON THE USE OF PHYSICAL MODELS TO SIMULATE ASSEMBLY PLANT OPERATIONS

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ABSTRACT

This paper describes the use of a physical model to emulate operation of a paint selectivity bank. The purpose of the selectivity bank is to allow re-sequencing of cars from the paint department prior to going to the trim and chassis departments in an automotive assembly plant. The physical model has been used to study dynamic interaction among system components and to validate computer simulation models. The presentation will conclude with a videotape of both the plant selectivity bank and the physical model in operation.

I. INTRODUCTION

The typical American made car has a relatively large number of individually specifiable options available. For a given car line, the number of combinations of options can run into the millions. Assembly plants are set up so as to assemble all of the combinations as efficiently as possible. One of the tools used in this process is a paint selectivity bank. This paper describes the use of a physical model to emulate paint selectivity bank operations.

II. DESCRIPTION OF ASSEMBLY PLANT OPERATIONS

While no two of Ford's assembly plants are exactly alike, they share certain characteristics in common. A typical assembly plant is subdivided into five areas or shops: body, paint, trim, chassis and pre-delivery, with a paint selectivity bank between the paint and trim shops. The typical sequence of operations is as follows:

1. Body Shop - The day's orders begin here, where pressed and stamped metal components are welded together to form the unpainted vehicle body.

2. Paint Shop - The assembled metal body is completely painted in this shop. This includes washing, anti-corrosion processing, spray painting, baking and any special processing such as two-tone work.

3. Paint Selectivity Bank - Units emerging from the paint shop are sorted into a number (from 4 to 10) of parallel conveyors according to option content. At the bank exit, units are pulled from any of the parallel conveyors and placed on a cross-over conveyor for transport to the trim shop.

4. Trim Shop - Here, the painted body receives interior and exterior hardware, electrical wiring and electronic components, and all interior trim.

5. Chassis Shop - The completed vehicle body is equipped with all powertrain components in the chassis shop. This includes engine, transmission, drive train, suspension system, wheels and tires.

6. Pre-delivery Shop - Upon exit from the chassis shop a fully functional vehicle has been assembled. It can then be moved to any of several locations in the pre-delivery shop for final processing, testing and, if necessary, repair.

The body and paint shop operations are highly automated while the trim and chassis operations have a relatively high manual labor content. The impact of the availability of large numbers of options (termed "option complexity") is relatively muted in the body and paint shops. Typically, the number of body styles made in any one plant is on the order of 8 to 15. Furthermore, these styles are exclusive, i.e., one and only one style per unit. Similarly, the number of paint treatments is on the order of 20, including two-tone treatments. Here, again, only one paint treatment is selected per unit. Thus, it is relatively straightforward to process a given vehicle order stream or sequence through the body and paint shops.

However, option complexity strongly affects the operation of the trim and chassis shops. There can be as many as one hundred options which must be installed in trim and chassis operations. Furthermore, a customer may order air conditioning (A/C), power steering (P/S), sun roof (S/R), rear windshield washer/wiper, power seats, etc. in any combination. The work content (work required to assemble a given vehicle) is a function of the specific set of options ordered. Thus, in order not to exceed the dynamic production capability of the trim and chassis shops, it is necessary to control the sequence of vehicles going into the trim and chassis shops according to their option content.

The paint selectivity bank has two main functions. First, it provides a buffer between the paint and trim shops. While trim and chassis operations can be stopped in place (for example at the end of a shift), paint operations cannot. Vehicles must be taken out of ovens, spray booths, dip tanks, etc., in order to complete a shutdown. Likewise, on start-up, the paint lines must be refilled before painted bodies begin emerging from the paint shop. The paint selectivity bank is used to smooth out the flow of vehicles from paint into trim. Secondly, the selectivity bank is the primary tool used to control the flow of option content through the trim shop. This is done by sequencing the vehicles to go into trim on the basis of "sequencing priorities."

III. PAINT BANK EXAMPLE

To illustrate these concepts and the problems involved consider an example consisting of a set of 3 sequencing priorities, a bank of 4 lines and a sample sequence of 10 vehicles. Table 1 gives the three sample priorities.

Table 1

Sample Sequencing Priorities

Priority	Restriction
1. Air conditioning (A/C)	1 in 2
2. Power steering (P/S)	1 in 3
3. Sun roof (S/R)	1 in 5

In terms of line balance[1] the sequencing restrictions mean that the stations installing air-conditioning (A/C) have been balanced (manned) so that there is sufficient time to install it on every second car. Likewise power steering (P/S) can be installed on every third car and a sun-roof (S/R) on every fifth car.

Table 2 represents a string of 10 vehicles (V1, V2,...,V10) listed in order of arrival from the paint shop. A vehicle requires the installation of an option if there is an "x" in the appropriate column.

Table 2

Sequence of Painted Bodies from Paint

Vehicle	Option Content		
	A/C	P/S	S/R
V1	x		x
V2	x		
V3		x	x
V4	x	x	
V5			x
V6	x		
V7			
V8		x	
V9			
V10	x		

As each vehicle arrives it is assigned a number called the rotation number. The rotation number specifies the position that the vehicle will occupy in the sequence of work going through trim and chassis. Once the rotation number has been assigned, the corresponding vehicle description will be broadcast to all downstream operations, including off-line sub-assembly areas. Major sub-assemblies such as the instrument panel, the engine, the transmission, etc., are built up off-line and then placed on conveyors for delivery to the appropriate station on the main line. This is timed so that the sub-assembly and vehicle both arrive at the station at the same time. The rotation number is the key to keeping the sub-assembly work and the main line work synchronized. In order to maintain the integrity of the timing, the broadcast of vehicle information only takes place when a contiguous block of rotation numbers has been assigned. With this noted we return to the example.

Assuming that no vehicles have been sequenced - i.e., that the bank is empty, vehicle V1 arrives and is assigned rotation number 1. It is then assigned to one of the files in the bank, say file 1. Next comes V2 and because it requires A/C (restricted to 1 in 2) it is assigned rotation number 3 and assigned to a file in the bank, say file 2. Since V3 requires both P/S and S/R with the limiting option being S/R, it is assigned rotation number 6 and placed in file 3. Likewise, V4 is assigned rotation number 9 and placed in file 4. V5 is assigned rotation number 11 and placed in file 1 and V6 gets rotation number 5 and is placed in file 2. This would give us the situation illustrated in Figure 1.

Vehicle	Rot. No.
V1	1
V2	3
V3	6
V4	9
V5	11
V6	5

Rotation numbers assigned

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E  ___________ 11 _ 1   B
N                       A
T  ___________  5 _ 3   N
R                       K
A  _______________ 6
N                       E
C  _______________ 9    X
E                       I
                        T
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Assignment of vehicles to bank

Figure 1

Notice that a problem has been created in that there is no place left in the bank for rotation numbers 2 and 4. No matter where 2 is placed it cannot be withdrawn from the bank immediately after 1, nor can 4 be withdrawn after 3. (Each file in the bank is physically a FIFO buffer -- the front car must be removed before the second one can be removed.) If we now assign rotation number 2 to an incoming vehicle it will be withdrawn from the bank out of order, which in turn will destroy the downstream synchronization. The best that can be done is to resequence the vehicles already in the bank (for example, call V2 rotation number 2 and V3 rotation number 3) which would destroy the balance of the sequence.

This illustrates that the problem of where to place a vehicle with an assigned rotation number is non-trivial. Two fairly simple observations can be made:

- A necessary and sufficient condition that a set of consecutive numbers distributed in some order among a set of FIFO files, as above, can be removed in numerical order is that the numbers be arranged monotonically (lowest number first) within each file.
- If the sequence of numbers, in the order in which they are placed in the bank, contains a decreasing subsequence of length N+1, where N is the number of files in the bank, then it is not possible to place them into the bank in such a way that they can be withdrawn in numerical order.

The reader is invited to reassign the rotation numbers to bank files in a different fashion and to complete the process for the remaining vehicles. Note that since there are three vehicles with a 1 in 5 restriction the best that can be done is to assign them rotation numbers 1, 6, and 11 as above, which will leave one of the rotation numbers 1 through 11 unassigned.

IV. SIMULATION OF PAINT SELECTIVITY BANK OPERATIONS

The objective of the investigation was to analyze the operation of the bank to determine what could be done to improve the balance of the outgoing sequence of vehicles. Initially, a mathematical analysis of the sequencing and bank placement algorithms was performed. Then a simulation model was written to study the effect of several factors in bank performance including such things as various sequencing and placement algorithms, number of priorities considered, mix of incoming sequence of vehicles and number of vehicles in the bank. The results of this study suggested several areas for follow-up investigation. The main conclusion of interest for the purposes of this paper was that the operator's ability to generate a balanced sequence was, in general, quite good up to four or five priorities and deteriorated badly beyond seven. This observation was consistent with plant experience. Results also showed that a significant improvement in over-all balance could be achieved by considering more priorities, however to do this would require mechanization. At the same time the plant had been looking into automating operations for improved productivity. As a result of these studies, the decision was made to investigate paint selectivity bank mechanization. The physical model was a key element in this investigation.

V. OBJECTIVES OF THE PHYSICAL MODEL

The objectives behind the construction of the physical model were to:

1. Domonstrate Feasibility

While most people were willing to agree that, theoretically, the operation of the bank could be automated, the critical nature of the operation made it necessary to demonstrate that the automation could actually be implemented with complete reliability of function. The physical model was to be a concrete demonstration of the feasibility of the project.

2. Provide a Realistic Test Environment for Evaluation of Design Options

The design of the production system would go through the normal cycle of design and testing with evaluation of various hardware/software trade-offs in terms of functionality and cost-effectiveness. It often happens that the weakness in a particular design option lies in its impact on other, apparently independent, design decisions. This kind of system level problem can remain hidden until the implementation phase, when the dynamic interaction of system components reveals it. The physical model provides a way of evaluating design options under dynamic conditions.

3. Provide a Realistic Environment for the Development and Testing of Algorithms

As mentioned earlier, the algorithms for the assignment of rotation numbers and the assignment of a vehicle to a line in the bank had been developed and tested using a simulation model. The model had been run using thousands of vehicles, both randomly generated and actual production sequences. Based on this work, algorithms which would work "in the aggregate" had been developed. However, the details of how these algorithms might need to be adjusted for the multiplicity of potential operating conditions under which they would have to work had not been developed. Specifically, the question of how the dynamics of the moving vehicles might affect the timing of when certain decisions would have to be made, and the resultant effect on those decisions had not been studied. In a sense, a strategy had been developed, but the application of it to a specific situation — the tactical considerations — had not been developed. While it might be possible to do this using a simulation model, it would entail a significant amount of programming, testing and debugging before credible results could be obtained. Moreover, since the system did not exist in reality, the question of validation would remain open.

The physical model would already have all of the requisite real-time dynamics built in for this kind of study and, in addition, provide a tool for at least partial validation of the simulation model. If the algorithms worked properly in the physical model then they could be made to work in the actual plant.

4. Provide an Environment for the Implementation of the Actual In-Plant System to Minimize the Impact of Implementation Problems on the Plant

As mentioned earlier, the broadcast of vehicle descriptions based on assigned rotation number governs the synchronization of downstream operations. Problems or errors in the operation of the bank can create major problems. If, for example, a vehicle is withdrawn from the bank out of order, it creates the potential for a string of misbuilt vehicles. Thus it is imperative that this system be tested and debugged as much as possible before its introduction into the plant. The physical model provides an environment in which the plant-bound system can undergo a pilot implementation, the object being to identify and correct as many potential implementation problems as possible prior to production implementation. The gap between a system which adheres to a design specification and a fully operational problem-free system can be enormous. The physical model helps fill this gap.

VI. DESCRIPTION OF THE PHYSICAL MODEL

The model itself is a small scale (roughly 1/35) model based on an actual production bank. It has 62 position sensors, 39 stops activated by solenoids, 31 pneumatically operated lift tables and 46 motors. The operation of the bank is completely controlled by a Data General mini-computer. All programming was done in Fortran.

Construction of the model began in July of 1983 and was completed by early September, including all interfaces to the computer*. Programming began in August and the model was functioning by October.

VII. STUDIES USING THE PHYSICAL MODEL

Initially the objective of the work was to determine that the model was functioning properly. Specifically the requirement was to demonstrate that the model could, completely under computer control, place a sequence of vehicles with pre-assigned rotation numbers into the proper line in the bank and draw them out in proper order. (It is this level of operation which is shown on the videotape.) Technical feasibility of the project was thus demonstrated.

The second phase of the work consisted of using the model to evaluate a number of hardware/software design options. Several reductions in required hardware were shown to be possible (including a reduction in the number of required laser bar-code scanners).

The third phase of the work was aimed at using the model to evaluate sequencing and placement algorithms under the dynamic conditions of a real-time operating environment. Initially, the model was used to run subsets of the vehicle sets used in the simulation model for purposes of validation. Next, a series of studies was performed to determine required modifications to the algorithms in order to improve their performance under marginal operating conditions (for

* Design and construction of the physical model was performed by Prof. M. P. Deisenroth, then of Michigan Technological University

example, a low bank or a mechanical breakdown in one or more bank components). One of the results of this work was an enhancement to the placement algorithm. The trim and chassis shops process vehicles at a rate of over one vehicle per minute. The line runs at a fixed rate so that the paint bank must deliver vehicles at a rate necessary to support this operation. The studies showed that under the conditions of a low bank, the time delay between successive vehicles could exceed one minute even though the average rate was under one minute. The major cause of this was the placement algorithm which needed to be adjusted for this condition. The adjustment brought virtually all of the inter-departure times into the proper range.

Finally, work is under way to interface the plant-bound system with the model for a pilot implementation trial.

VIII. SUMMARY AND DISCUSSION

The importance of simulation as a design tool is well known and well accepted. Rathmill and Chan[2] have observed that in the design of complex manufacturing systems, there is a steady progression from more generic mathematical models which are readily uncluttered with details (thus relatively easy to verify) to increasingly complex and detailed simulation models which require increasingly more time and effort to code, debug and verify. At the end of this process there is still a large gap between a design which functions in a world simulated by a computer and a design which functions in the real world. Young et al.[3] have identified this gap and offer physical simulation as a methodology to fill it. Our experience tends to confirm these views. The physical model has played a major role in:

- Demonstration of feasibility (Young calls this education[3]),
- Evaluation of hardware/software design options,
- Validation of simulation model and refinement of algorithms for real-time operation.

While these results might have been achieved by other means, it is very doubtful that they could have been achieved as quickly or as decisively.

The presentation will now conclude with a video tape of the physical model and an actual paint selectivity bank in operation.

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