Modeling and Simulation of Automotive Engine Sub-Assembly for Production Improvement

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Abstract

Automotive Manufacturing Powertrain includes engines and transmissions. Assembling engines involves the integration of a large number of components. Simulation is commonly applied in the design and implementation of such production process. The objective of the simulation study is to identify process throughput for the Head Sub-Assembly line. The simulation analysis will reveal any potential machine bottlenecks, to prevent blockages and starvation to improve process throughput. Input data should include machine cycle times. The performance measures include machine utilization and confidence interval validation. The Arena simulation software will be used in this study. The target is to increase production of the current Head Sub-Assembly to a forecasted capacity with existing machines. The simulation results will identify the processes in the Head Sub-Assembly that could affect the production schedule. The findings will be validated through comparison of the actual process throughput. Moreover scenario and statistical analysis will be conducted for performance improvement.

1 Introduction

Simulation has been commonly used to study behavior of real world manufacturing system to gain better understanding of underlying problems and to provide recommendations to improve the production process. The objective of this study is to analyze machine cycle times to identify any potential machine bottlenecks, to prevent the starvations and blockages of the assembly line to improve process throughput. This paper begins with computer simulation research in the Automotive Powertrain Division. Powertrain is made up of engines and transmission which includes the engine head sub-assemblies. The engine sub-assembly lines include machines in sequence that assemble parts and then move the parts on pallets with conveyors. Assembly lines are measured by their throughput which includes machine cycle times, Work In Progress (WIP) and bottlenecks. A representative sketch of a typical engine Head Sub-Assembly loop is given in Figure 1 below with no stations. The process flow of a typical head sub-assembly is also illustrated in Figure 1. The paper identifies the input data, machine cycle time distributions through an Arena Model simulation. The Arena Sub-assembly model illustrates the process flow through the modeling function blocks with queuing systems. The Arena simulation results analyze the machine cycle times after multiple replications. The results will reveal bottlenecks scenarios through system queues and WIP data. The results will be validated with confidence interval testing and machine utilization results. Conclusion of the simulation will be summarized and all references will be listed. The simulation software allows runtime setup. The runtime setup gives the ability to add time to the Head Sub-Assembly preparation similar to real time manufacturing.

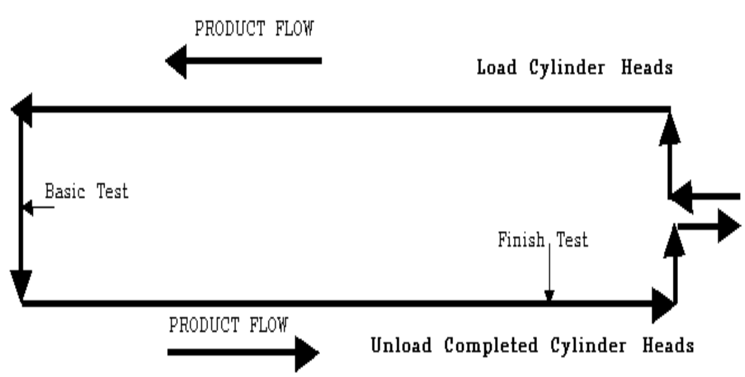


Figure 1: Typical Engine Head Sub-Assembly Line Setup

Over the last thirty years, suggested that computer simulation has enjoyed a great deal of popularity in the manufacturing and production. Simulations are often used to analyze systems that are too complicated to attack via analytic methods such as calculus, standard probability and statistics, or queuing theory. Through the current trend of information technology as well as automation technology, companies are urging a solution to produce varieties of products with low volume as market demand is fast changing into it (Ali, Seifoddni 2006). The use of computer simulation in design and operation of automotive industries is very helpful especially in car and truck assembly plants. Most of the automotive manufacturers worldwide currently require new and modified manufacturing system designs to be verified by simulation analysis before they are approved for final manufacturing design (Wirabhuana, Haron, Rofi Imtihan 2008).

Automotive manufacturing powertrain is a complex task that requires the production and integration of thousands of different components (Jayaraman, Gunal 1997). 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, cylinder head assembly, 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. Objectives for using simulation vary (Kibira, Mclean 2007). This paper focuses on the use of simulation for automotive manufacturing powertrain production systems. The benefits of simulation are demonstrated by focusing on a small part of engine final assembly systems. 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 (Jayaraman, Gunal 1997). Each of these sub-assemblies is 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. All sub-assemblies are assembled to the engine block at different stations. 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 mechanical stops. Subsequent pallets queue up behind the station and wait for the current pallet in station to complete processing.

The goal of a simulation model is to mimic the real world system being delivered, including real world conditions and assumptions. Goals for using simulation vary. Common goals, to name a few, are as follows (Jayaraman, Agarwal 1996):

- Process throughput determination of a point where throughput increases are worth it.
- Detect machine bottlenecks through machine utilization.
- Work-in -Progress and Queue Numbers.
- The machine cycle time for any station.

The speed of the machines will drive the productivity. This implies that Little's Law which states:

(Work-in-Progress (WIP) = Throughput * Cycle Time)

(Altuger, Chassapis 2011), discussed their assembly line research project which is based on the simulation tools used to develop the model. This is then followed by the methodology adopted in the project. The main body of research is presented by the following design approach, DCOV (Design, Characterized, Optimize and Verify). (Govil, Magrab 2000) emphasized that production computations should always include scheduling of the operations. (Faget, Eriksson, Herrmann 2005) presented a successful bottleneck detection method in discrete event models developed by Toyota Motor Company. (Roser, Nakano, Tanaka 2001) at Toyota Motor Company has developed a bottleneck detection technique. This technique identifies a bottleneck by measuring the duration of the periods in which the station is active and calculates it's average. (Roser, Nakano, Tanaka 2001)] states that the machine with the longest average active period is considered to be the bottleneck, as this machine is least likely to be interrupted by other machines, and in turn is most likely to dictate the overall process throughput.

(Chong, Sivakumar, Gay 2003), presented a simulation-based real-time scheduling mechanism to deal with the changes in a dynamic discrete manufacturing system. In order to have an effective understanding of the expectations from a production line, (Venkateswaran, Son, Jones 2004), their paper was to investigate how to increase process throughput and detect machine bottlenecks in a mature Engine Head Sub-Assembly line. Machines and conveyors are wearing out in the typical loop-conveyor assembly configuration. At each machine, each engine Head Sub-Assembly is processed for a period of time called the "Machine Cycle Time". The machine cycle time of manual stations tends to be slightly longer and more variable from one cycle to the next compared to automatic stations. The machine cycle time for a station is set based on a number of criteria, which is typically determined by the target annual vehicle assembly volumes. The behavior of many parts of an engine assembly plant can vary greatly over time. All simulation software provides the capability to model random downtime occurrences, variable machine cycle times, and machine repair times.

The goal of this study is to verify that the Head Sub-Assembly can double the current line production with existing equipment. Utilizing the modeling and simulation analysis, the Head Sub-Assembly can be analyzed without initial capital investment. The original line at launch could produce two assembled heads per minute. Therefore 120 heads assembled per hour and 960 heads assembled per eight hour shift. After years of wear and tear, there is only 200 heads assembled per eight hour shift. The manpower utilization has been reduced by half (6 to 3) operators and the conveyor line speeds have reduced with pallets removed.

The Head Sub-Assembly in Figure 2 is an automatic line with 17 assembling stations with a manual load and unloads stations. The line has two repair loops, Repair Loop #1 after Station #10 and Repair Loop #2 after Station #18.5. This gives the sub-assembly line the opportunity to repair heads if there is a Leak Test failure after Station#10 and Torque to Turn Test failure after Station#16. The Head assemblies are manually repaired and reintroduced into the line at Station#12 or after Station#15. The production line is made up of four chain conveyors with Head Sub-Assembly pallets which move from station to station. The pallets are tracked between stations with radio frequency identification (RFID) tags. RFID is the use of a wireless non-contact system that uses radiofrequency electromagnetic fields to transfer data from a tag. Each station is networked together and data collected as shown in the process flow in Figure 2.

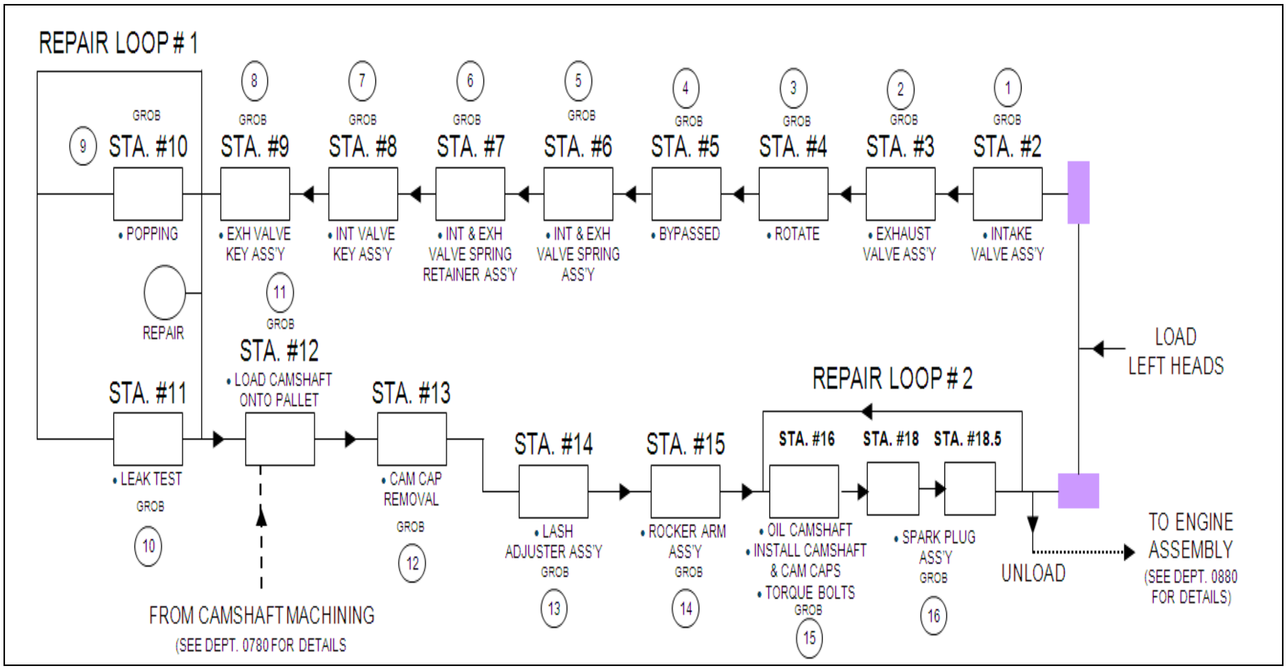


Figure 2: Process Flow for Head Sub-Assembly

2 Input Data

The left Head Sub-Assembly CAD drawing is shown in Figure 3. The CAD drawing shows the conveyors and stations. Machine cycle time of each sub-assembly is 19.3 seconds per station. No down times are considered for sub-assembly operations. Pallet length is 27.56 inches (700 mm) from front to rear. Pallet unloads at cycle time is 19.45 seconds. Conveyor system dimensions and stop locations are measured from the layout. Conveyor chain speed is 30 feet per minute for all sections. The sub-assembly runs left heads only with the number of available pallets in system averaging (88). Throughput is 185.1 jobs per hour and average cycle time is 21.45 seconds.

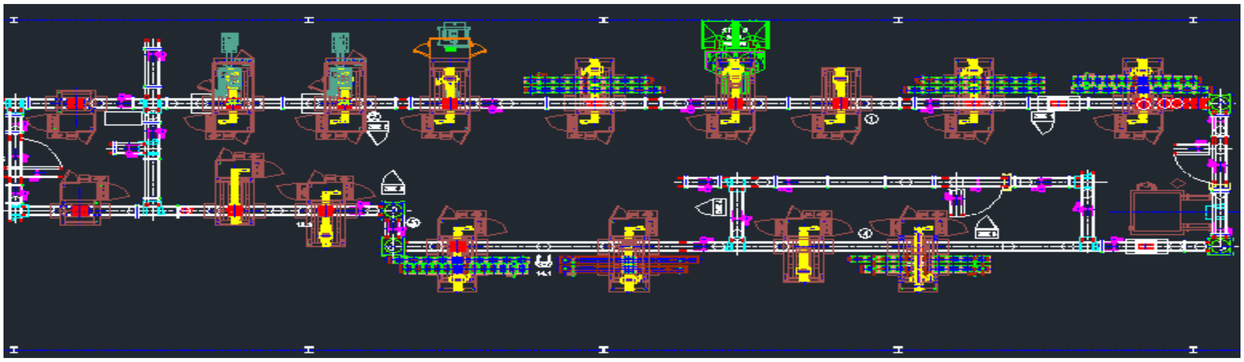


Figure 3: CAD Drawing for Left Head Sub-Assembly

Table 1 has the measured conveyor lengths in feet between machine stations. Pallets counts are between stations which carries the head components to the sub-assembly. For example there is 23 feet of conveyor between Station #2 and Station #3 with the capability of having 10 pallets between them. The number of pallets on the line and the conveyor length's plus speed can determine process throughput, total cycle time and machine bottlenecks.

Table 1: Conveyor Length and Pallet Counts between Stations

Station	Conveyor Length (Feet)	Pallet Count
Load Station	0	0
Station#2 Intake Valve Assembly	15	6
Station#3 Exhaust Valve	23	10
Station#4 Rotate	12	7
Station#5 Bypassed	14	7
Station#6 Intake & Exhaust Valve Spring Assembly	19	6
Station#7 Intake & Exhaust Spring Retainer Assembly	19	9
Station#8 Intake Valve Key Assembly	15	7
Station#9 Exhaust Valve Key Assembly	15	7
Station#10 Popping	21	10
Repair Loop #1	10	4
Station#11 Leak Test	36	16
Station#12 Load Camshaft onto Pallet	21	9
Station#13 Cam Cap Removal	13	4
Station#14 Lash Adjuster Assembly	18	8
Station#15 Rocker Arm Assembly	23	10
Station#16 Install Camshaft and Cam Caps, Oil Camshaft	23	10
Station#18 Spark Plug Assembly	16	7
Station#18.5 Spark Plug Assembly	23	10
Unload Assembled Left Head to Engine Assembly	7	4
Total	280	147

3 Machine Cycle Time Distributions

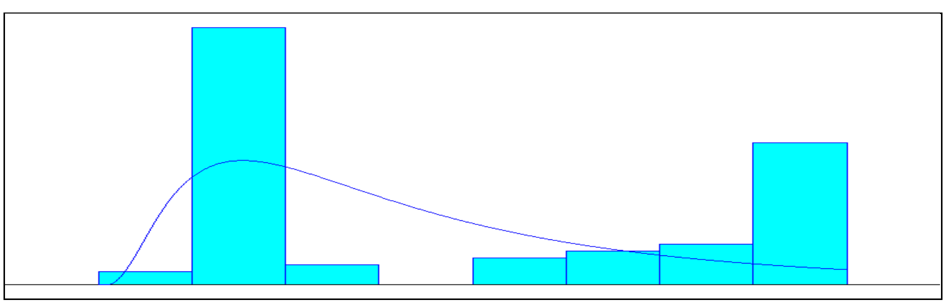
The real time data was collected from Factory Information Systems, cycle time reports and application software. The application prompts you to select the Head Sub-Assembly start and stop dates required. The shift preference and details for report are also selected. The Analysis Tool is then run and the results are displayed. From the results, the data is exported to a spreadsheet format (datafile.xls) as shown in Table 2. The data is now imported into the spreadsheet application where it is sorted and saved into a (datefile.txt) text format. The Arena Input Analyzer is now used to analyze the datafile.txt. The data is used in a best fit analysis to determine the distribution expression shown in Table 3 and displayed in Figure 4.

Table 2: Factory Information System Data Sorted to (datafile.txt) Format

0:16:42	**0:17:14**	**0:21:28**	**0:22:25**	**0:23:37**	**0:27:51**	**0:27:52**	**0:29:33**
0:30:22	**0:30:51**	**0:31:23**	**0:40:15**	**0:44:17**	**0:45:04**	**0:45:41**	**0:45:56**
0:57:07	**1:02:19**	**1:08:31**	**1:16:14**	**1:18:47**	**1:29:47**		

Table 3: Machine Cycle Time Distribution from Collected Data for 90 days

Station #	Distribution	Expression	Square Error	Chi Square Test p-value	Kolmogorov-Smirnov Test p-value
Load Station	Normal	NORM(23.3, 11)	0.02799	< 0.005	> 0.15
Station 2L	Normal	NORM(16.1, 1.32)	0.166862	< 0.005	< 0.01
Station 3L	Lognormal	14 + LOGN(6.1, 5.83)	0.16965	< 0.005	< 0.01
Station 4L	Normal	NORM(20.2, 0.484)	0.004351	0.195	> 0.15
Station 6L	Normal	NORM(20.2, 0.484)	0.004351	0.195	> 0.15
Station 8L	Normal	ORM(13.6, 0.842)	0.021396	0.0291	> 0.15
Station 9L	Weibull	8.01 + WEIB(3.35, 7.31	0.007954	0.157	0.15
Station 10L	Normal	NORM(15.9, 0.659)	0.002847	0.608	> 0.15
Station 11L	Beta	14.1 + 4.86 * BETA(3.35, 3.17)	0.036446	< 0.005	> 0.15
Station 12L	Beta	15 + 2.86 * BETA(19, 8.53)	0.044425	< 0.005	> 0.15
Station 13L	Weibull	16.4 + WEIB(3.62, 7.89)	0.034197	0.0151	0.0245
Station 14L	Erlang	12.4 + ERLA(0.106, 11)	0.012095	0.0474	> 0.15
Station 15L	Erlang	12.4 + ERLA(0.106, 11)	0.012095	0.0474	> 0.15
Station 16L	Normal	NORM(19.4, 0.919)	0.254687	< 0.005	< 0.01
Station 18L	Weibull	6 + WEIB(9.67, 13.4)	0.014208	< 0.005	< 0.01
Station 18.5L	Beta	13 + 8 * BETA(5.89, 0.718)	0.018395	< 0.005	< 0.01
Unload Station	Constant	19.43			



(Station 3L Lognormal 14 + LOGN(6.1, 5.83) Sq.Error=0.1696 p-value< 0.005 p-value-< 0.01)

Figure 4: Input Analyzer Best Fit Results for Station 3L Machine Cycle Time

4 Simulation Model Building

Sub-assembly model in Figure 5 is designed to mimic the real time Head Sub-Assembly in a manufacturing process. The head arrives at the load station where it is emulated with an "Enter Module" which creates heads arriving into the model. The connecting lines in the model represent the conveying system which is assuming to give zero transfer time for this model. The next block used was Assign block, which assigns "TNOW" variable that will track the System Cycle Time throughout the process. The connecting lines move the part to the next module known as

Process and named Intake Valve Assembly. The Process module is intended as the main processing method in the simulation. Therefore the model has twenty Process modules to formulate the sub-assembly. Part of each module there is a Queue. The Queue allows parts to arrive in a First In First Out (FIFO) mode. The Queue also collects the waiting time, waiting cost and number of waiting. The model also has two decide blocks that are setup for entering repair loops if the Head Sub-Assembly has rejects. To conclude the model we used a Record module to finish data collection and Dispose block to end the simulation. Variable displays blocks are used throughout the model to display system values such Cycle time, WIP and Number Out.

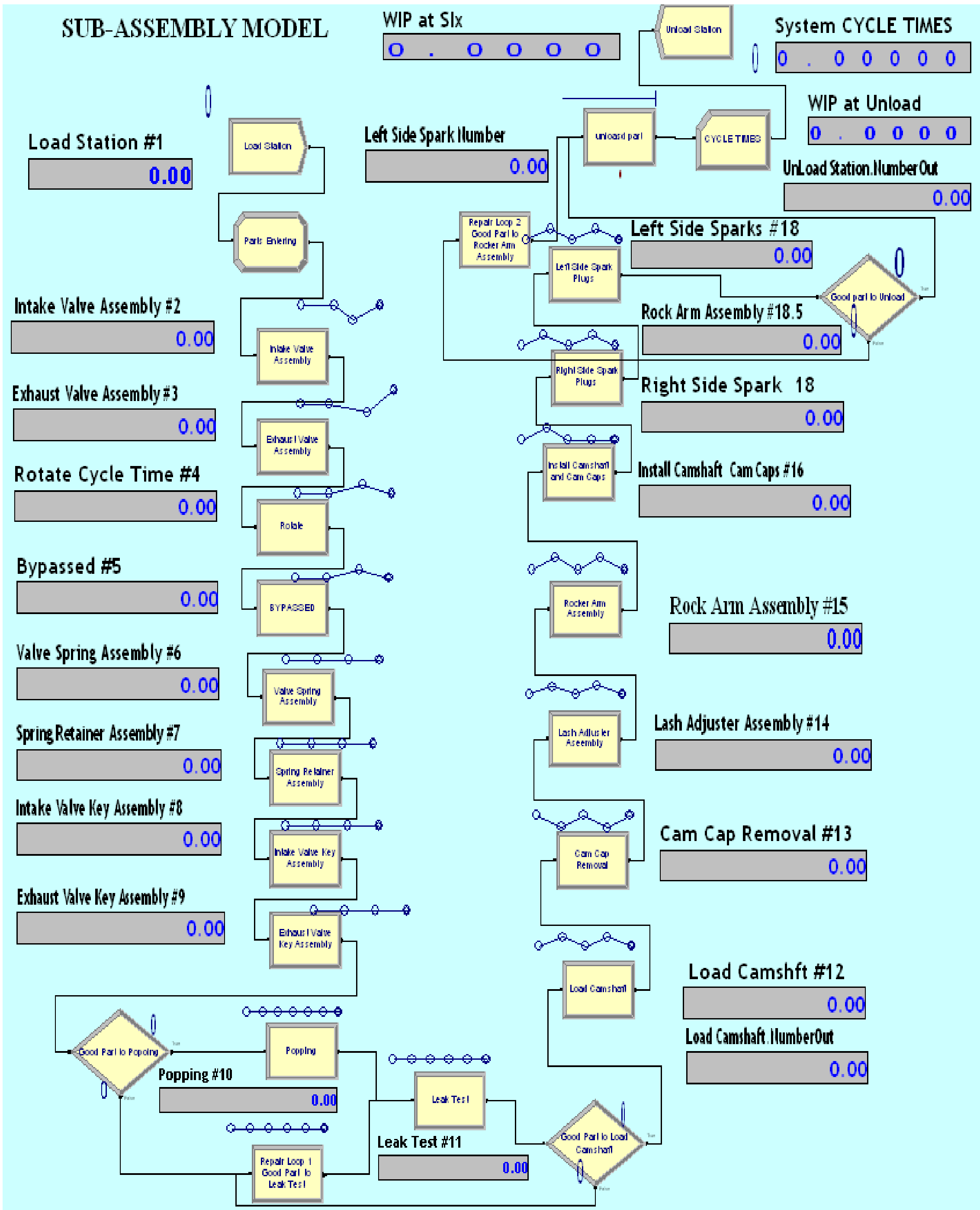


Figure 5: Arena Model with Machine Cycle Times

5 Results and Discussion

The objective of the simulation analysis is to identify any potential bottlenecks, to prevent the starvations and blockages of the assembly line to improve process throughput. Thus the trade-off between throughput loss due to rejects generated and the cost to install better quality checks can be effectively analyzed. Thus the work develops an intelligent modeling tool in simulation where the user can build up a more realistic model to identify machine bottlenecks and enhance system performance in terms of productivity, queues, and work in process (WIP) as well as machine cycle time. Comparison between the actual process throughput and the simulated one is used for the proposed model validation. The machine cycle time comparison is done, which also proves the validity of the intelligent simulation model.

5.1 Outputs and Machine Cycle Times

A fundamental problem in simulation modeling is that of determining the proper input random variables to drive the simulation. If there are multiple replications and statistics have been cleared between replications, then the value displayed is the average of the replication values. Table 4 below shows multiple results for the model.

Table 4: Modeling Results From Multiple Replications

Modeling Results	Wait Time per Entity Station #3	Entity WIP	Accumulated Wait Time Station #3		Queue Time Station#3	Maximum Number Waiting #3	Utilization Station #3
Replication 10	0.003764	39.178	20.0412		0.5822	12	0.6911
Replication 15	0.003859	38.405	23.7865		0.5948	13	0.6889
Replication 20	0.003798	40.806	23.4140		0.5854	13	0.6891
Replication 30	0.003772	40.470	23.2422		0.5811	13	0.6889

	Tally Total Cycle Time	23.24sec.
	Entity Total Time	25.07sec.
	Entity WIP (Bottleneck)	40.47jph
	Accumulated VA. Time Station #3 (Exhaust Valve Assembly) (Bottleneck)	34.36sec.
	Accumulated Wait Time Station #3 (Exhaust Valve Assembly)	23.24sec.
	Waiting Time Station #3 (Exhaust Valve Assembly Queue)	0.003772sec.
	Queue Number Waiting Station #3 (Exhaust Valve Assembly Queue) (Bottleneck)	0.5811sec
	Utilization Station #3 (Exhaust Valve Assembly) (Bottleneck)	0.6889sec

The Arena model was run with different replication to verify that the input data was consistent and valid. The results revealed a Bottleneck condition on Station#3,the Exhaust Valve Assembly machine. The accumulated times, waiting times and utilization of Station#3, all point to a bottleneck condition. You can evaluate which operations are bottlenecks by reviewing the number in queue (NQ(Station#3)) values for the modules. If the maximum and last values are the same or close, there could be some bottlenecking occurring at the specified module. The machine number busy values from the result report for Station #3 and Station #6 are relatively the same. This suggests that the usage is similar and could be a source of a bottleneck condition. The maximum number in waiting queue is for Station #3, which strengthens the criteria for bottleneck conditions.

5.2 WIP and Machine Bottleneck Analysis

The Process module has an animated variable below the module. This variable represents the WIP of (40.47) for that module. This module uses a graphical queue above the module handle that will show multiple entities waiting in the queue to either seize a resource or be batched. Machine bottlenecks can be spotted by reviewing the WIP values for the module. The report also reveals the average number of entities in a Process module with the maximum and last values. If the maximum and last values are the same or close, there could be some bottlenecking occurring at the specified module(s). The plot below in Figure 6 shows the number parts though the station as Jobs per hour (JPH.)

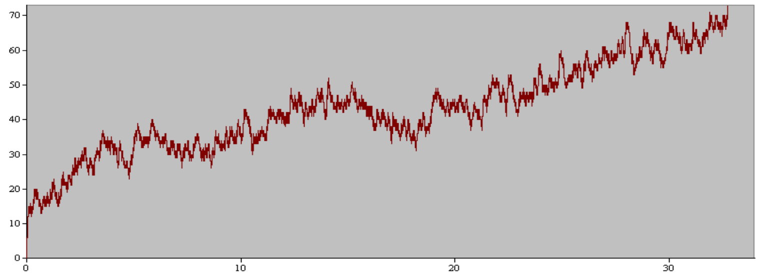


Figure 6: Work in Progress (WIP)

5.3 Machine Utilization

From the chart in Figure 7, the x-axis represents time, the y-axis the values of utilization which represents the potential bottleneck on the head subassembly. The largest quantity of all automatic machines in the sub-assembly is Station# 6(Exhaust Valve Assembly). This depicts that station#6 can also be the bottleneck machine on the head sub-assembly line.

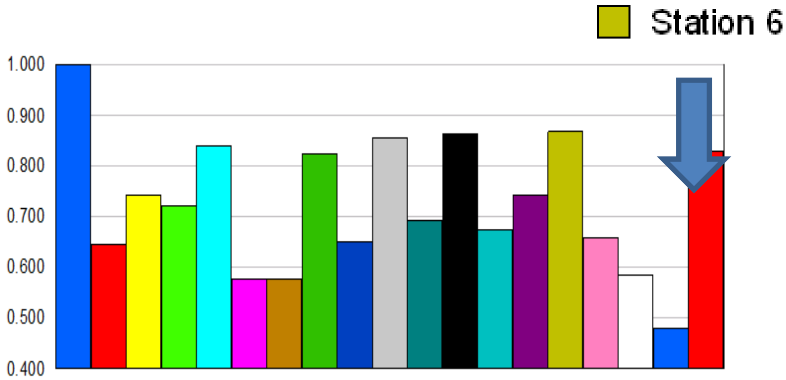


Figure 7: Arena Model – Output Results

5.4 Confidence Interval

A degree of confidence level must also be considered for the analysis. A 95% confidence interval is considered for the cycle time analysis. The model returns the half width value of the 95% confidence interval around the mean for the specified output statistic across all replications run so far. This considers only the final values of completed replications. The sample mean of the difference is .243. The result falls within the 95% confidence interval. Since the calculated value of the test statistic does not fall in the rejection region, we do not reject it. Thus, data does not present sufficient evidence to indicate that the results can be rejected.

5.5 Improved Model Results and Validation

The production environment is considered for four weeks (one month), each week for five days, and each day for one shift for process throughput validation purposes. A degree of confidence level must also be considered for the analysis. A 95% confidence interval is considered for process throughput and cycle time analysis. The sample mean of the difference is 0.243. The sample variance is 0.0515. , the result falls within the 95% confidence interval. The model can be enhanced by adding the conveyor speeds and the number of pallets on the assembly line. Further scenarios involving downtime and shift patterns can be studied to improve the model. The next step in throughput improvements would be the redundancy of the machine with the bottleneck conditions. Another scenario would be the adding of a buffer before the bottleneck machine. This is a direct advantage of simulation by running models with different variables to seek optimum solution with minimum cost and waste. The machine cycle times can be also lower through physical improvements and adjustments. The input data would direct change and the model reflect through WIP and queue times.

6 Conclusion

The simulation results reveal the potential Head Sub-Assembly machine bottlenecks at Station #3, Exhaust Valve Assembly and Station#6, Valve Spring Assembly. This also can be validated with the real time data from Station #3 and Station#6 machines. Station #3 machine inserts four exhaust valves into the head assembly. While Station#6 machine installs both the intake and exhaust valve springs. This assembly machine picks up four springs for the intake valves and places them into the head assembly. Next it picks up four springs for the exhaust valves and places them into the head assembly. Finally the machine lowers the head assembly onto the conveying system where it's transported to next station. The above process description depicts a busy Head Sub-Assembly which can have multiple potential machine bottlenecks. The Queue time for the Exhaust Valve Assembly Queue is high, meaning that the station has potential to have a machine bottleneck. Machine cycle time of these Head Sub-Assemblies equals 19.3 seconds per station compare to 23.24 seconds from the simulation. The values are similar which shows the data collected for the model was realistic. Throughput is 185.1 jobs per hour from real time data which is greater than 104.48 (WIP/Cycle Time) from the model. This reveals that the current head subassembly is under producing by 44%. This is not a profitable situation and improvement strategy should be put in place. The average cycle time is 21.45 seconds compared to 23.24 seconds from the model. A formal goodness-of-fit test (such as a Kolmogorov-Smirnov test) was performed to all Stations. The Station#6 which is a potential machine bottleneck had p-value >0.15 which depicts that the fitted distribution is reasonable.

The simulation flags that expose bottlenecks could affect the production schedule. The process throughput of the Head Sub-Assembly line will be affected and the original goal to increase the production of the current Head Sub-Assembly to original capacity with existing machines will be in jeopardy.

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