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APPLICATIONS OF DISCRETE EVENT SIMULATION IN THE DESIGN OF AUTOMOTIVE POWERTRAIN MANUFACTURING SYSTEMS

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ABSTRACT

Manufacturing automotive powertrain components (engines and transmissions) is a complex task involving the integration of hundreds of components. Simulation is commonly applied in the design and implementation of such production systems. Examples of such systems are the crankshaft machining line, engine final assembly and transmission final assembly, to name a few. Invariably, different engine and transmission sub-assemblies are machined and assembled on separate systems. The completed sub-assemblies are then assembled to the engine or transmission main assembly. There are many areas within a powertrain assembly plant that show complicated behavior due to the varying nature of manufacturing processes. Not only the variation in process, but the schedules, availability of workers, and the performance of material handling equipment are only few of the factors contributing to the randomness in operation. Test areas where the final assembly is inspected for functionality present an example of such highly random operation. Simulation is a very useful tool for investigating the behavior of such complicated systems. This paper discusses the need for and uses of discrete event simulation in the design of manufacturing systems for powertrain assemblies. The benefits of such applications of simulation are illustrated by using a sample study of the final engine test and repair area.

1 INTRODUCTION

Automotive manufacture is a complex task that requires the production and integration of thousands of different components. The powertrain system is one of the most important pieces of every automobile. The engine and the transmission are the major components that constitute a powertrain system. Manufacturing engines and transmissions of good quality is essential to the quality of the automobile. Typically all major automotive components or sub-assemblies such as engines and transmissions are produced separately and assembled to each other and to the chassis in the final assembly stage of an automobile. Thus, the major components that make up the engine such as camshaft, crankshaft etc. are machined and/or assembled into respective sub-assemblies. The sub-assemblies are then assembled together to make an engine.

Discrete event simulation is now a standard tool used in the design and implementation of different automotive manufacturing systems ranging from a connecting rod machining sub-system all the way up to the automotive assembly system. Examples of some successful applications can be found in Ulgen et al. 1994, Gunal et al. 1996, and Jeyebalan et al. 1992. Objectives for using simulation vary. Common objectives, to name a few, include (Jayaraman and Agarwal 1996)

- System throughput determination
- Bottleneck detection
- Manpower allocation and optimization
- Comparing operating philosophies
- Logistics systems design and analysis
- Analysis of materials storage issues
- Optimizing shift patterns
- Materials handling systems design

This paper focuses on the use of simulation for automotive powertrain production systems. The benefits of simulation are demonstrated by focusing on a small part of engine final assembly systems: engine final test and repair area. In every engine and transmission assembly, one of the final operations performed on each assembly is testing. Testing is performed on each assembly at a specially designed test stand. Typically test stands take a longer time to process an assembly compared with other stations in the system. Also, the repair operation shows a random process time as the nature of faults in an engine assembly can be due to many different reasons. Those characteristics lead to a requirement for more than one test stand. As in a typical setup each test stand is connected to the rest of the assembly line through conveyors, arrangement of test stations for utilizing them uniformly and effectively is essential to save cost and to satisfy the demand. Given the dynamics of the testing area, simulation is frequently applied to evaluate different alternatives and to select the best configuration.

In section 2 of the paper, a typical engine assembly manufacturing setup is introduced with an emphasis on the problems that can be best addressed through simulation. Then in section 3, a detailed discussion of the need for using simulation in the design of such systems is discussed. Illustration of the uses of simulation in design of similar areas is given in section 4. The conclusions of the study are presented in section 5.

2 TYPICAL ENGINE ASSEMBLY SYSTEM CONFIGURATION

The major sub-assemblies that make up an engine are popularly called the 5 C's - Camshafts, Crankshafts, Cylinder Blocks, Cylinder Heads and Connecting Rods. Each of these sub-assemblies are composed of hundreds of separate components. These major sub-assemblies are machined/ assembled at their respective production systems. Completed sub-assemblies are delivered to the final engine assembly line where they are assembled together at a final assembly line.

An engine final assembly line consists of a series of assembly stations connected with accumulating conveyors. The base component of an engine is a cast and machined engine block. All sub-assemblies are assembled to the engine block at different stations. Typically, each engine block travels from one station to the next on a pallet moving on conveyors. Completed engine assemblies are removed from pallets and transferred to storage. Empty pallets are returned to the station where new engine blocks are loaded to the pallet. Thus, the final engine assembly line is in the form of a conveyor loop with different assembly operations between a loading and an unloading station. Pallets are circulated and always kept within this loop.

The operations along an engine assembly line are either manual, semi-automatic or automatic. An example of a manual station would be one where the crankshaft sub-assembly is loaded from the storage area to the engine block pallet and aligned. An example of an automatic station is one where the crankshaft is secured to the engine block by torquing the bolts tight. Usually tasks like loading the engine block and unloading completed engines are manual. Semi-automatic operations consists of both manual and automated tasks. An example of a semi-automatic station would be a final engine test stand in a typical assembly line. Furthermore, the operations / stations can be in-line or off-line. At an in-line station the operation is performed without moving the pallet off the main conveyor. Pallets are stopped at the station by the use of pallet stops and they are released after the operations are completed. Subsequent pallets queue up behind the station and wait for the current pallet in station to complete processing. The release is usually triggered manually (for manual operations) or by using vision sensors and timers for automatic stations. With off-line stations, pallets are routed off the main transfer conveyors into smaller spur conveyors. The pallet rejoins the main conveyor after its operation is completed at the off-line station. The next pallet is then routed off-line. Most manual and automatic stations are in-line. Testing stations are typically off-line.

A representative sketch of a typical engine assembly loop is given in Figure 1. No stations are shown in the figure. All completed engine assemblies are tested before being unloaded from the line. Engine assemblies that fail the tests are pulled off the main line into a spur and repaired if possible. At each station, each engine assembly is processed for a period of time called the 'Station Cycle Time'. The cycle time of manual stations tends to be slightly longer and more variable from one cycle to the next compared to automatic stations. The cycle time for a station is set based on a number of criteria. The more complex and greater the number of tasks to be performed at a station, the longer the cycle time would be. An important criterion in assigning assembly tasks to stations is the "Line Rate" which is the number of engines to be produced per unit time. This number is typically determined by the target annual vehicle assembly volumes. The line rate is also expressed in terms of seconds per engine based on production volume and shift patterns utilized in the plant.

Clearly, the maximum cycle time for any station along the assembly line cannot be greater than the line rate. This requirement poses a constraint for tasks that cannot be divided to more than one station. A good example is the testing operation as it typically requires a considerable amount of time - usually twice or thrice the cycle time that can be achieved at other stations. Consequently, to maintain line rate, testing stands are duplicated such that engines are parallel processed.

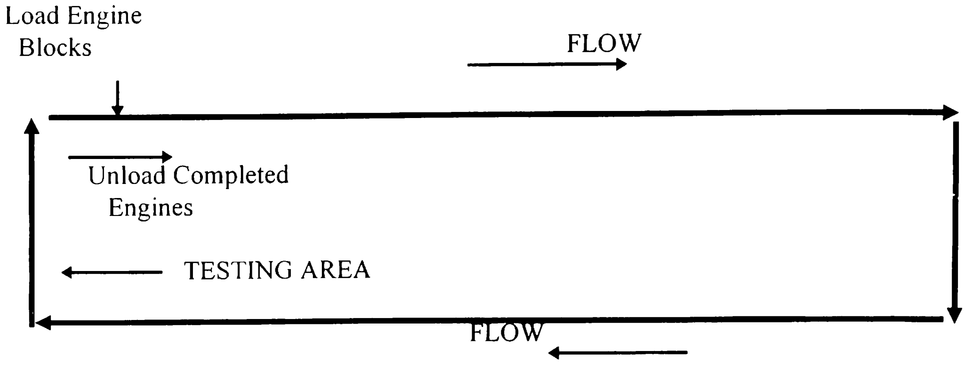

Figure 1: A Typical Engine Assembly Line Setup

3 THE NEED FOR SIMULATION

The behavior of many parts of an engine assembly plant can be varying greatly over time. Routing engines in and out of one of multiple parallel stations for an operation, arranging traffic priorities at intersections of conveyors where engines are diverted to off-line stations, randomness in manual operation times, machine breakdowns, and randomness of repair times are all factors effecting the design of an engine assembly line. Some of the typical design parameters that can be analyzed through the use of simulation are:

1. The number and cycle time of parallel stations.
2. Off-line versus in-line operation mode.
3. Reliability of machines and other equipment.
4. Conveyor and transport speeds.
5. Repair time for rejected pallets.
6. Arrangement of parallel stations for optimal use of space.
7. Method of sequencing pallets for uniform utilization of stands.

The foremost advantage of simulation is its capability to include the impact of randomness in a system. All the dynamics and the non-deterministic nature of the parameters eliminate the use of static tools such as spreadsheets for solving many line design problems. Discrete-event simulation tools available today provide built-in constructs to accommodate the manufacturing system parameters discussed above. All simulation software provide the capability to model random downtime occurrences and variable cycle times and repair times. Discrete-event simulation is also very useful in evaluating different alternatives subject to different values of the parameters involved. A sensitivity analysis for each option can be performed by modification of the key parameters. For example, designers and process engineers can determine the maximum allowed time to repair a faulty engine. This will in turn help with other decisions such as whether the manpower in the repair area will have to be increased for smooth flow. Another alternative is to improve quality across the entire engine line so that fewer rejects are generated at the test stands. However, rejects are not completely avoidable. On a typical line the reject rates at the test stands tend to be in the range of 3 - 5%. In the simulation, rejects are generated randomly based on this percentage at each stand. Thus the trade-off between throughput loss due to rejects generated and the cost to install better quality checks can be effectively analyzed. Furthermore, all commercial simulation software provide detailed animation capabilities. The animation of the assembly line operation can help engineers to visually detect problems or bottlenecks and also to test out alternate line designs.

In general, there are several areas on engine and transmission lines that are similar to the test stands described above. Wherever there are three or more parallel stations on a line, the same problem exists. For example, some manual assembly workbenches on transmission lines require longer cycle times. The problem becomes more complicated because the pallets have to be supplied to all operators uniformly to ensure uniform utilization.

The arrangement of the manual workbenches tends to be a general problem in many engine assembly systems. In front of parallel stations, a decision has to be made where the next pallet should be routed to. This decision has to be made based on where the previous pallets were sent to and based on which operator needs a pallet. Programmable Logic Controllers (PLCs) and switches are used to execute the control logic on the conveyors. Simulation offers an easier method to evaluate different strategies before the PLC code is generated. Thus the best strategy to distribute (sequence) pallets to the manual workbenches can be optimized using simulation rather than testing during implementation.

Another common application for simulation in such lines is optimizing the number of pallets required. Too many pallets can bottleneck the system in areas like the test stands. Too few pallets can starve stations and cause loss of production. The number of pallets required is closely tied to the operating philosophy for the test stands and manual assembly workbench areas. Tying up too many pallets in the testing and repairing areas can cause other bottleneck sections of the engine assembly line to be starved for pallets. On such systems, a pallet can cost between $5,000 and $25,000. Saving ten pallets can be substantial. In some cases, saving two pallets justifies the cost for a simulation.

4 CASE STUDY: FINAL TEST AREA DESIGN

The following is a description of a test area that was subject to an analysis using simulation. The objectives of the study were to determine whether there would be a need for buffers, and to determine the best model of operation regarding the control of traffic in the testing area. First, the system is described with the a discussion of potential issues that required the use of simulation. Then, a summary of the study is given with the significant results.

4.1 System Description

There are two major types of testing in a typical engine assembly system: the leak test and the cold test. During the design of an assembly line, once the problem of test stand cycle time and the initial number of stands is determined, the relative location and arrangement of stands should be considered. Certain constraints affect this decision. The most important constraint is layout related. Automotive plants are typically constrained for plant space. Efficient arrangement of test stands (typically space consuming) is important to saving space. Another constraint is the fact that test stands have some special requirements for additional equipment such as piping for water and gas. Consequently, bringing the test stands closer together is very desirable. Since time on test stands is scarce, it is essential that all stands are highly utilized. However if other stations upstream from the stands (especially the automatic stations) are down for extended periods of time, the test stands might be starved for pallets. To avoid this situation, some form of buffer in front of the test stands serves well increasing the area requirements. Furthermore, to keep travel distance to a minimum, it is desirable to keep the repair area close to the test stands.

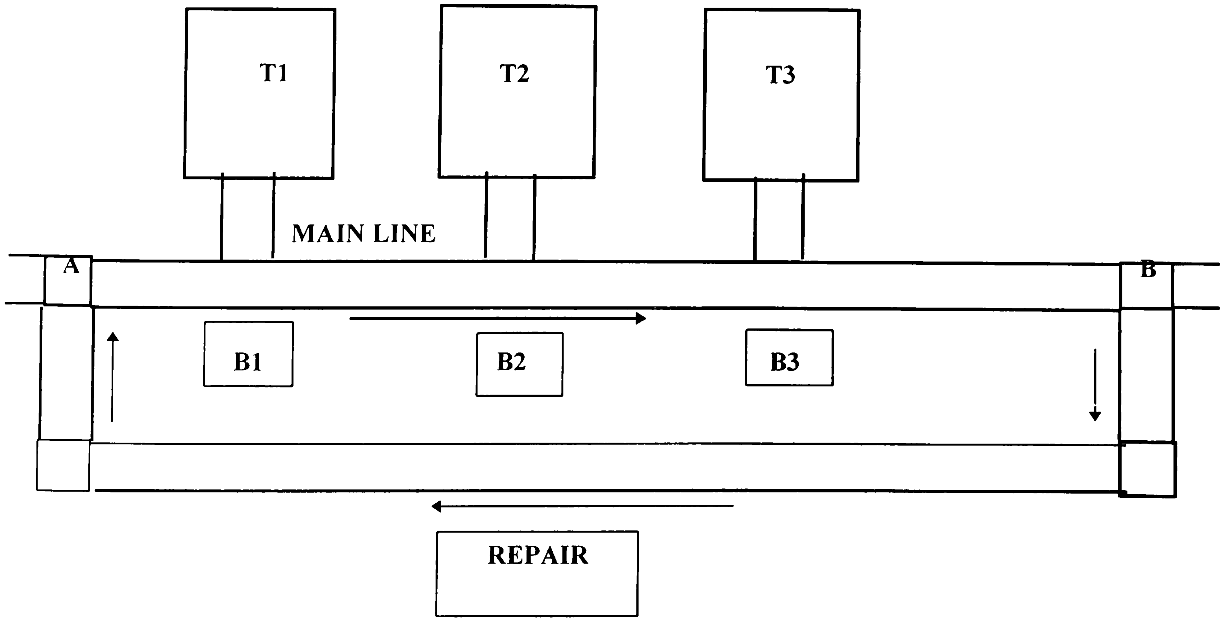

Figure 2 : A Typical Final Testing Area Configuration

A common arrangement is to have a conveyor loop leading out from the test stands area to the repair area and coming back to the test stands. This leads to an increased traffic of pallets in the testing area and it becomes important to control the traffic to avoid choking off the loop. The following sketch illustrates the arrangement described above.

The sketch shows a common arrangement of the test stands and repair area. Henceforth the term pallet refers to a pallet with an engine assembly on it. After finishing most of the assembly operations, pallets are routed to one of three test stands: T1, T2 or T3. Pallets are routed off-line to one of the stands using the spur conveyors connecting each test stand to the main line. Pallets are tagged as 'good' or 'rejected' based on the test typically by using Radio Frequency (RF) tags. At point B, good engines continue on the main conveyor. Rejected pallets are routed to point D. The rejected pallets are then repaired and routed by conveyor to point C and then to Point A again. The repaired engines are then go through the same steps. In routing the pallets through the test area there are two modes of operation. In the first mode (Mode 1), engines are not allowed past point A unless a test stand is available. Pallets tagged to be repaired are routed to the repair area. The repair operation is usually in-line. Once repaired, these pallets are routed back to point A where they are given higher priority to be re-tested (to avoid back-ups at the repair area). In the second operation mode (Mode 2), engines to be tested travel on the main conveyor without stopping at point A.

At each test stand, an untested pallet checks to see if there is room in the test area or in the adjacent buffer area. If an untested engine has to bypass all three stands because they are occupied, then at point B, the pallet is sent to point D and re-circulated back to point A. This cycle is repeated and only a successfully tested pallet is allowed to travel straight past point B on the main conveyor. The repair operation is done off-line on a separate piece of conveyor acting as a spur. These pallets are manually unloaded from the spur and put back on line at point D after repair.

In either mode of operation, there are many issues that lend themselves to an analyses by simulation. First of all, traffic management can become complicated when a large number of faulty engines arrive at the area. Consequently, the number of pallets in the testing loop should be regulated to avoid potential congestion. Furthermore, if the test stand cycle time is not balanced with the rest of the line, pallets may start backing up behind point A. Such a situation can have a more severe impact in Mode 1 operation. Also, in Mode 1, a pallet has to travel some distance to a test stand after receiving a test stand availability signal. Clearly, this travel time reduces the overall capability of the test stands. With Mode 2 untested pallets are available to be transferred into a test stand as soon at it becomes available and the test stands are utilized better. However, there will be a mix of pallets in the area of tested and untested engines. The size and location of buffers then become an important design issue. The ability of holding extra untested engines in buffer can provide additional capability to the test stations. In Mode 1, the issue of sequencing should be addressed. Sending pallets to the first available stand might be optimal. Other options include choosing the nearest stand first (reduces travel time) or choosing the least utilized so as to keep all stands uniformly utilized. In addition to all those issues, the situation gets even more complicated by the fact that test stands have their own reliability issues. Similar to other stations on the line, test stands experience failures randomly. This can be a major problem with traffic management and smooth flow for rest of the line until the stand is repaired. Buffers before and after the area or incorporation of manual backup test stands will have to be investigated. Frequent downtimes for the stands and a high demand for engines might entail the need for one or more extra stands.

Clearly, the operation mode to be adopted depends mostly on the demand, testing cycle times, and controls logic incorporated at the test stands. It is costly to adopt one operation mode and switch to the other at implementation. Consequently, adequate comparison of options under the stochastic behavior of the area becomes a significant task requiring the use of simulation for detailed analyses.

4.2 Experiments

A model of the testing system shown in Figure 2 was developed in the WITNESS simulation language. The repair area operates in an off-line manner where engines are moved off the conveyor for repair. The system performance was measured in average number of Jobs Produced Per Hour (JPH). The time taken by a test stand to repair an engine was 57 seconds, across all four models. The time to repair a rejected engine was assumed to be triangularly distributed with a most likely value of 5 minutes (and the minimum time was 2 minutes and the maximum time was 8 minutes). All conveyors operated at a speed of 20 feet/minute. A total reject rate of 3% was used across all three test stands creating rejects on a random basis. It was assumed that all rejected engines could be repaired in the repair area. In other words, there is no scrap. The objective of the study were to determine the best operation mode (Mode 1 versus Mode 2) and buffer size (buffer versus no buffer) combination. The alternative scenarios are summarized as follows:

Scenario 1: Operation Mode 1 was used without buffers at test stands thereby, holding engines at point A until a test stand becomes available.

Scenario 2: Operation Mode 2 was used without buffers at test stands thereby, circulating engines in the loop until one test stand becomes available.

Scenario 3: Operation Mode 1 was used but, one buffer for each test stand was added as shown in Figure 2 as B1, B2 and B3. If the test stands are busy, then engines can be routed to an empty buffer. Thus, as soon as a test stand becomes available, it can draw an engine from the buffer across it. In the simulation model, it takes 5 seconds for an engine to be transferred from the buffer to the stand. This reduces the idle time of the stands due to lack of untested engines waiting to be transferred immediately to the stand when it becomes available.

Scenario 4: Operation Mode 2 was used but, one buffer for each test stand was added as shown in Figure 2 as B1, B2 and B3. Thus untested engines circulate continuously and enter a test stand or buffer if one becomes available. Also, priority is given for an engine waiting in the buffer to be routed to the test stand as opposed to an engine from the main conveyor. However, it takes five seconds for an engine to be transferred from the buffer to the test stand across it.

Common random number streams were used across all four models in order to reduce variance among the simulation runs. Each model was simulated for a period representing 1000 hours of production. In each simulation, the first two hours were designated as the warm-up period. It was assumed that none of the test stands experienced random breakdowns. The results from the simulation runs are summarized in the following table (the confidence are not reported as they are so small that did not impact the relative ranking of the results) :

Table 1 : The Simulated System Throughput

Operation Mode	Buffer Size	
	0	1
1	125.2	171.4
2	178.1	172.3

The table indicates some interesting results. For example, clearly, in the second scenario, the average throughput capability of the system was determined to be 178.05 JPH which is a significant improvement over scenario 1. This can be explained by the fact that for the most part, test stands will not have to wait for engines to travel from point A after a stand is freed. The reduced waiting leads to better utilization of the test stands. As evident, the savings in travel time leads to an improvement of 60 JPH. Also, scenario 1 results are much improved to 171.4 JPH in scenario 3 with the addition of buffers to the system. Somewhat counter-intuitively, the average throughput capability of the system was determined to be 172.3 JPH in scenario 4 with a loss over Scenario 3. The increased transfer time from the buffer to the tests stand causes the loss in throughput as the engines from buffers take priority over those that are coming to the loop for the first time.

From the simulation experiments on the test area, it was determined that Scenario 2 was the best among those investigated. The model for each scenario was a simple modification of the model for the first scenario. With fairly limited commitment of time, four test stand configuration designs were compared. These experiments demonstrate the ability of simulation in aiding the design of the testing area. Further analyses can be performed using the above models. The impact of reliability issues on each of the above scenarios can be studied with relative ease if the reliability data is available.

5 CONCLUSIONS

Discrete-event simulation has a lot of applications in the design and implementation of automotive powertrain production systems. In particular, in engine and transmission production systems, the testing areas are very dynamic and require careful attention to design and operating philosophy. Discrete-event simulation can be very useful in designing and optimizing the number and arrangement of the test stands for the best results. All the issues in the test stand design can be solved using simulation before implementation. Important logic issues that are addressed in reality using Programmable Logic Controllers (PLC) can be tested using simulation to save valuable time and expense during actual implementation. This paper presented an application of simulation in the design of similar systems with a simple example. The primary objective of the paper was to introduce the reader to a small yet complex area in automotive manufacturing systems where simulation is increasingly being used as a design, debugging and decision making tool.

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