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The Effects of System Failures in a Robotic Assembly Line-Simulation Modeling and DOE Analysis

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Abstract

This research paper demonstrates how to design and develop a simulation model for an automated robotic assembly line production process. The layout consists of 10 process stations including sealing, piercing, welding, optical gauging, and dimensional check stations. The complete assembly line processes consist of 41 robots including 26 welding, 12 material handling and 3 sealer robots. The assembly line is fully automated without any manual process stations. The simulation model was developed using Arena software for this complex production system. The simulation model results were verified and validated using the actual plant data. The simulation model presented here identified the effects of the system failures on production. The findings were analysed using Design of Experiment (DOE) and presented improvement ideas to increase production. The general tendency of the plant staff is to buy more equipment to build more. But, more equipment also requires more maintenance. It is interesting to see how the system failures affect the production.

Keywords
BIW Process, Simulation, DOE, Robot Failure

1. Introduction

The US auto companies are always under tremendous pressure to keep up with the foreign competition. The US automotive industry came back roaring like a bull after a few worst years. The US auto industries have strived to maintain continuous improvement methods, eliminate waste, and maintain productivity at maximum efficiency. There are numerous quality tools and methods are in place to make quality automobiles that customer wants to buy. However, making profit for the US auto companies is always tough in this bad economy. The assembly plants are left with daunting task of producing more with fewer resources. In the assembly plant, each department staff is expert in their own area. For example, the welding engineer may have good understanding of robotic welding; however, he or she may not have the necessary background to understand the simulation modeling of a welding cell. The facility engineer and/or the process engineer may not even understand the basic theory behind the simulation modeling software. The plant engineers are always chasing the shortage of materials, manpower issues, machine breakdowns, and production losses. The simulation engineer may have the necessary modeling skills but, may lack the knowledge in complex manufacturing processes of building a vehicle. There are lot of studies published on productivity improvements. This research paper is unique because it uses authors' professional experience in the automotive field combining with expertise in simulation modeling software. This paper aims to predict the production based on the assembly line system stations uptime and down time. The Arena simulation modeling is a great tool to study the automotive assembly line performance. But, the plant staffs do not have the time or the simulation expertize to develop the model accurately. The verification and validation becomes challenging since, the modeling expert do not understand the process and process engineers do not understand the modeling. There is a huge disconnect understand the processes and the proposed modeling solution. This paper aims to improve the plant production using various "What-If" scenarios using DOE analysis.

The automotive assembly line process stations are highly automated with complex process robots that perform operations like, material handling, and welding, sealing and visual inspections. These assembly lines are controlled by Programmable Logic Controllers (PLC). The manual processes are limited to less than 10% compared to 90% automated process stations. The production plant must meet the production requirements demanded by the marketing group on a weekly and/or monthly basis. Nowadays, the assembly plants are running more than one model in the plant. The vehicle types and the quantity to produce change very often based on the sales volume. It is very hard for the plant staff to manipulate the vehicle types and the required output. The plant production is affected by various factors such as, station uptime and down time, wait times, and process intensive bottleneck stations.

This paper addresses the challenges involved in understanding the production processes, model development and simulation. In this paper, an investigation is conducted using discrete event simulation modeling to study the effects of system failures of a robotic assembly line. The DOE analysis has revealed the effects of the breakdowns in the system.

2. Literature Survey

There are lot of research work done by subject matter experts on Discrete Event Simulation modeling and techniques. There are many approaches used for validation and verification of the simulation model. Various validation techniques such as conceptual model validity, model verification, operational validity, and data validity and minimum recommended procedure are discussed by Sargent (2004). Model accreditation standard (DoDI 5000.61) is available from Department of Defence (DOD) for specific application.

Jack Hu and Stecke (2009) offered parallel and hybrid combinations and their trade-offs that improves productivity and dimensional quality compared to traditional assembly systems for automotive bodies that have been designed using serial configurations. Guidelines are developed to aid the selection of a system configuration that is appropriate for total system performance. Bottleneck causes most of the productivity losses. Roser et al. (2001) developed a novel method to detect the bottleneck in a discrete event system by examining the average duration of a machine being active for all machines. The machine with average uninterrupted active period is considered the bottleneck. Dessouky et al. (2007) presented a simulation based productivity study to compare the performance of the conventional and Shorter Trailer Combination Vehicles (STCV) operations with respect to a stochastic Multi-Vehicle Pickup and Delivery Problem (MVPDP) in which the demand is random with random delivery due dates. They determined the number of trucks and trailers, the pickup-and-delivery dispatch rule, and the type of transportation operations (conventional vs. STCV) that optimise various performance measures. Tjahjono et al. (2008) proposed a methodology to assist experimentation procedures. The methodology entails the 3 key stages to increase productivity of the line namely: bottleneck detection, bottleneck reduction/elimination and efficiency. Cycle time, machine reliability, and buffer allocation (or removal) variables are weighted into the calculation effort. By constantly validating the model by inputting real time data, efficiency can be improved with production disturbance system in manufacturing systems based on discrete event simulation is studied by Ingemansson et al. (2004).

We rarely encounter real-life sampling situations in which the correct form of distribution is "known". Another issue we encounter in automotive assembly line is unbalanced cycle times due to product and process mix variations. Shaaban and McNamara (2009) studied the impact of unpaced, unbalanced lines with respect to both their mean operation times (MTs) and Coefficients of Variation (CVs) were simulated with different lengths, buffer capacities, degrees of imbalance, and patterns of imbalance. Idle Time (IT), throughput and Average Buffer Level (ABL) data were generated and analysed. The best patterns provided generally superior performance to that of a balanced line counterpart.

Another important factor in automotive assembly process is ergonomic issues that contribute to vehicle build issues. In order to gain from existing ergonomics knowledge within a company, the possibility to implement such wisdom in the current simulation software becomes important. Backstrand et al. (2007) integrating an established ergonomics work process into a virtual environment that benefits ergonomics work process where simulation and evaluation at early stages of a design process are key factors. Pandian and Ali (2011) illustrated how to improve robotic automotive body shop throughput by feeding back actual plant data for input variables for entities to improve discrete simulation model prediction and validation. They also proved that the mean time to repair and mean time between failures critically affect the throughput.

Tiwari et al. (2009) formulated an exact and efficient heuristic-based solution methodology, which covers three segments of the machine-loading problem, i.e., part-type sequence determination, operation allocation decision and reallocation of part-type in a flexible manufacturing environment. An iterative reallocation procedure has been devised to ensure minimum positive system unbalance and maximum throughput. The proposed heuristic method proved these objectives in the presence of constraints posed by availability of machining time and tool slot in a given planning horizon. K.T. Hung, J. K. Liker (2007) used the simulation approach to study the batch size effect on production lead-time in a multi-stage assembly pull system considering the combined effect of these production conditions. They found internal and external production conditions have significant impacts in reducing the responsiveness of a pull system.

3. Process Flow Descriptions

The body side aperture (BSA) complete assembly line layout for this simulation study is shown in Figure 1. This is a 10 station automated robotic assembly line which welds outer aperture to the inner aperture. The parts flow from left to right. The robots are depicted in pink and the robot numbers are donated as R1 thru R62. The parts that are welded progressively in each station are depicted in green. The stations 6A & 6B and stations 8A & 8B are parallel process stations. The sub-assemblies parts i.e. the inner and the outer apertures are fed through the conveyor system in the beginning of the line from left side. The completed assemblies exit thru outgoing assembly at the end of the line on right.

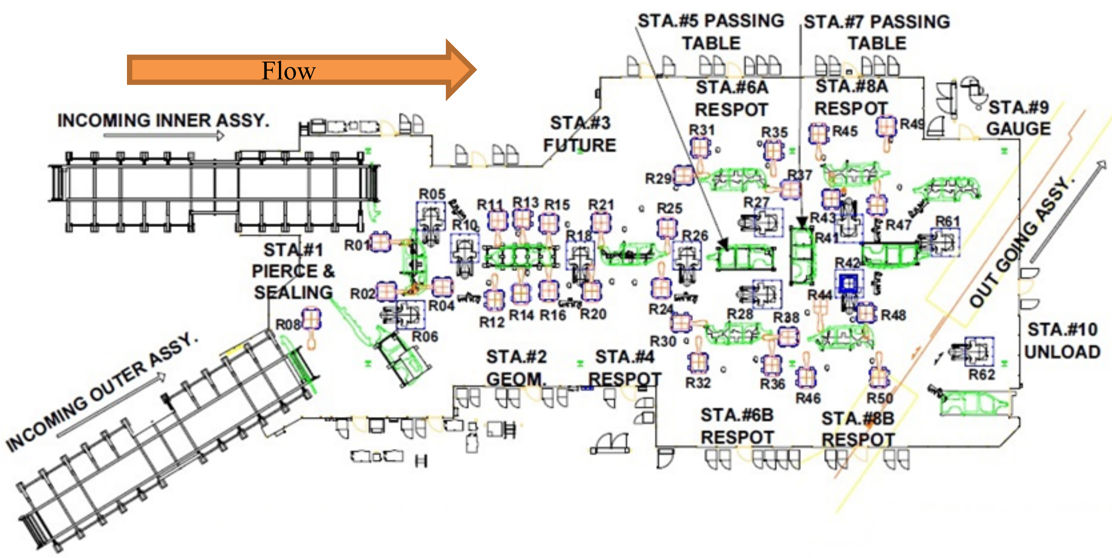

Figure: 1 BSA Assembly Line Layout

- **Station: 1 (Piercing & Sealing)**
  The MH-R8 unloads the outer aperture from overhead conveyor and loads it to the piercing fixture. The MH-R6 unloads the outer aperture from the piercing fixture and loads it to the sealer fixture. The sealer robots: 1, 2, 4 apply sealer in the outer aperture. The MH-R5 unloads the inner aperture from overhead conveyor and loads it inside the outer aperture in the sealer fixture. The MH-R10 unloads assembled parts from sealer station and loads parts to geometry welding station 2.
- **Station: 2 (Geometry weld)**
  The weld robots 11 thru 16 weld inner aperture to outer aperture in the geometry welding fixture.
- **Station: 3 (Idle -future model)**
- **Station: 4 (Respot weld)**

The MH-R18 unloads and load assembly in fixture. The weld robots 20, 21, 24, 25 weld assembly in respot fixture. The MH-R26 unloads assembly from station 2 and loads in passing table 5.

- **Station: 5 (Passing Table)**
- **Station: 6A (Respot weld)**
  The weld robots 29, 31, 35, 37 respot weld assembly in respot fixture 6A. The MH-R27 unloads and loads assembly in sequence: passing table 5, fixture 6A and passing table 7.
- **Station: 6B (Respot weld)**
  The weld robots 30, 32, 36, 38 respot weld assembly in respot fixture 6B. The MH-R28 unloads and loads assembly in sequence: passing table 5, fixture 6B and passing table 7.
- **Station: 7 (Passing Table)**
- **Station: 8A (Respot weld)**
  The weld robots 43,45,47,49 respot weld assembly in respot fixture 8A. The MH-R41 unloads and loads assembly in sequence: passing table 7, fixture 8A and station 9.
- **Station: 8B (Respot weld)**
  The weld robots 44, 46, 48, 50 respot weld assembly respot fixture 8B. The MH-R42 unloads and loads assembly in sequence: passing table 7, fixture 8B and station 9.
- **Station: 9 (Optical Gauge)**
  In the optical gauge station, cameras take pictures and compare it with the critical locating points. In case of discrepancy, assembly requires quality buy-off. The MH-R61 unloads completed BSA and handover assembly to MH-R62
- **Station: 10 (Unload)**
  The MH-R62 loads completed assembly to conveyor for next process or load assembly in weld quality and dimensional check pull-off cart mounted on the floor at predetermined sampling frequency.

The parts are welded by welding robots (200 kg. pay load) using servo weld guns. The parts are moved by the heavy (400kg. payload) material handling robots. The parts are loaded on to the overhead power and free conveyor for the next stage of the assembly process. The weld and dimensional quality check pull-off cart station is incorporated at the end of the line on the floor.

4. Problem Descriptions

The automated manufacturing system is so complex that it is not easy for the simulation engineer to understand the complexity of process tooling, process sequence, process variables, buffer limitations and the process intensive bottle neck stations. It requires lot of communication and understanding upfront between the model developer and the plant staff to implement the model results and the recommendations. The design process cycle time for the above layout is 90 Jobs per Hour (40 seconds cycle time). The assembly line tooling and processes were designed to build about 540 bodies per shift @85% efficiency with 7.15 hours actual production time in the plant. The assembly plant is always seeking cost effective solution to increase the throughput in the plant. In this study, stations up time and down time actual plant data is incorporated to study the effects of the system failure on production output. The historical station break down data is incorporated in to the simulation model to accurately predict the output for the given layout.

5. Simulation Development

Developing an accurate simulation model requires understanding of the robotic welding, conveyor interaction, function of the tooling, process parameters, and PLC to extract actual data. These factors affect the plant throughput, quality and delivery. The simulation model verification and validation of a robotic welding process system is a great challenge. In this paper, an earnest attempt is made to provide valuable information to the plant staff to forecast the plant throughput using simulation modeling using the plant data.

The development of the 10 station robotic process simulation model is shown in Figure 2. The simulation model captured during the run is shown in Figure 3. The model station resource data matrix is shown in Figure 4.

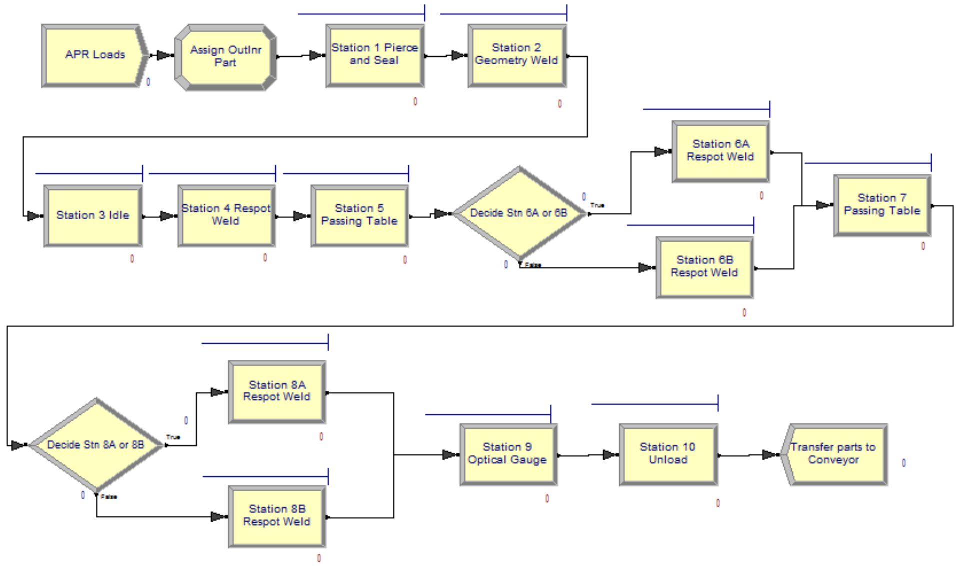

Figure 2: Simulation model design

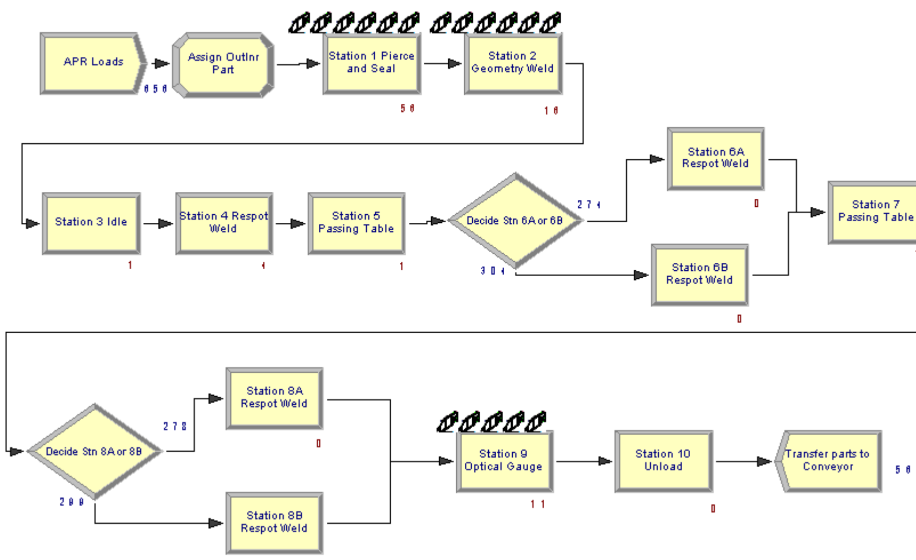

Figure 3: During model run

Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1 ▶	Station 1	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
2	Respot 4	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
3	Gauge	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
4	Unload 10	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
5	Passing Table 5	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
6	Passing Table 7	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
7	Idle	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
8	Respot 8A	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
9	Respot 8B	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
10	Respot 6A	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
11	Respot 6B	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑
12	Station 2	Fixed Capacity	1	0.0	0.0	0.0		1 rows	☑

Figure 4: Resources data matrix

All the process stations have 4 welding robots except one geometry welding station which has 6 welding robots. The passing tables and parallel processes are included in the simulation model. The system uptime and down time are also incorporated in the simulation model.

The Table 1 shows the actual production data based on one month data. The number of replications required for the different simulation run close to actual mean prediction values are shown in Table 1. To find the required number of simulation runs for the plant data, one could use equation 1.

The number of replications is determined using the Equation 1 per Kelton (2007).

$$n = \left(\frac{Z \cdot s}{p}\right)^2 \qquad \text{… (1)}$$

Where,

n = Number of replications
Z = Z value taken from the Normal Probability table with % of confidence interval
S = Six sigma Standard Deviation
P = Value, How close to actual mean

Table 1: No. of Replications required

Production- Max =	492
Production-Min =	273
Production- Range =	219
Production Mean =	**397**
Standard Deviation =	54

How Close to Actual Mean (P=Production)	CI= 95% (α= 5%)
1	5118
5	205
10	51
20	13
30	6

To get to the actual mean within +/- 1 vehicle, the simulation model must be replicated ~ 5000 times for 95% confidence interval (CI). In this paper, the investigation is conducted based on the actual mean value (397 vehicles) within +/- 30 vehicles output with 95% CI. The authors have decided to run 6 replications to test the model accuracy @95% CI.

The investigation was performed by running the simulation model for one production shift. The actual production is scheduled for only 7.15 hours. The operator's lunch and break times are not included in the model. The simulation model study was conducted and entity animations were observed visually to understand the queue behaviour at each process station. The simulation model animation was recorded and captured through AVI file. The various model parameters are analysed and evaluated in the next section.

6. Model Analysis using DOE

The simulation prediction model was developed using Arena Version 13.90 (2009) for the above layout processes. The simulation model is verified and validated with the actual production data. The major variables considered for this research paper are the system failures. The simulation model produced 569 vehicles at the base level. The DOE analysis revealed the critical effects of the uptime vs. downtime on production.

The DOE analysis is developed to study the effect of the system failures on production. The 2^2 Factorial Design is conducted with two factors: low (1/2 of the actual value) and high values (2X the actual value) with two variables: uptime and down time. The DOE studies were conducted using the standard order test with random replication using Minitab 16.0 (2010). The simulation DOE study results are shown in Table 2. Please note that the less downtime i.e. low number is better. The main effect plot is shown in Figure 5. The steeper lines show that the uptime and the down time critically affect the production. The interaction effect plot is shown in Figure 6. The steeper line (downtime) in the plot shows that the down time affects the production more critical compared to the uptime (less steeper). The cube plot is shown in Figure 7. The production numbers are shown at the corners at two level settings. The normal plot of the effects is shown in Figure 8. The normal plot of the effects show the downtime, the effect of both the uptime and the downtime and the uptime affect the production numbers in that order.

Table 2: Simulation study results

Std. Order Test	Uptime -A	Down time -B	Production
1	0.5 (low)	2 (low)	500
2	2 (high)	2 (low)	570
3	0.5 (low)	0.5 (high)	580
4	2 (high)	0.5 (high)	574

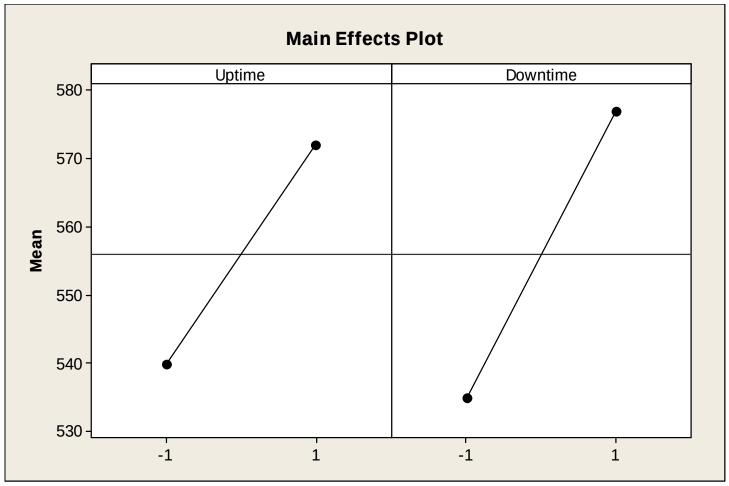

Figure 5: Main Effects Plots

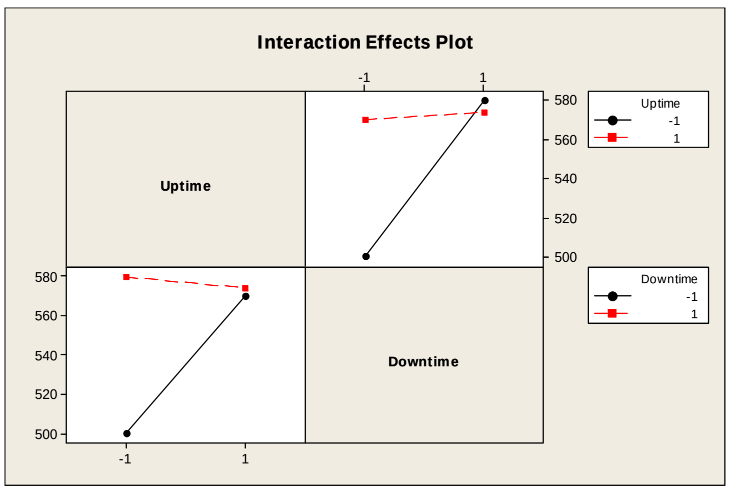

Figure 6: Interaction Effects Plots

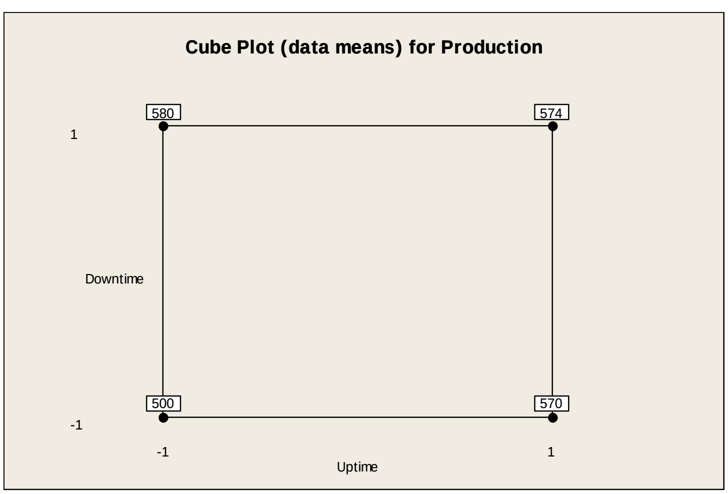

Figure 7: 2^2 Cube plot for the production

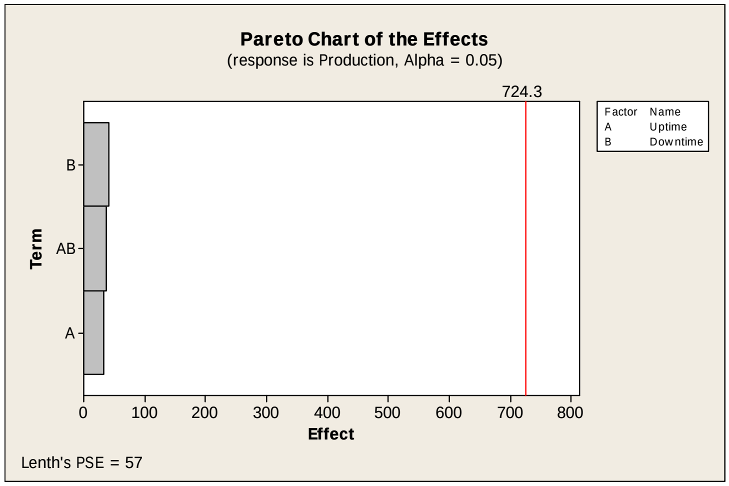

Figure 8: The Normal Plot of the effects

The simulation result produced average cycle times for each station, throughput, wait times, work-in-process (WIP). From the simulation result, the main bottleneck for this layout is the station 1 process. The simulation results showed the production output range from 500 vehicles to 580 vehicles. An increase of 80 vehicles per shift would have tremendous effect on the company bottom line. A plant running 2 shifts per day for 200 working days would produce 16,000 more vehicles in turn produce millions of dollars for the company. Improving the plant production is very critical for the plant survival as well as the company's survival in this economy.

7. Discussions and Recommendations

One needs to understand the actual assembly build processes to find the problem in the system. The assembly plant staffs are always under pressure to minimize the scarp, rework, the inventory of the spare parts, and the manpower. However, the plant staffs need to maintain the required daily and monthly throughput. Having more equipment in the plant will not solve the issues. The more equipment may break down more, requiring more spare parts and more staff to maintain. The plant staff must understand the simulation results and act upon the recommendation to improve the production. To meet the daily production, the plant may schedule overtime for the shift workers. Scheduling the over time is never a good idea. It has a domino effect on the overall vehicle quality, preventive maintenance schedule and operator fatigue. It is very critical that the production department closely work with the maintenance department on a daily basis to achieve production goals.

This paper has demonstrated how to develop simulation model using Arena simulation software with proper input parameters. Based on the modeling results, it is obvious that the assembly layout is capable of producing the required output provided the maintenance people are available to repair the break down machines quickly. The DOE study showed that both the uptime and the downtime have major effect on the throughput. The results also showed that the system down time severely affect the production numbers compared to the uptime. The system uptime obviously has a positive effect on the production. This simulation study accurately predicted the throughput based on the system uptime and downtime data. Further investigation is needed to understand the effects of the buffers, material shortages, robot counts, conveyors, and line balancing the upstream and downstream processes.

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Biography

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