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Simulation analysis for managing and improving productivity – a case study of an automotive company

1. Introduction

The current economic crisis has intensified competition and forced organizations such as the automotive Big Three (Chrysler LLC, General Motors, and Ford) to adopt, develop and implement new initiatives and practices to reduce cost and improve efficiency (Evans, 2012). According to Wilson (2010) the new initiatives are driven by two new concepts: 1) Lean Management (LM) philosophy, also known as Toyota Production System (TPS) and 2) Flexible Manufacturing System (FMS). The TPS philosophy utilizes several techniques such as work standardization, total productive maintenance, and error/mistake proofing in order to improve quality, reduce cost and waste (Boyle *et al.,* 2010; Groover, 2010; Rahman *et al.*, 2010), whereas FMS relies on technology and grouping in order to improve the different types of flexibilities within the manufacturing system (Dennis, 2007; Gunasekaran *et al.*, 2000). Designing and testing the impact of system initiatives (such as LM and FMS) on the actual shop floor is costly (Wainer, 2009). Computer simulation provides a cost effective, quantitative means for planning, designing, and analyzing systems proposals (Greasley, 2005). Multiple simulation software's currently exist in the market (e.g. Witness, Arena, Simul8, and Pro Model). These software's are capable of providing analysis such as quantity of equipment and personnel need, performance evaluation (e.g. Throughput and bottleneck analysis), and operational procedures assessment (e.g. scheduling, inventory, quality control). Due to the complexity of the body shop system and the efficiency improvement problem, *Witness* simulation software using discrete event approach was used for the purpose of this study.

The sponsoring facility (one of the Big Three) has been experiencing intense competition from "local and foreign" automotive competitors in the market place. External variables, such as financial crises and fuel price fluctuation, are directly impacting consumer demand in an unpredictable way. As consumer demand shifts, the manufacturing process needs to adjust accordingly. The facility body shop process studied was originally designed at a capability of 90 Jobs per Hour (JPH) Gross and 81 JPH Net. It produces three different vehicle model types (A, B, and C) and contains 903 stations (840 automation/Robots and 63 manual). Variables, such as downtime, scrap, rejects, and buffer size are some of the inefficiencies limiting the body shop system, to an average of 71.1 JPH. The body shop facility cost for each vehicle (body shell) lost is about $920. The utilization of *Witness* software for analysis was requested by the sponsoring company.

This paper presents a discrete-event simulation case study with two-fold objective: (a) To determine bottleneck stations and give recommendations on optimizing buffer stations in order to increase throughput within a limited budget (not to exceed $8.5 million) with a high Return of investment (ROI) that is above 100% during the life of the program (5 years) ;(b) To determine the optimal model mix for production.

The data utilized to create the base model was obtained from a current body shop at one of the Big Three facilities in Detroit, Michigan. All financial information and data presented throughout this paper were discussed and agreed upon by the management personnel at the facility.

2. Literature Review

Improving manufacturing and assembly operations is a complex and challenging task. This complexity is driven by the amount of variables involved within the assembly process. These variables include items such as people, equipment, and material (Neumann *et al.*, 2006). Effectively improving business operations is achieved by first identifying critical stations (e.g. machines, people) that directly impact throughput (production), quality, delivery, cost, and morale (Adel *et al.*, 2013; El-Khalil, 2009; Gunasekaran and McGaughey, 2003; Kumar and Phrommathed, 2006). The next step after identification of critical operations is to determine the characteristic and to generate analytical data for each operation that can support proper system analysis (Anand and Kodali, 2009; Kumar and Phrommathed, 2006). Testing the feasibility of the proposed alternatives based on the data analysis is critical. Traditionally, companies such as the Big Three relied on prototypes and other testing means to prove their system's capability (Fishman, 2001). Since its early development in the 1960's computer simulation have advanced drastically (Law, 2007). Simulation software provided engineers and managers with a cost effective tool that models operations and determine alternatives and improvements prior to the actual floor implementation (EL-Khalil, 2013, Ingemansson and Bolmsjo, 2004; Law, 2007; Wainer, 2009).

Several simulation modeling software exist in the market and most are capable of planning, testing and analyzing manufacturing systems (Anand and Kodali, 2009; El-Khalil, 2009). According to Law (2007) simulation software are classified into two categories: discrete (for statistical events) and continuous (physical phenomena) and that the "two most common criteria" for utilizing specific simulation software are "modeling flexibility and ease of use". Law (2007) indicates that manufacturing systems are dynamic and stochastic systems (i.e. generally utilize discrete event simulation). The changes within the manufacturing and assembly process can be dynamic (as a variable of time) or stochastic (Kumar and Phrommathed, 2006; Gunasekaran *et al.*, 2000). Based on a study conducted by EL-Khalil (2009) manufacturing companies such as Toyota and the Big Three have been utilizing discrete computer modeling and simulation for issues such as design, analyzing behavior, predicting performance (at different range of variables), recommending system changes, studying labor and machine changes on throughput within the manufacturing process. The following are some of the advantages of utilizing discrete event simulation (Adel *et al.,* 2013; Anand and Kodali, 2009; EL-Khalil, 2013; Liker, 2003; Law 2007; Zulch and Becker, 2010):

(1) Understand systems deviation level (i.e. capability in comparison to actual performance).
(2) Analyze and determine the effect of changes on the overall system performance, as well as the impact of changing process variables, such as machines, robots, and labor, and evaluate changes without disturbing the actual process.
(3) Determine bottlenecks and establish alternatives for resolution.
(4) Determine and prove out new processes or systems before actually building them.
(5) Systems can be tested for a long period of time to understand the impact of time on the process (i.e., control time).

The discrete event simulation is capable of addressing a number of issues, such as (El-Khalil 2009; Hlupic *et al*., 2005; Intgemansson *et al*., 2005; Law, 2007; Sandhu *et al*., 2013; and Santos *et al*., 2012):

(1) Evaluation and verification of new proposed processes.
(2) Determining resource requirements, such as machines, robots, labor, pallets, and buffer size.
(3) Determining the optimal size of buffers.
(4) Determining the optimal mix or batch size for production.
(5) Determining systems performance for a range of variable conditions.
(6) Performing different types of analysis for issues such as throughput, time-in-system, bottleneck, sensitivity (machine, robot, and labor), reliability, maintenance, time to repair, and time between failures.

Kumar and Phrommathed (2006) presented a case study that utilized simulation software (*Arena)* to design, analyze and implement several lean principles (tools) to resolve process inefficiencies in a paper manufacturing facility. This study was able to improve cost by $450,000 annually. According to EL-Khalil (2013), 147% return on investment utilizing Witness simulation was achieved at one of the Big Three axle manufacturing facility. The simulation illustrated in the study indicated bottleneck/critical stations and analyzed the results that can be achieved using more flexible processes. Ingemansson and Bolmsjo (2004) used simulation in order to identify disturbance (problems) within a manufacturing process and design alternatives utilizing lean tools and FMS in order to improve productivity. The study was able to achieve 18 percent efficiency improvement and reduce scrap by 4%. Other scholarly work (Ingemansoon *et al*., 2005; Greasley, 2005; Gunasekaran *et al*., 2000; Sandhu *et al.,* 2013; Santos *et al.,* 2012) using different software's such as QUEST, Arena, and Pro Model at different manufacturing facilities clearly illustrate the ability of simulation to identify problems and analyze alternatives achieving significant improvements. Generally, simulation studies vary based on the facility studied, product produced and proposals or scenarios considered. For example a simulation study conducted at one of the General Motors manufacturing facilities (manufacturing Trucks) utilizing Simul8 software investigated the implementation of FMS for buffer and rework stations. The study was able to reduce cost by \$1.1million annually (Simul8, 2013). Another study using Simul8 at a Chrysler LLC manufacturing facility (manufacturing small vehicles) was able to reduce cost by \$6,000,000 annually through implementing work standardization, 5Ss, and 7 Wastes (Simul8, 2013).

Early in the 21st century, driven by the need to improve flexibility and reduce waste, the Big Three started looking for innovative philosophies and or systems to improve its productivity, cost, and quality (Law, 2007). Based on the success achieved by Toyota, the Big Three adopted Lean Management (LM) philosophy and Flexible Manufacturing systems (FMS) as an alternative for the current way of conducting business (Law, 2007; El-Khalil, 2009).

The LM philosophy focuses on maximizing customer value while minimizing waste, whereas the FMS focuses on implementing changes within the process that would allow it to absorb problems and/or downtime without affecting the overall system and quality (Dennis, 2007; El-Khalil, 2009; Liker, 2003; and Wilson, 2010). According to Liker (2004), the LM philosophy consists of 14 principles designed to reduce cost and improve both quality and lead time. For example standardization of work (SOW) is one of the main principles intended to improve labor efficiency in manufacturing operations (Liker, 2003). The SOW principle focuses on studying the current tasks conducted by technicians within the manufacturing process and providing recommendations which improve employee efficiency and utilization within a waste-free environment (Liker, 2003). According to a study conducted by Gunasekaran *et al.* (2000) at a manufacturing facility in the UK that produces wiper systems, implementation of lean tools such as Just-In-Time (JIT), Hoshin, and 5Ss provided significant improvement in quality and productivity.

The FMS provides the manufacturing organization with the capability to sustain down time with minimum or no effect on the overall output of the process (Ramasesh and Jayakumor, 1991). Womack *et al.* (1990) and Elkins *et al.* (2004), indicate that successful implementation of FMS in a facility presupposes that the manufacturing facility has successfully implemented lean techniques. One of the main techniques in FMS is equipment flexibility, which is defined as the ability of equipment to provide support and/or products while downstream systems are down. The main idea behind this concept is that the system will continue its production until the down machines are repaired within a certain time limitations. An example would be creating a buffer system that could feed upstream machines "for a specific period of time" while downstream machines are being mended. Both LM and FMS, if applied properly can lead to significant process improvements (Wilson, 2010).

The automotive manufacturing and assembly process sequence at all the OEMs follow the same steps, illustrated in Figure 1 (El-Khalil and Halawi, 2012). The ability to improve such a process depends on the capability of utilizing all resources to their optimal levels (e.g., LM and FMS). Computer simulation provides a tool that is capable of producing a robust analysis that can depict system bottlenecks and forecast improvements that can be achieved by implementing new philosophies and or systems, such as LM and FMS.

The Big Three Company studied in the following paper utilize *Witness* software as its main software package at all its manufacturing facilities, in addition it requires that all manufacturing vendors provide a simulation study using *Witness* for all purchased services.

[insert Figure 1 about here]

3. Methodology and discrete event simulation

The assembly line is a dynamic system which is subject to changes that can occur randomly or as a variable of time (Fishman, 2001). The discrete event simulation presents a powerful tool for analyzing and optimizing complex systems, such as the automotive assembly process (Ingemanson and Bolmsjo, 2004; Ingemansoon *et al.*, 2005; Hlupic and de Vreede, 2005; Sandhu *et al.,* 2013). According to Law (2007) and Anand and Kodali (2009), due to the complexity of these highly automated manufacturing systems, very few publications utilized discrete simulation in order to model and analyze the automotive body shop process.

The discrete event simulation model approach is a total system approach that can provide a method for analyzing the dynamic and stochastic behaviors of a process and all its subcomponents (Santos *et al.*, 2012).

According to Sandhu *et al.* (2013), the discrete event simulation is a powerful, cost-effective tool for designing, analyzing and optimizing manufacturing processes. The methodology that is followed in this paper to perform the simulation is illustrated in Figure 2. This methodology is common for most simulation work conducted (Intgemansson *et al.*, 2005; Sandhu *et al.*, 2013). Law (2007) explained that the methodology for simulation is not “strictly a sequential process”. For instance, collecting data and problem formulation can occur in parallel.

[insert Figure 2 about here]

A simulation model, called “base model” or “current state model”, that identically mimics the actual body shop facility performance, was created. The success of any such simulation study depends on the ability of identifying system problems or bottlenecks and providing lean or flexible solutions that will resolve these problems and improve operational performance. The body shop department studied is equipped with a computer logging system that records data and upload them by subsystem. This information only includes data on 650 robots. Other information (i.e. robotic, manual, conveyor, buffer…etc) and or data was collected manually from the actual shop floor.

4. Process layout and data preparation

The body shop general layout follows an identical process at all automotive manufacturing companies. This process is divided into several stages. For example the body shop facility at Toyota Motors Georgetown Kentucky is comprised of 8 stages while the body shop at General Motors Grand River facility is divided in 7 stages (EL-Khalil, 2009). The following section will describe in detail the body shop process studied.

4.1 Current Body Shop Process

The current body system studied comprises six different stages, as illustrated in Figure 3. The assembly process consists of semi-palletized loop (i.e., each stage has its own palletized loop conveyor). Transportation of parts in stages 2 and 5 is performed by material handling robots.

[insert Figure 3 about here]

Each stage within the body shop consists of several robots and manual stations, as presented in Table 1.

[insert Table 1 about here]

Six hundred and eighty eight robots and 18 manual stations are value added to the product. The remaining stations (i.e., 132 robots and 45 manual stations) are utilized for material handling and inspection. There is no machining performed through the process. The tasks conducted in the body shop stages include mainly robot spot welding, bending, placing, inserting, pressing, gauging, verifying, and testing. The assembly process stages contain buffer stations and part transportation conveyors that connect subsystems or stages to each other; each subsystem within the stage varying in size and based on the process or task being conducted. The current body shop process operates on two shifts with 7.23 working hours per shift and produces three different vehicles (A, B, and C) with the following percentages respectively, 26%, 37%, and 37%. This model mix was followed based on an established demand rate plan (provided by the organization marketing and finance departments). The facility management indicated that these percentages are currently designed and followed to maximize facility throughput. The company studied noted that if higher throughput can be achieved through changing model mix, finance and marketing can adjust accordingly.

In order to create a base model, each stage in the process was studied and charted with its conveyor and buffer system details; a sample is presented in Figure 4. The body shop studied is equipped with a computerized system that record all information on multiple stations (included information on 650 robots and all conveyor data), all other station's data was collected manually for the period of the study.

[insert Figure 4 about here]

An Excel sheet was produced in order to detail all other simulation inputs for the base model. The data sheet samples are illustrated in Table 2 and Table 3. The input data include variables such as Jobs Per Hour (JPH), mean time between failures (MTBF), mean time to Repair (MTTR), scrap, availability, robot actual cycle time and conveyor variables. The data included in the simulation model is based on actual outputs obtained between October 2011 and August 2012 from the existing facility studied.

[insert Table 2 about here]

[insert Table 3 about here]

5. Model conceptualization

The base simulation model constructed for the body shop studied mimics the actual process flow at that facility with all the details obtained and presented in previous sections.

5.1 Modeling approach

The modeling of this system went through two phases. In phase one, a total system approach was utilized in order to optimize the interactions among the elements (i.e., robots, conveyors, and technicians) within the process. In phase two, each sub-system was considered separately in order to sub-optimize it, by focusing on specific bottleneck machines and investigating improvements that could be made and their impact on the sub-system and the overall body shop throughput.

A proposed system design simulation was developed utilizing "*Witness* software". All the different elements that are part of the process, such as robots, parts, conveyors, operators or technicians, and machines, were included in the model.

5.2 Model assumptions and creation

All the assumptions listed below were based on actual system outputs and observation conducted for the purpose of this study (for a period of one year), and were concurred upon with the facility personnel.

(1) The Body Shop produces three different models A, B, and C. All processes for the different models are identical except for the framing stage.

(2) Down: No production due to robot or machine failure.

(3) Busy: Machine or robot is processing parts.

(4) Blockage: Robot or machine is not operational because the downstream robot or machine is running slower and there is no space for work in process (WIP).

(5) Starvation: Robot or machine is down because parts are not coming from the upstream station.

(6) Dunnage parts are always available to load the system.

(7) Downtime data for each station is dependent on estimated tooling content in the station and is generated utilizing the facility automated tracking system (Valley report) that track downtime, MTTR, MTBF, cycle time, and number of rejects by station.

(8) Door lines and Decklid line are modeled as black-boxes. Cycle time and down time input for these lines are derived from the Valley reports.

(9) Data for the door lines (based on analysis that was conducted on actual data obtained and confirmed by facility personnel):
   a. Front Door: MTBF = 8.12 min, MTTR = 0.73 min, Availability = 92%, Cycle Time = 39.8 sec.
   b. Rear Door: MTBF = 8.41 min, MTTR = 1.15 min, Availability = 88%, Cycle Time = 39.7 sec.
   c. Decklid: MTBF = 9.2 min, MTTR = 0.91 min, Availability = 91%, Cycle Time = 39.6 sec.

(10) In order to simulate all manual stations in the model, data was obtained from the shop floor based on observation “for 12 days”; time to repair (TTR) and time between failures (TBF) was determined and the best-suited distribution was established by station. Most of the TBF data followed a Gamma distribution, and most of the TTR followed a Scale and Shape distribution with a standard deviation around 1.17.

(11) Tool downtime is based on equipment, busy time and conveyor down time is based on available time. They both follow negative exponential distribution.

(12) The failure rate in pallet inspection in the framing system is assumed to be 1 out of 500. The repair time is 60 minutes average and follows a negative exponential distribution. In the underbody pallet system, no failure is assumed at pallet inspection.

(13) All stud weld operations have backup. The maximum time loss per breakdown due to stud weld is 10 seconds (to switch on backup).

(14) Power and free conveyors are 100% available (no down time). For a period of 2 years (including October 2011-August 2012) the power and free conveyors did not cause system interruption due to their flexibility.

(15) The selectivity bank from door line left hand (LH) or right hand (RH) to panel operates as a First in First Out buffer. The schedule call is given at the beginning of the rear door line and the front door line. These selective banks are not used as true selective banks to avoid lock-out type situations.

(16) The current model mix A: 26%, B: 37%, and C: 37.5%.

(17) Three call points are modeled: a) Dash-Engine calls Rear Frame-Floor at station S02 and Splice at station S03 of the UB main line; b) Underbody calls body side at framing station Zone 01 S04; and c) Body calls doors and decklid at the framing station Zone 13 S04.

(18) There is no job loss at pull-off (Framing Zone 13 S 01). Replacement body is always available for reinserts.

(19) The facility operates on two shifts with 8 hours per shift and 46 minutes for breaks and lunch (20 minutes of break time and 26 minutes lunch). The actual working hours per shift is 7.23 hours (434 actual working minutes).

(20) Interactions between all the elements of the system were modeled in order to verify the base or current body shop process. The basic elements of the model are robots, different body part components, conveyors, pallets, machines, technicians, and buffers. In order to measure the effectiveness and performance of the model created, the following output variables were utilized:
   a. Jobs per hour (JPH) throughput;
   b. Work in Process (WIP);
   c. Total finished vehicle bodies produced per day.

6 Analysis of the current and processed system

A validation and verification was conducted for the base (or current) simulation model, created in order to ensure that it does mimic the actual body shop system and is capable of generating identical throughput.

6.1 Base model verification

The following steps were taken in order to ensure that the base model created is identical to the actual body shop simulated:

(1) The model developed is based on a conceptual model that mimics an actual body shop facility at one of the Big Three companies.

(2) All elements constructed within the model were given their own JPH counter and downtime tracking. In addition, each element was checked separately and as a sub-system to ensure accurate logic and process flow.

(3) In running the model, an excel sheet that feeds the model with all data input was utilized. A sample is illustrated in Table 2 and Table 3. Model debugging features were utilized in order to check for model error, which is part of the *Witness* software modeling features.

(4) Animation was utilized in order to ensure proper element flow within the model.
(5) All model outputs were checked for accuracy under a range of different input parameters.

6.2 Base model validation

In order to validate the base model created and to ensure its accuracy, "simulated production" runs were utilized. The validation process of the current base model was determined by comparing the actual throughput of facility (body shop) to the base model simulation throughput. The base model was given a two-week warm up period running at 8 hours per shift (excluding 20 minutes break time per shift and 26 minutes lunch break) and two shifts per day; the average throughput for the base model was 71.1 JPH, as illustrated in Table 4.

[insert Table 4 about here]

For validating the current system, a two-sided "student T-test" was utilized to compare the existing real system average throughput with the simulation model average throughput. The test verifies the null hypothesis H_0 that both averages are equal:

$$H_0 : \bar{X}(n) = \mu_0$$
$$H_1 : \bar{X}(n) \neq \mu_0$$

The student's t distribution calculated value is determined using the following equation:

$$t_0 = \frac{(\bar{X}(n) - \mu)}{S/\sqrt{n}}$$

If $|t_0| < t_{\alpha/2,n-1}$, therefore H_0cannot be rejected and the model is valid.

Where S is the standard deviation, $\bar{X}(n)$ is the model output variable average, μ is the real system average, t_0 is the calculated value of t at the specified distribution, n is the number of runs and $t_{\alpha/2,n-1}$ is the critical value of the student's t distribution at $(1 - \alpha)$ confidence level.

The actual throughput of the system based on the data obtained ranged between 68.5 and 73.3 JPH. The test statistics obtained was $t_0 = 1.4$. The critical t value at 95% confidence level is: $t_{0.975,4} = 2.78$. Since $|t_0| < t_{0.975,4}$ we cannot reject H_0 at 95% confidence level. This implies that the model created is valid. The actual system weekly throughput generated at the facility is compared with the simulation model throughput, as illustrated in Figure 5. The data generated based on the weekly throughput comparison confirm that the simulation model is accurate and that it mimics the actual body shop system performance and throughput. The data collection followed by "verifying and validating" the model created with facility managers proved to be the most challenging and time consuming task in this research.

[insert Figure 5 about here]

6.3 Base model analysis

The body shop system capacity based on machine cycle time is 90 JPH. The base model simulation throughput indicated an average of 71.1 JPH, therefore the overall system efficiency is 79%. The system indicates that the expected losses are distributed as follows: 16.5 % starvation and blockage, 3.2 % scrap, and 1.3% maintenance related issues. The base model indicates that the Aperture marriage station (stage #3) is the primary bottleneck with the lowest average throughput of 71.1 JPH. The secondary bottleneck system is the framing system (apertures to underbody - stage #4). The three different models produced (A, B, and C) show different cycles at different stages, but overall, the differences are insignificant with model B at highest JPH followed by model A and C, respectively, as illustrated in Table 5. The base simulation model shows that the farming pallet system is statistically not significantly different from the underbody integrated system (i.e., identical min, max, and float).

The detailed data indicates that the bottleneck within the framing system stage #3 is driven by the aperture sub-system Inner-Outer marriage robots station number 30 B. The station consists of 4 robots, performing 9 welds at an average 71.1 JPH, with a technician feeding one of the robots two brackets per cycle. The simulation model indicates starvation upstream (from the 30 B station) and blockage downstream (after the 30 B station). The technician cycle time for loading brackets based on actual observation at station 30 B ranges between 48.5 sec and 50.5 sec (74.2 JPH and 71.3 JPH). Two main issues drive the technicians high cycle time, namely: the complexity of the part (i.e., size and location for feeding robot station), and the design of the safety system that does not allow the technician to load parts until the robot is at home position (i.e., safety protocol). The 30 B station robots cycle time ranges between 48.2 sec and 51.8 sec (74.7 JPH and 69.5 JPH). The detailed simulation data indicates that 75.8 % of the job losses at aperture integrated station 30 B welding robots are driven by starvation.

The second bottleneck is driven by the stage #4 framing pallet integrated system station # 1UB load with an average of 72.3 JPH (three-model combined average). The station performs loading and welding of the apertures to the underbody. Station #1 UB load is comprised of 10 robots; 2 robots load right hand (RH) and left hand (LH) aperture from the overhead conveyor and deliver them to 2 other robots that locate the apertures over the underbody so that the other 6 robots can perform the welding of the apertures over the underbody. The cycle time for the welding robots ranges between 48.2 sec and 48.8 sec (74.7 JPH and 73.8 JPH); the loading robots locating the apertures on the underbody operate at a cycle time that ranges between 47.2 sec and 49.7sec (76.2 JPH and 72.3 JPH).

[insert Table 5 about here]

6.4 Proposed simulation model result analysis

Based on the data previously collected for the base model, the following two scenarios were considered:

Scenario one:

(1) Extend station 30 B to alter current layout by adding a gravity conveyor that can hold up to 15 parts which feed the welding robots, instead of one-at-a-time part feed process.
(2) Increase the buffer size contacting the aperture marriage to framing station #1 UB Load (i.e., connecting stage #3 to stage #4) from 10 apertures to 30 apertures (LH and RH).
(3) Increase the buffer size connecting the other 4 stages (i.e., other than buffer connecting stage #3 to stage #4) by three different percentages: 10%, 50%, and 75%.

The model for the proposed scenario was simulated for over 2000 continuous production hours (to insure that the system reached steady state). As illustrated in Figure 5 steady state was achieved only after 5 weeks of production run. The results show the following improvements:

(1) Technician cycle time was improved from an average of 72.7 JPH to 110 JPH. The new process layout allows the operator to load parts freely to the conveyor without being dependent on the welding robot cycle. In the new process, the welding robots are fed parts by a gravity conveyor that is loaded by an operator (recommended process) instead of directly being fed parts by the operator (old process). This process increased 3 operators efficiency by an average of 8%. Note that all operators with in the body shop perform work at an average efficiency of 65% (due to the nature of the department and operations performed).
(2) Increasing the buffer size which connects the apertures to the framing process from 10 to 30 apertures has resulted in increasing the average JPH by 1.1.
(3) Increasing the different buffer connecting the other stages by different percentages did not result in any increase in process throughput and/or efficiency improvement. In addition, the simulation model shows that reducing the buffer size connecting stages: #1 to #2, #2 to #4, #4 to #6 and #5 to #6 by a maximum of 20% (i.e., average of 15 JPH) will not impact the overall efficiency of the body shop.

The simulation result (based on the changes listed above) predicted that the efficiency of the overall system would improve from 79% to 81.6% and that the production rate average would increase from 71.1 JPH to 73.5 JPH (i.e., an increase of 2.4 JPH). Scrap rate was reduced from 3.2% to 2.9%.

For calculating the return on investment (ROI) associated with the recommended scenario implementation, the following was utilized:

1. At 245 working days annually with 2 shifts per day at 7.23 hour per shift, the total additional vehicles produced at the body shop would increase by 8502 vehicles.
2. Net profit per vehicle body produced is \$1720 (provided by the comptroller's office at the facility studied).
3. The ROI equation (1) utilized:

$$ROI = \frac{CS-C}{C}$$

Where: CS is the cost saving that is driven by the new process during product life cycle. And C is the cost of the design change during product life cycle. All data utilized for the calculation of ROI was verified by the facility comptroller. The product life-cycle is measured by the vehicle program lifespan which typically is 5 years (given by the facility program manager at the facility studied). Therefore,

CS = 5 years x \$920 per vehicle x 8,501 vehicles per year = \$39.1 Million

C = \$2.9 million (increase buffer size between stage #3 and stage #4) x \$1.5 million (increasing station 30 B layout and addition of gravity conveyor) x \$450,000 labor cost for implementing changes (skilled trade and or vendor) x (\$190,000 maintenance cost x 5 years) x (\$ 150,000 x 5 years "other: tooling, parts…etc") = \$6.55 million

$$ROI = \frac{\$39.1 - \$4.7}{\$4.7} = 497\%$$

The simulation output for the proposed changes shows the following:

1. Increase in the body shop overall system capability.
2. Increase in system uptime. Increasing the buffer allows the system to absorb downtime with less or no impact to the body shop overall performance.
3. Increase efficiency by an average of 7.5% in stages #3 and #4. The overall system efficiency improved by 2.6%.
4. JPH increased by 8501 vehicles (body shells) annually.
5. Other changes, such as overall speed improvement and safety improvements.

The disadvantages of scenario one are as follows:

1. Increase in Work in Process between stages #3 and #4. This can be absorbed if the other buffers are reduced by 20% (simulation concurs with the reduction but the cost based on the facility comptroller's calculation can be about \$10.2 million).
2. Significant increase in facility space. For station 30 B, around 24 feet square space, and for the additional buffer, 70 feet on overhead conveyor.
3. Additional maintenance is required for the new buffer and equipment. That might require additional skilled trade personnel.

Scenario Two:

The original model mix based on the current system is running at A: 26%, B: 37%, and C: 37%. For the second scenario, 10 different model mixes were tested at 8 replications each. The highest throughput was obtained with the following mix: A: 33%, B: 35.4%, and C: 35.5%, as illustrated in Table 6. For the other 9 different model mixes, the JPH result was lower than the current model mix throughput. The highest mix showed an improvement of 0.5 JPH (71.6 JPH) for a total of 1771 vehicles annually (245 days/year). The cost improvement of running the current mix is = 1771 vehicles x $920 per vehicle = $1.6 million/annually.

The disadvantages of scenario two are:

(1) The Model mix assumes that demand exists.
(2) Increasing model A will result in additional cost to the overall facility since model A requires more material and labor than B and C in the other departments of the assembly process (Trim, Chassis, and Final).

[insert Table 6 about here]

The difficulties encountered in developing such a complex model include:

(1) Collecting data and obtaining information on the system flow and procedures;
(2) Interacting and sharing information with facility managers on regular bases;
(3) Insuring the right data is being used and the problems are accurately addressed;
(4) Conducting facility walk through with engineers/managers to insure that the assumptions considered, from both labor and robot perspectives, are feasible.

The established model provides a tool to support cost effective decisions at the studied facility. Given the similarity of the automotive manufacturing processes among the various companies, the findings for this particular facility remain valid for other facilities.

7. Conclusion

The *Witness* "computer simulation" software has provided a "cost-effective" way for studying the impact of different alternatives on the optimization process of the overall body shop system. The base "current" system was analyzed, bottlenecks within the process were identified, and alternatives were recommended. The recommended "proposed" system increased the body shop throughput by 2.4 JPH (2.6% overall improvement), improved uptime to 79.5%, and reduce scrap by 0.3%. From a cost perspective, the proposed system has resulted in a 497% ROI. The proposed system changes were implemented at the body shop facility based on the model presented in this paper and the actual body shop throughput was 73.8 JPH (based on three weeks of data gathered after implementation). The focus of this study was driven by the facility manager's needs and requirement.

Nevertheless, the simulation model constructed did not consider other issues such as:

(1) Downtime related to manual operations. For example, operator misleading parts, operator late shift start, or operator early shift finish.
(2) Robot uptime (Individual robots or subsystems) improvements that can be achieved.
(3) Tooling or retooling cycle time that can be improved (robots and machine) when different models are running since, in most cases, the cycle time is different based on the model sequence that the facility is processing.

Future work should focus on identifying the above-mentioned gaps or issues for each subsystem and come up with solutions to improve the body shop overall process.

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Figure1: Automotive manufacturing and assembly process flow

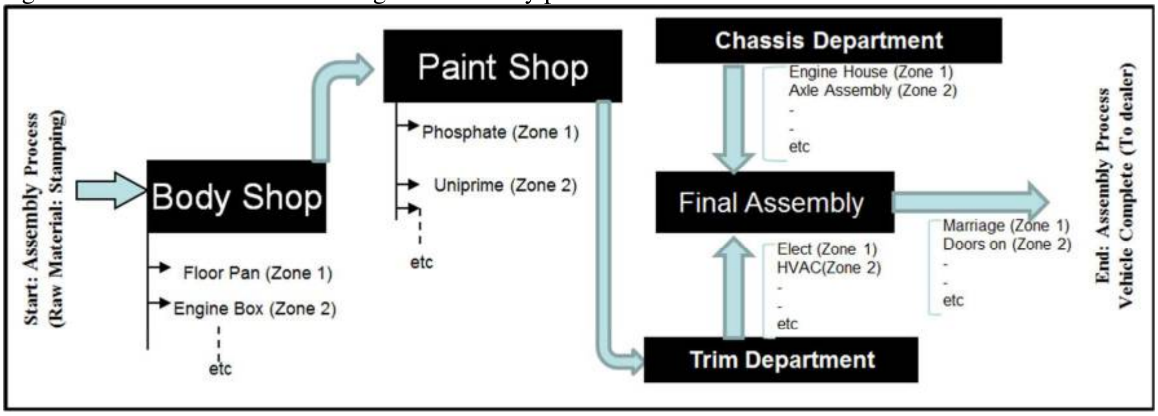


Figure 2: Simulation Methodology

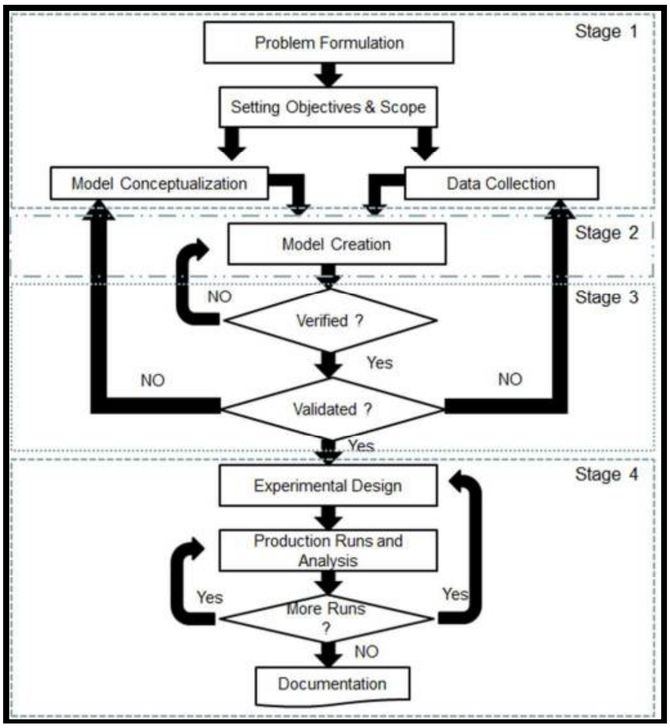


Figure 3: Body shop stages and process flow

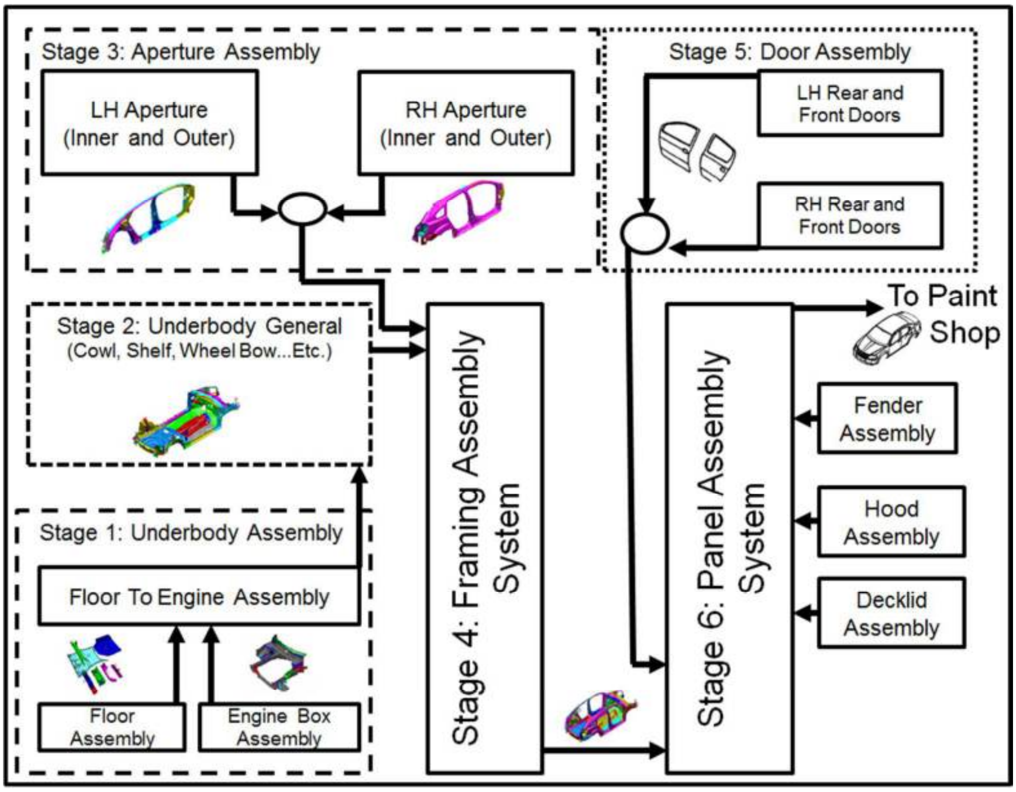


Figure 4: Subsystem process details for Underbody stage #1

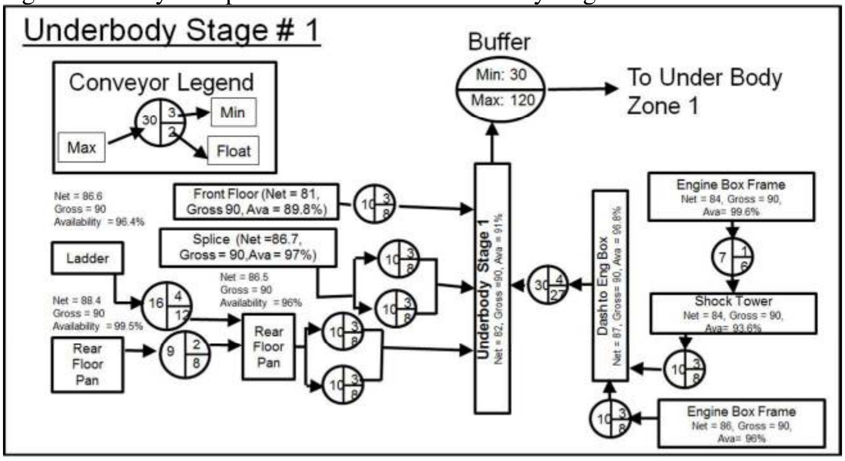


Figure 5: Simulation model weekly output Vs actual facility output

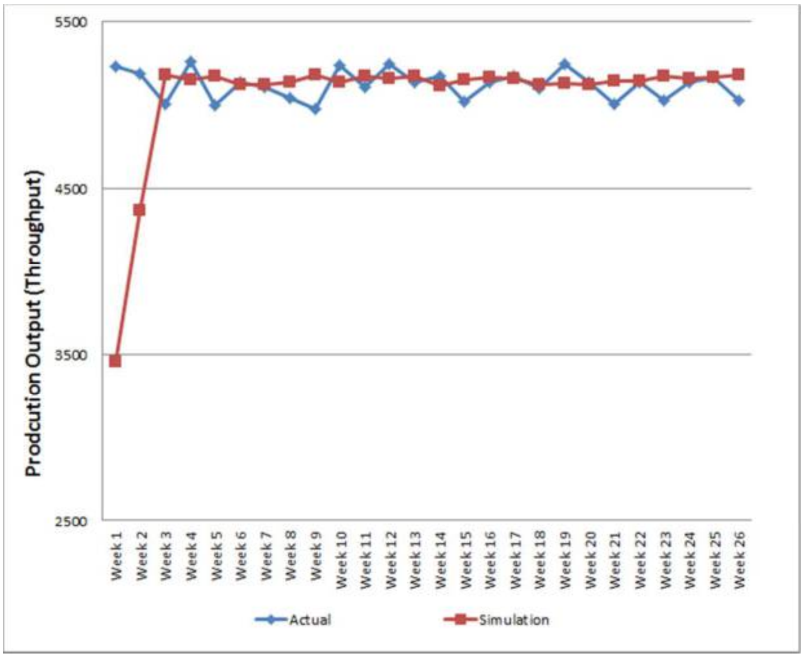
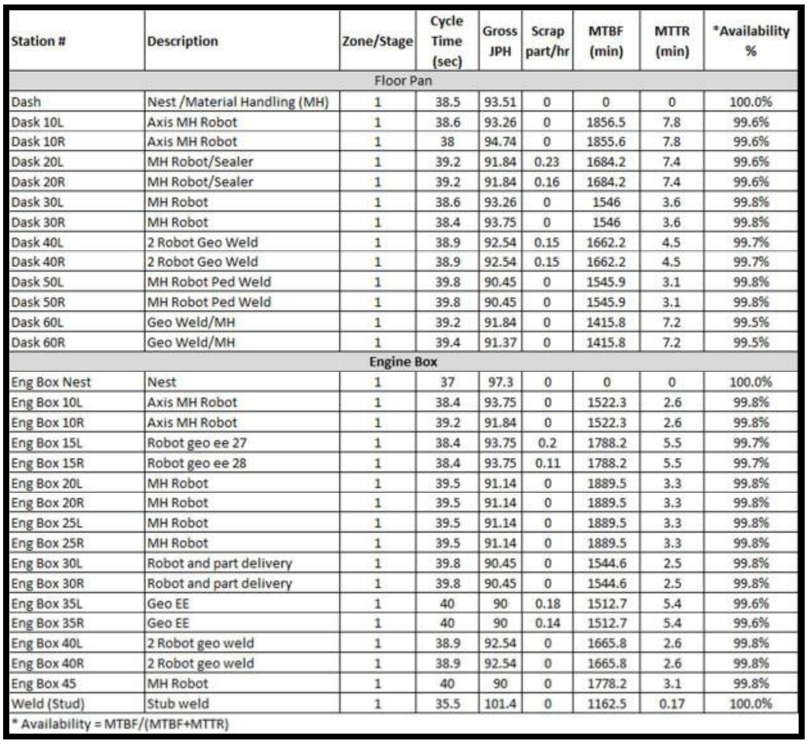


Table 1: Body Shop robots and manual station count by stage

Stage #	Description	Number of Robots	Number of Manual Stations
1	Underbody Assembly	135	6
2	Underbody General	140	6
3	Aperture Assembly	216	8
4	Framing Assembly	126	6
5	Door Assembly	219	12
6	Panel Assembly	4	25
Total		**840**	**63**

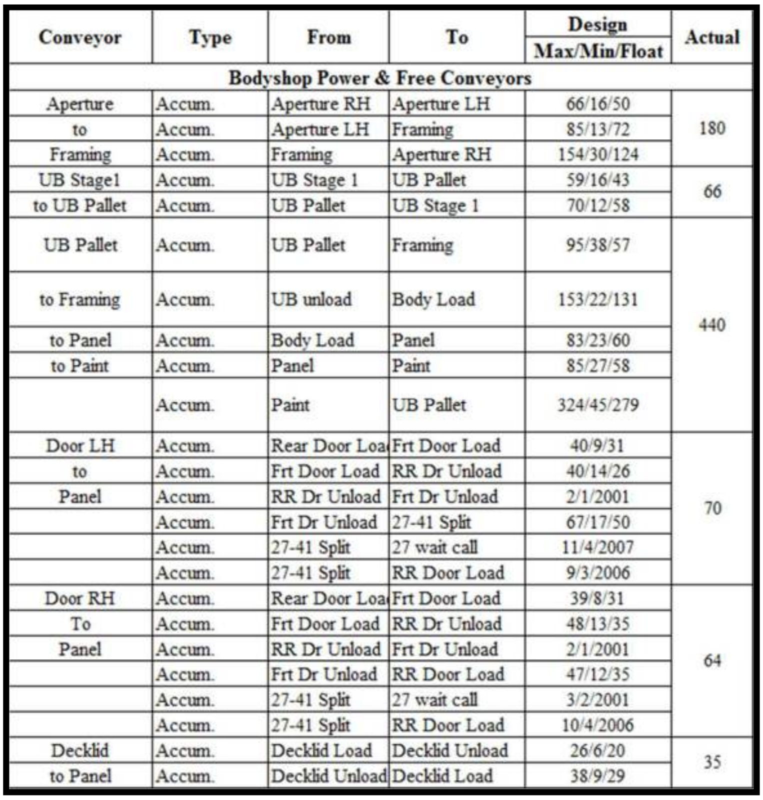
Table 2: Data sheet for robots and machines utilized for simulation input



Station #	Description	Zone/Stage	Cycle Time (sec)	Gross JPH	Scrap part/hr	MTBF (min)	MTTR (min)	*Availability %
Floor Pan								
Dash	Nest /Material Handling (MH)	1	38.5	93.51	0	0	0	100.0%
Dask 10L	Axis MH Robot	1	38.6	93.26	0	1856.5	7.8	99.6%
Dask 10R	Axis MH Robot	1	38	94.74	0	1855.6	7.8	99.6%
Dask 20L	MH Robot/Sealer	1	39.2	91.84	0.23	1684.2	7.4	99.6%
Dask 20R	MH Robot/Sealer	1	39.2	91.84	0.16	1684.2	7.4	99.6%
Dask 30L	MH Robot	1	38.6	93.26	0	1546	3.6	99.8%
Dask 30R	MH Robot	1	38.4	93.75	0	1546	3.6	99.8%
Dask 40L	2 Robot Geo Weld	1	38.9	92.54	0.15	1662.2	4.5	99.7%
Dask 40R	2 Robot Geo Weld	1	38.9	92.54	0.15	1662.2	4.5	99.7%
Dask 50L	MH Robot Ped Weld	1	39.8	90.45	0	1545.9	3.1	99.8%
Dask 50R	MH Robot Ped Weld	1	39.8	90.45	0	1545.9	3.1	99.8%
Dask 60L	Geo Weld/MH	1	39.2	91.84	0	1415.8	7.2	99.5%
Dask 60R	Geo Weld/MH	1	39.4	91.37	0	1415.8	7.2	99.5%
Engine Box								
Eng Box Nest	Nest	1	37	97.3	0	0	0	100.0%
Eng Box 10L	Axis MH Robot	1	38.4	93.75	0	1522.3	2.6	99.8%
Eng Box 10R	Axis MH Robot	1	39.2	91.84	0	1522.3	2.6	99.8%
Eng Box 15L	Robot geo ee 27	1	38.4	93.75	0.2	1788.2	5.5	99.7%
Eng Box 15R	Robot geo ee 28	1	38.4	93.75	0.11	1788.2	5.5	99.7%
Eng Box 20L	MH Robot	1	39.5	91.14	0	1889.5	3.3	99.8%
Eng Box 20R	MH Robot	1	39.5	91.14	0	1889.5	3.3	99.8%
Eng Box 25L	MH Robot	1	39.5	91.14	0	1889.5	3.3	99.8%
Eng Box 25R	MH Robot	1	39.5	91.14	0	1889.5	3.3	99.8%
Eng Box 30L	Robot and part delivery	1	39.8	90.45	0	1544.6	2.5	99.8%
Eng Box 30R	Robot and part delivery	1	39.8	90.45	0	1544.6	2.5	99.8%
Eng Box 35L	Geo EE	1	40	90	0.18	1512.7	5.4	99.6%
Eng Box 35R	Geo EE	1	40	90	0.14	1512.7	5.4	99.6%
Eng Box 40L	2 Robot geo weld	1	38.9	92.54	0	1665.8	2.6	99.8%
Eng Box 40R	2 Robot geo weld	1	38.9	92.54	0	1665.8	2.6	99.8%
Eng Box 45	MH Robot	1	40	90	0	1778.2	3.1	99.8%
Weld (Stud)	Stub weld	1	35.5	101.4	0	1162.5	0.17	100.0%

* Availability = MTBF/(MTBF+MTTR)

Table 3: Data sheet for conveyors utilized for simulation input

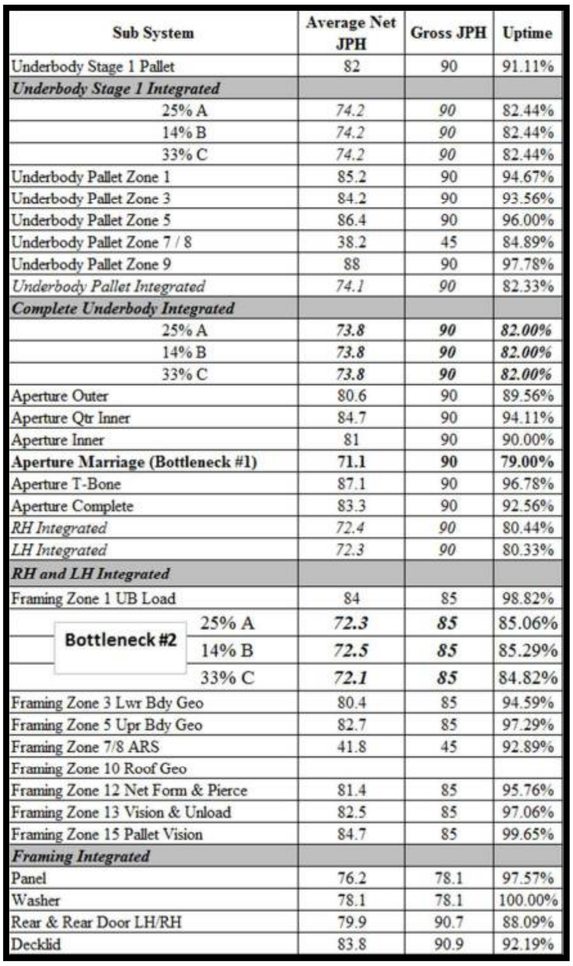


Conveyor	Type	From	To	Design	Actual
				Max/Min/Float	
Bodyshop Power & Free Conveyors					
Aperture	Accum.	Aperture RH	Aperture LH	66/16/50	180
to	Accum.	Aperture LH	Framing	85/13/72	
Framing	Accum.	Framing	Aperture RH	154/30/124	
UB Stage1	Accum.	UB Stage 1	UB Pallet	59/16/43	66
to UB Pallet	Accum.	UB Pallet	UB Stage 1	70/12/58	
UB Pallet	Accum.	UB Pallet	Framing	95/38/57	440
to Framing	Accum.	UB unload	Body Load	153/22/131	
to Panel	Accum.	Body Load	Panel	83/23/60	
to Paint	Accum.	Panel	Paint	85/27/58	
	Accum.	Paint	UB Pallet	324/45/279	
Door LH	Accum.	Rear Door Loa	Frt Door Load	40/9/31	70
to	Accum.	Frt Door Load	RR Dr Unload	40/14/26	
Panel	Accum.	RR Dr Unload	Frt Dr Unload	2/1/2001	
	Accum.	Frt Dr Unload	27-41 Split	67/17/50	
	Accum.	27-41 Split	27 wait call	11/4/2007	
	Accum.	27-41 Split	RR Door Load	9/3/2006	
Door RH	Accum.	Rear Door Loa	Frt Door Load	39/8/31	64
To	Accum.	Frt Door Load	RR Dr Unload	48/13/35	
Panel	Accum.	RR Dr Unload	Frt Dr Unload	2/1/2001	
	Accum.	Frt Dr Unload	RR Door Load	47/12/35	
	Accum.	27-41 Split	27 wait call	3/2/2001	
	Accum.	27-41 Split	RR Door Load	10/4/2006	
Decklid	Accum.	Decklid Load	Decklid Unload	26/6/20	35
to Panel	Accum.	Decklid Unload	Decklid Load	38/9/29	

Table 4: Simulation JPH output for base model

Replication no	*Number shipped (per week/two Shifts)*	*Throughput (JPH)*
1	5126	70.9
2	5118.8	70.8
3	5161	71.4
4	5185	71.7
5	5128	70.9
Mean	5143.76	71.1
Standard Deviation	28.2	0.4

Table 5: Simulation output for base model



Sub System	Average Net JPH	Gross JPH	Uptime
Underbody Stage 1 Pallet	82	90	91.11%
Underbody Stage 1 Integrated			
25% A	*74.2*	*90*	82.44%
14% B	*74.2*	*90*	82.44%
33% C	*74.2*	*90*	82.44%
Underbody Pallet Zone 1	85.2	90	94.67%
Underbody Pallet Zone 3	84.2	90	93.56%
Underbody Pallet Zone 5	86.4	90	96.00%
Underbody Pallet Zone 7 / 8	38.2	45	84.89%
Underbody Pallet Zone 9	88	90	97.78%
Underbody Pallet Integrated	*74.1*	*90*	82.33%
Complete Underbody Integrated			
25% A	***73.8***	***90***	***82.00%***
14% B	***73.8***	***90***	***82.00%***
33% C	***73.8***	***90***	***82.00%***
Aperture Outer	80.6	90	89.56%
Aperture Qtr Inner	84.7	90	94.11%
Aperture Inner	81	90	90.00%
Aperture Marriage (Bottleneck #1)	**71.1**	**90**	**79.00%**
Aperture T-Bone	87.1	90	96.78%
Aperture Complete	83.3	90	92.56%
RH Integrated	*72.4*	*90*	80.44%
LH Integrated	*72.3*	*90*	80.33%
RH and LH Integrated			
Framing Zone 1 UB Load	84	85	98.82%
Bottleneck #2 25% A	***72.3***	***85***	85.06%
14% B	***72.5***	***85***	85.29%
33% C	***72.1***	***85***	84.82%
Framing Zone 3 Lwr Bdy Geo	80.4	85	94.59%
Framing Zone 5 Upr Bdy Geo	82.7	85	97.29%
Framing Zone 7/8 ARS	41.8	45	92.89%
Framing Zone 10 Roof Geo			
Framing Zone 12 Net Form & Pierce	81.4	85	95.76%
Framing Zone 13 Vision & Unload	82.5	85	97.06%
Framing Zone 15 Pallet Vision	84.7	85	99.65%
Framing Integrated			
Panel	76.2	78.1	97.57%
Washer	78.1	78.1	100.00%
Rear & Rear Door LH/RH	79.9	90.7	88.09%
Decklid	83.8	90.9	92.19%

Table 6: Sample of model mix results

Model Mix	**A: 26%** **B: 37%** **C: 37%**		**A: 28%** **B: 36%** **C: 36%**		**A: 33%** **B: 33.5%** **C: 33.5%**	
	Jobs / hr	**Jobs / day**	**Jobs / hr**	**Jobs / day**	**Jobs / hr**	**Jobs / day**
Average of 8 Replications	71.1	1028	70.3	1017	71.6	1035
95% Confidence Interval	(70.2,72)	(1015, 1041)	(69.8,70.8)	(1009,1024)	(70.8,72.4)	(1024, 1047)
Gross	90	1301	90	1301	90	1301
Uptime	79.00%	79.00%	78.11%	78.11%	79.56%	79.56%

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Raed EL-Khalil is currently working as an Assistant Professor of Business at the Lebanese American University. In addition, he is a consultant for Advance Manufacturing Engineering at several companies in the automotive Industry in North America. His previous professional experience includes: different management and engineering positions at Chrysler LLC, where he severed over 12 years, Production Supervisor Ford Motors and part time lecturer/Adjunct at Baker College and Henry Ford Community College. He holds a Doctorate degree in Manufacturing Engineering from Lawrence Technological University. In addition, he holds several MS and BS degrees in Engineering and Management from University of Michigan. His research and teaching interests focus on optimization and management of manufacturing processes. He is the author of several publications in the area of flexible manufacturing systems and lean management