Constraint Analysis and Throughput Improvement at an

Automotive Assembly Plant

by

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Submitted to the Department of Mechanical Engineering and the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Mechanical Engineering and
Master of Business Administration

In Conjunction with the Leaders for Manufacturing Program at the
Massachusetts Institute of Technology
June 2003

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Abstract

To effectively increase throughput of a process, one must understand where the constraints are and how to manage them effectively. In complex manufacturing environments, locating the bottleneck is not a simple task in the absence of good information about the equipment, production yield rates, and the interaction between the various machines. This thesis describes the process of analyzing a complex production line at an automobile company and identifying opportunities for productivity improvement.

The task of collecting an increasing amount of accurate and reliable data for evaluating the performance of a production system has become a challenge for manufacturing companies. Web-deployed machine monitoring software seemed to be the solution to real-time data collection at the automobile company. A proposed template for how to set up the software is included as well as the implementation process and recommendations for future installations. Unfortunately, these systems are still "hard-wired" to the Programmable Logic Controllers (PLC) on the plant floor. Changes made to the PLC programs will alter the data collected and put at risk the reliability of the information every time a change is made to them.

In addition to deficient information, line supervisors lack the necessary analytical tools for locating the bottleneck(s) in their subsystems and thus, are unable to focus their throughput improvement efforts. The result is wasted effort focused on areas that do not directly impact throughput. Much time is devoted to firefighting daily production issues. Firefighting and continuous improvement methods should be data driven to ensure that limited resources are used efficiently when trying to increase throughput. Tools such as man/machine mapping and discrete-event type simulation techniques are explained. Recommendations developed from the use of both tools are listed.

Regardless of the tools and methods employed, worker involvement with its continuous improvement work group is essential to the success of the lean manufacturing improvement initiatives. Improvements will be limited if this key element is ignored.

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Acknowledgements

The author gratefully acknowledges the support and resources made available to him for this project through the Leaders for Manufacturing Program, CONACYT, and the Ford Motor Company. I specifically want to thank Song Lee, my company supervisor, for going "above and beyond the call of duty" and offering all the different training opportunities needed to develop the project.

I would like to thank my advisors, professors Roy Welsch and Dr. Daniel Whitney for their patient guidance throughout this entire project. Especially, I would like to thank Dr. Daniel Whitney for jumping into the project halfway down the road and providing his invaluable assistance.

I would like to thank the many employees at the Ford Motor Company who took the time to share their ideas and insight with me. In particular, I would like to thank Hossein Nivi, Lee Dimascio, Doug Crossman, Paul Lagrich, Steve Beeler, Shigeru Sadakane, Mark and Raymond for providing me with the majority of the knowledge that I acquired during this internship. I would also like to thank the many engineers, operators and supervisors who made my time on the shop floor at Dearborn Assembly Plant a rewarding experience.

I am thankful to have been a part of the LFM Class of 2003 and to have had an opportunity to know the outstanding individuals in the program. I wish to thank all of my classmates for sharing their knowledge, experiences, and fun times over the past two years.

I would also like to thank my family and friends, who provided me with support and words of encouragement through the entire Leaders for Manufacturing program, particularly my parents José Leoncio Valdés and Sylvia Graciela Reynoso.

Most of all, I would like to thank my wife, Liza Fernanda, for her patience and dedication, and for helping me during the past two years so that I could accomplish my priorities. I could never have persevered this challenging experience without her support, encouragement, and love.

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Chapter 1: Introduction

Having the drive for continuous productivity improvement has become a necessity for manufacturing organizations. Companies that have failed to keep up in the productivity competition have paid the price on the bottom line, suffering declining profits and loss of market share.[1,2] To maintain competitiveness, companies are implementing a variety of improvement methodologies, such as Lean Manufacturing and Theory of Constraints. Identification of the operations that most constrain productivity is a critical step in many of these improvement methodologies. The "most constraining operations" are called the system bottlenecks. The identification of system bottlenecks is important in the improvement process because it allows limited resources to be focused on the most effective improvement activities.

While improvement methodologies such as Lean Manufacturing techniques aid at recognizing system bottlenecks, the methods for identifying the system constraints in complex, unstable manufacturing environments are not fully developed in an easy to follow procedure so that line supervisors can understand them and use them on a daily basis. In these environments, analytical tools must be developed and applied to the task of data collection and bottleneck identification.

This thesis presents one example that illustrates the need for these tools. This example is taken from the research conducted in an automotive assembly plant. Serial production lines, semi-automated material handling, and poorly defined buffers between operations characterize the manufacturing process in this plant. In this environment, it was not possible to use simple heuristics to identify the bottlenecks. The research for this thesis was conducted as part of a

Leaders for Manufacturing internship conducted at the Ford Motor Company Dearborn Assembly Plant (DAP), sole manufacturing site for the Ford Mustang during the time of the project.

The improvement methodology applied at the DAP plant is based on the Theory of Constraints (TOC). Eli Goldratt and Jeff Cox first presented the TOC methodology in *The Goal*.[3] The TOC states that improvement resources should be focused on the constraint (or bottleneck) process. In other words, improving a non-constraint process requires an investment without providing a return in improved productivity.

While the TOC presents a clear process for improving throughput, the methods for identifying the location of the system bottleneck(s) are less well developed. The method described in *The Goal* recommends observing the system and identifying where work in–process accumulates. The process step that occurs after the accumulated work in–process is considered the bottleneck. This thesis demonstrates that a more analytical method is required in environments where the process variables, including work in–process, are difficult or impossible to measure, such as the case of a continuous serial production system. Besides, reliable data collection systems should be in place in order to make assertive decisions.

Above all, in addition to the suggested tools, the methodology presented in this thesis requires a team structure to facilitate and support a continuous improvement process. Plant management, the engineering group and the hourly workforce, have to work together to identify avenues for improvement.

To meet the increased production demand of the Ford Mustang, plant management at DAP initiated a throughput improvement effort based on Ford Total Productive Maintenance and the Theory of Constraints, in which use of tools such as computer discrete-event type simulation were applied. I was able to join both efforts and assigned to the task of developing throughput improvement suggestions for the plant management.

1.1 Background

The DAP is located at the Rouge Complex, which dates back to 1917. Production lines within the Body Shop have been automated with the newest line, the Rear Pan Line, being about 10 years old. Among the different plans to revitalize the Rouge Complex area, the DAP is scheduled to be demolished in 2004. Production of the Ford Mustang is expected to move to the Mazda plant in Flat Rock for the 2004 model.

As part of the $2 billion redevelopment project, a brand new plant across the street, Dearborn Truck Plant (DTP), will start operations in mid-2004 to assemble the all-new 2004 Ford F-150. F-Series is Ford's best-selling vehicle and a key to the company's recovery plan. During 2001, they sold more than 900,000 F units and since the pickup's debut in 1948, they have sold 27.5 million F-Series pickups. F-Series has been the best-selling truck in America for 25 years and the best-selling vehicle in America for 20 years![*]

The Rouge project is remaking one of the world's largest and oldest industrial icons into a role model for sustainable, lean and flexible manufacturing. Concerning flexibility, the new DTP at

[*] *Padilla, Jim. True Blue News. The Ford Motor Co. September 10, 2002*

the Ford Rouge Center, will be Ford's most flexible assembly plant in North America. DTP will have the ability to produce three vehicle platforms and up to nine different models.

1.2 Project Setting and Motivation

While the plant management and operators at DAP look forward to moving to the new facilities, they still had the challenge to deal with an old and unreliable operation at DAP, in which the preventive maintenance culture on the machinery was low. In addition, plant management had to deal with pressure from upper management to accomplish the production numbers because orders for this model were backlogged several months and the company itself was going through a financial crisis.

Ford Mustang was in high demand. Its sales were up 29% from previous month during September, 2002 and the model had positioned itself as the best-selling small sports car, year-to-date.* To meet customer commitments, the employees in the area worked significant overtime. Two 10-hour daily shifts were the norm, and some weekends as required. The increase in overtime had become less and less beneficial because workers were exhausted and had lost motivation to improve. Therefore, the area was not achieving the additional throughput for the added costs.

Most of the time, plant management found itself "fire-fighting" problems in order to achieve its production goals. Little time was allocated to collect and analyze data that would enable them to make decisions that would solve the problem by addressing the root causes. The lack of these information enablers inhibited the virtuous cycle of continuous improvement.

* *Padilla, Jim. True Blue News. The Ford Motor Co. September 10, 2002*

The Body Shop was the bottleneck of the DAP and because of the large increase in technology complexity in its manufacturing processes, it was hard to determine the location of the bottlenecks within the Body Shop. The objective of the thesis project was to start with a foundation of Theory of Constraints and Lean Manufacturing knowledge, and to use this knowledge to help understand and improve the Body Shop throughput problems.

1.3 Goals and Objectives

As already mentioned, the overall throughput of the plant seemed to be constrained by the Body Shop area, where it was believed that the Rear Pan Line was causing a bottleneck. However, there had been little effort to back up this assumption using a numerical validation.

Since methods were lacking to clearly pinpoint the subsystem bottlenecks, the main objective of the project was to help the plant management validate the constraint and improve its throughput, elevating the whole system's throughput as a consequence. The goal was to efficiently focus daily firefighting activities, thus freeing up more time for effectively focused continuous improvement activities.

The project proposes a numerical validation to help determine the bottlenecks within the Body Shop and makes recommendations on how to collect data from this area on a real time basis in order to monitor its behavior and be able to focus the improvement efforts. On-line monitoring systems for manual/automatic lines, as well as discrete-event type simulation techniques are applied to develop the proposed suggestions.

1.4 Project Approach

The Body Shop lacked a data analysis method to identify the subsystem bottlenecks. Early during the project, as an interim solution, the Vehicle Operations Division (V.O.) assisted the Body Shop by outsourcing a machine down time study of the facility to independent data loggers. The purpose was to observe and gather detailed data on downtime occurrences on the plant floor as well as its root causes. The downtime data was fed to a discrete-event type simulation developed by V.O. in which the operation of the whole Body Shop was simulated and the state of each station monitored to check for the bottleneck(s) within the system. A throughput improvement roadmap was developed out of this project.

Initial efforts were also placed in a Ford Total Productive Maintenance (FTPM) Reenergization Program in which plant management at different levels interviewed maintenance skill trades and through a predefined procedure, a list of recommendations was developed. Statistical analysis on the line supervisor's manually input data led management to suspect that the Front End, Rear Pan and Underbody lines were the potential system bottlenecks.

After having both initiatives' feedback, the Rear Pan Line was chosen as the area of focus for the internship project. This line comprised a system with offline cellular production and traditional serial processes which was viewed as difficult to manage. While this was the area chosen for the project, the methodologies resulting from this project are applicable in other areas of the Body Shop.

Not long after focusing on the Rear Pan Line, we realized there was a lack of reliable and accurate information, which would, in turn, restrain our ability to spot improvement opportunities. As personnel associated with the area were interviewed, we discovered a general lack of understanding of the production goals as well as where and why the throughput was being constrained. This confusion was evidenced by the multitude of "root causes" which were described. As we looked into collecting data and information, we found a large gap between the information which was available and that which might be useful. This discovery prompted us to take a step back and analyze the manufacturing system further, to determine how the information was being collected and which information was in fact necessary to make effective decisions. Therefore, a strategy to obtain the right information and make use of it in a deliberate continuous improvement process had to be developed. While this was the area chosen for the project, the methodologies resulting from this project are applicable in other areas of the Body Shop.

1.5 Structure of Thesis

The thesis is divided into seven chapters:

Chapter 1 introduces the challenges of bottleneck identification, and describes the need for analytical tools. The plant environment and the specific problems faced are reviewed. Finally, the project approach is presented.

Chapter 2 explains in greater detail Ford's current financial position at the time of the project and gives more specifics on the DAP. Halfway in the chapter, the Rear Pan Line is explained in detail as well as a couple of policy decisions that were affecting the area's throughput.

Chapter 3 is a quick overview of Theory of Constraints and Lean Manufacturing as well as a comparison of both methodologies. The chapter ends by stating the applicability of both theories to the Rear Pan Line.

Chapter 4 presents the Ford Production System's manufacturing performance metrics and makes comments relating to the usefulness of these metrics for the proper bottleneck identification. Reliability and Maintainability indexes are explained since they will be used for the remaining of the thesis.

Chapter 5 first tries to define the plant's target throughput. It then relates to the difficulties faced in obtaining accurate data and how this data was used to define the Rear Pan Line as the area to focus. Man/machine mapping and discrete-event type simulation techniques are explained. Recommendations developed from the use of both tools are listed.

Chapter 6 stresses the need for data driven decisions. The used of a web-deployed on-line monitoring system is proposed as well as a template to be used in order to collect the information. Implementation challenges are listed.

Chapter 7 presents the conclusions and recommendations.

A Glossary of Acronyms used in the thesis is available after Chapter 7.

Chapter 2: Environment

During the course of the project, the Ford Motor Co. was feeling the consequences of an economic slowdown. In September, 2002 its market capitalization of $19.7 billion was less than the $24.9 billion in gross cash the company had on its books, which meant investors were effectively assigning a negative value to Ford's $131.5 billion a year automotive and finance business. There was a big concern from investors that Ford's need for cash to finance consumer discount deals and new products was currently outstripping its ability to generate cash from its day-to-day business. Company officials at Ford were expecting to return to positive operating cash flow by late 2003.[*]

As Stephen Girsky, Morgan Stanley's automotive analyst mentioned: "The good news is they're making progress on their [recovery] plan. The bad news is we're in a 17 million [vehicle sales a year] market and they're barely profitable". Company's top management had to cope with all the financial distress as well as having to rethink whether the company's target to reduce the cost of an average Ford North American vehicle by $700, one major element of their recovery plan, may not have been enough in the face of the industry's price wars.[*]

In October 2002, in just one week Ford's stock lost 16% of its value. For the year, it had lost 60% of its value – and almost 90% if we went back 3 years.[**] The above had a big impact on

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* *Ford Expects 'Small Profit' In Period, Beating Forecasts, JOSEPH B. WHITE and NORIHIKO SHIROUZU, THE WALL STREET JOURNAL, 09/10/2002*

** *THE SPARK at Ford Rouge, Week of October 20, 2002* employee's morale and made it hard to have any improvement project that required even little investment approved.

2.1 Assembly Plant

The Body Shop at DAP is one of three main sub-plants within the overall automotive assembly plant, the others being the Paint Shop, and General Assembly.

Body Shop. The Body Shop is the most upstream process within the assembly plant. Its function is to build up the body of the vehicle, which includes the structural frame and sheet metal shell of the vehicle (the Body Shop will be discussed in more detail in subsection 2.2). Once the body-in-white, the Body Shop's final product, has been fabricated, it flows into the Paint Shop.

Paint Shop. The Paint Shop's function is to receive the body-in-white from the Body Shop, and paint it. This involves cleaning, treating, applying undercoats, and applying a finish coat. The product then moves on to the General Assembly.

General Assembly. The General Assembly receives the painted body structure from the Paint Shop and adds all minor and major vehicle components to assemble the complete vehicle. General Assembly consists of two main areas: Trim and Chassis.

As of June, 2003 the Assembly Plant was running into some serious problems. As reported by the Manufacturing Plant Manager, actual production for the week ending June 25, 2003 was 13%

below the weekly target, representing $3.7 million in lost economic profits. Besides, the plant's budget performance for the week was over budget.*

Due to the fact that the plant was assembling the Ford Mustang, for which there was a long order backlog and this model was in fact a cash generator for the company, there was pressure from top management to increase the plant's throughput, especially with the financial crisis that the company was going through. Because of the machinery unreliability, plant management claimed to have an unstable working environment at the Body Shop and was proving to be very difficult to manage thus, required help from the V.O. Division within Ford. Vehicle Operations responded by assisting the plant with the machine down time study as well as launching the Ford Total Productive Maintenance (FTPM) Reenergization Program.

2.2 Body Shop Process Flow

A Body Shop assembles the metal of an automobile together through various welding serial processes. Some of the welding is used to locate the pieces of sheet metal in the right position while other welds (known as re-spot) are additional welds added for structural integrity.

The evolution of operations at DAP's Body Shop from a manual Body Shop to an automated, capital intensive Body Shop has created some throughput issues. As shown in Figure 1, twelve main processes make up the process flow for a particular model.

* *The Botton Line at DAP, June 25, 2003, Vol. 1, Issue 3, Mark Boldin-Manufacturing Manager*

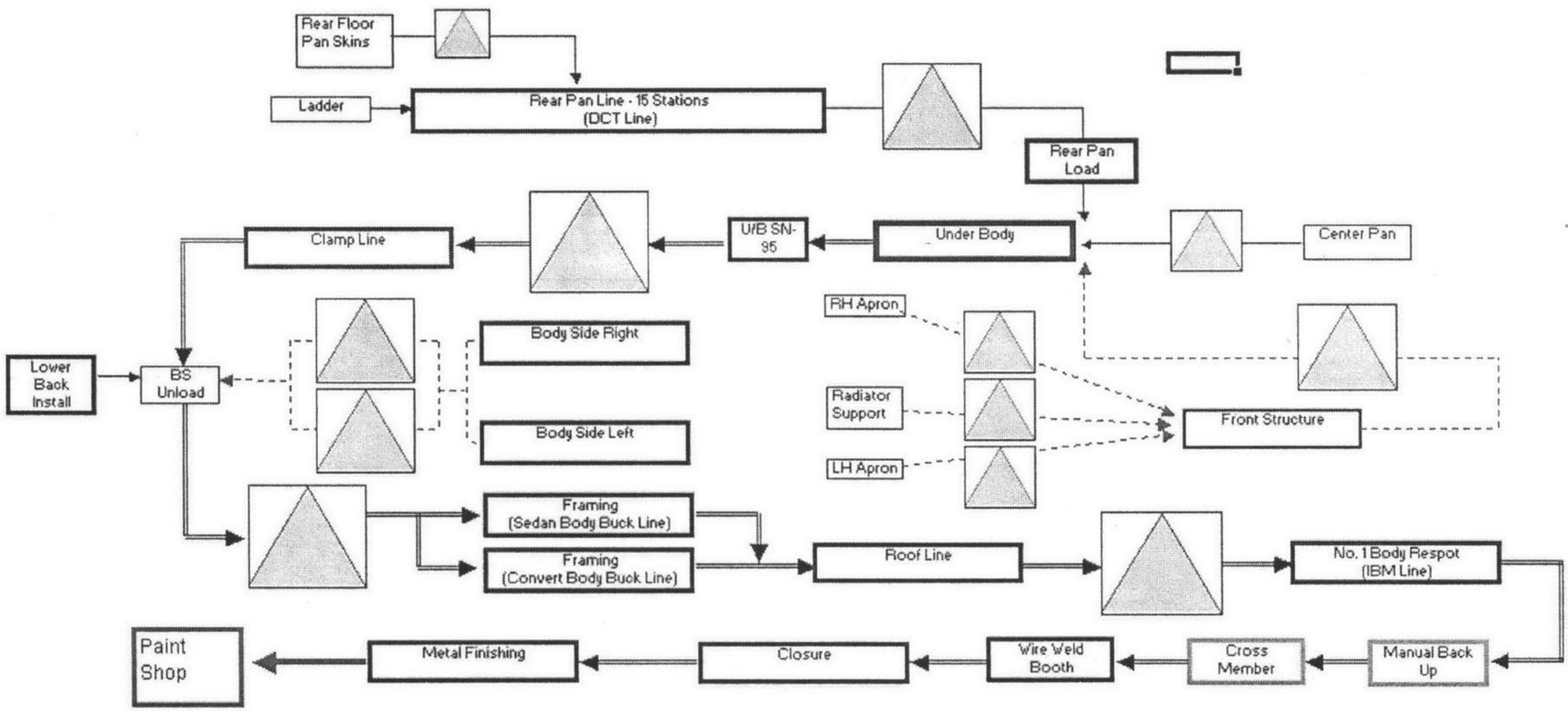

Figure 1. Body Shop Layout

The Rear Pan, Center Pan and Front Structure of the car's underbody are welded together at the "marriage point", just before the Underbody Line, a re-spot line. The underbody is also checked for dimensional control at this point. At the Clamp Line, additional welds, subassemblies and sealant are added to the underbody so that it is ready for the body side assemblies. Once the body sides are attached at the BS Unload Station, the unit goes into the Framing Line, where it is clamped in a fixture and re-spot welded in order to guarantee the dimensional specifications. Later, the roof is positioned and attached by robots in the Roof Line, just to undergo a series of steps, mainly welds and metal finishing, in order to be ready and sent to the Paint Shop.

The plant machinery at the Body Shop was unstable and there was a lack of focus on preventive maintenance. Several years ago, Ford Motor Co. paid a great deal of attention to their Ford Total Productive Maintenance Program (FTPM). As the Ford Production System (FPS) emerged and was implemented in response to the competitive environment caused by facilities implementing Lean Manufacturing techniques, the people implementing FPS in the plant failed to integrate successfully the FTPM portion in the implementation process. In addition, DAP's Body Shop had gone through a couple of cost-cutting initiatives in which the maintenance manager in place reduced the head count of skill trades in order to show operational savings. Both former maintenance managers were promoted as part of their "successful" cost-cutting strategy just to leave the current maintenance manager with a clear shortage of human resources.

Figure 2 shows the percentage of the current Body Shop maintenance trade human manpower versus the required manpower. The required manpower was estimated by the plant, collecting the number of hours per year required for each preventive maintenance procedure needed for all the production lines within the Body Shop. It is easily noticeable that manpower is low in every trade required. In total, maintenance skill trades manpower is covered at 34%

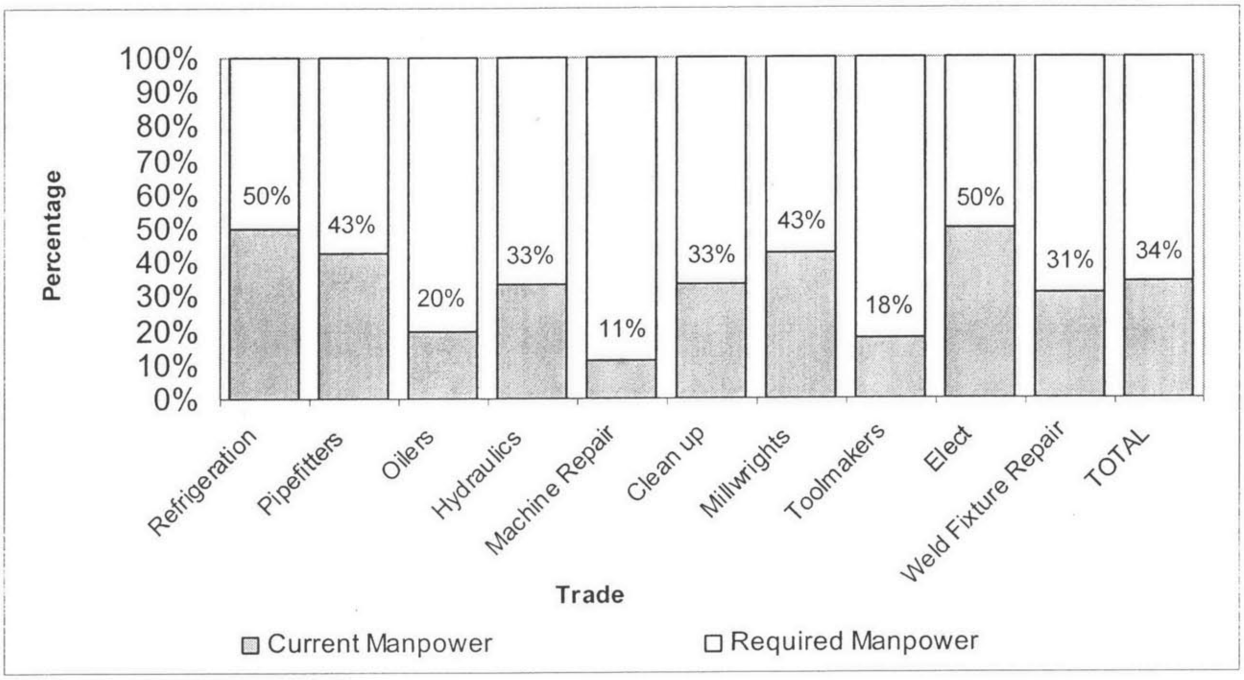

Figure 2. Percentage of Required versus Current Maintenance Manpower Heads

The V.O. division started a 3-week FTPM Reenergization Program in which upper and middle plant managers, as well as skill trades, were involved in finding the root-causes of the problems and developed a plan of action. Most of the observations made in the final report clearly showed the lack of reliable data on which to back up the recommendations. Among its conclusions, the working group stated that "given the data that we have, downtime and production counts, [it] shows that our constraint [within the Body Shop] is up front (Front End, Rear Pan, & Underbody)". Besides, "[the] majority of losses are from equipment downtime and history at other plants that are running in automatic suggests that minor stoppages are the constraint, but we don't record and log the minor issues."

Besides making two observations on inconsistencies between the real data and the data presented in the plant's value stream map, all the remaining 18 observations, recommendations and next steps had to do with the way the data had to be collected and analyzed.* It was obvious from the recommendations that the plant was lacking the necessary information to make data-driven effective decisions.

2.3 Focus Area: Rear Pan Line

The Rear Pan Line assembles the bottom rear of the Mustang. The rear pan consists mainly of two support rails, two shock towers to position the shock absorbers and a rear sheet metal floor pan. Sedans and convertibles use the same rear pan while the Mustang Cobra version (sedan) has some additional parts added at the starting manual stations (i.e., extra positioners for seat belt buck). Figure 3 shows the layout of the Rear Pan Line.

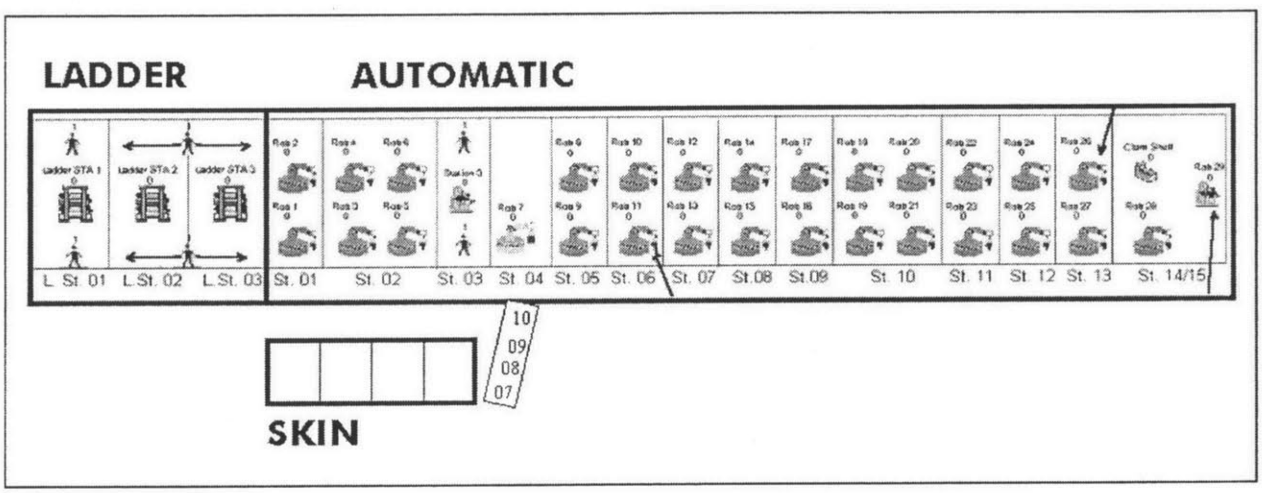

Figure 3. Rear Pan Line Layout

* *FTPM Reenergization Program,Dearborn Assembly Plant, June 26, 2002*

The Rear Pan Line consists of three main areas: Ladder, Skin and Automatic Areas. Ladder and Skin Areas feed the Automatic Area at Automatic Stations 1 and 4 respectively.

Ladder Area

The Ladder Area has three workstations and two operators to load the parts per side (one of the operators loads Ladder Station 2 and Station 3 every cycle). At Ladder Station 1, operators on each side load the support rails as well as two other small subassemblies. Operators taking care of Ladder Station 2 and 3 load the shock tower, seat belt buck and three other small subassemblies on each side. Operators manually feed all the rear pan parts (besides the rear sheet metal floor pan) in these first 3 manual stations.

Within the Ladder Area, welding cycles vary for each station. Operators start loading as soon as the cycle is completed in each of the stations. Nonetheless, the automatic welding cycle and activation of the overhead transfer will not happen until all the operators have pushed a button in their station signaling that their assigned station has been successfully loaded.

Operator over-cycle lights (lights that turn on when the operator has taken more than the required time to complete a cycle) are small and mounted to the equipment switchboards, far away from the operator's line of sight. The cycle time programmed for the over-cycle lights is wrong and none of the operators pay attention to it because of this error.

Skin Area

The Skin Area produces the sheet metal floor pan. It is an off-line cell with 4 stations and two operators (2 stations per operator). A mechanical conveyor with space up to 4 sheet metal floor pans link the Skin and Automatic Areas. The buffer is linked to the Automatic Area but extra skins produced can be stored, if desired, besides the conveyor #7 spot. The floor pan is added in Station #4 by a loading robot.

Automatic Area

The Automatic Area is a fully automated re-spot area with 15 stations: 26 weld robots, 2 unload robots and a stud welder referred to as the "clam shell".

Out of the 15 stations, only 3 perform a different activity than re-spot welding. Automatic Station 3 is a manual re-spot station that works as a "back up" station just before the sheet metal floor pan is added to the subassembly. Automatic Station 3 was not being used as a back up in reality. Full-time welders (one per side) were performing a couple of re-spot welds that were required because of safety regulations. Programming the welds into Station 1 or 2 seemed to have the potential to slow the line down, so the two operators remained on the line for the full seven months of the project.

Automatic Station 4 loads the sheet metal floor plan onto the line and Station 15 unloads the finished rear pan. At station 15, a material-handling robot loads the completed subassembly either to an electrified monorail buffer or to an off-line buffer. The off-line buffer can accumulate hundreds of additional completed underbody rears if desired. The finished rear pans are then either placed in a buffer or married to the center pan and front structures at the "marriage" station just before the Underbody Re-spot line.

2.3.1 Policy Decisions that Affect Throughput

Peter Senge's book *The Fifth Discipline*[4] describes several archetypes of behavior by using system dynamics principles. System dynamics essentially uses the concepts of feedback theory to describe the effects of behavior and policy decisions. One of the archetypes in Senge's book is called Shifting the Burden. In the Shifting the Burden archetype, there are two possible policy solutions to implement: long and short-term policies. The long term, fundamental solution takes time to create a long-lasting improvement, while the short-term solution creates a temporary, quick improvement. As the short-term solution is utilized more often, the fundamental solution for the problem becomes less feasible and is used even less often. Over a long period, managers continue to depend on the short-term solution and never use the long-lasting improvement. Two policies used in the DAP plant demonstrate this shifting the burden archetype: the production overtime policy and the inventory policy. These two policies negatively affect the plant's throughput.

2.3.1.1 Production Overtime Policy

In the Production Overtime policy case (see Figure 4), the DAP Body Shop is trying to solve their throughput problem by building the scheduled amount of jobs each week. A portion of the throughput loss stems from poor equipment uptime that relates to incomplete preventative maintenance work orders and unscheduled continuous improvement projects on the equipment for better reliability. This fundamental solution of scheduling maintenance time and manpower takes plant management discipline.

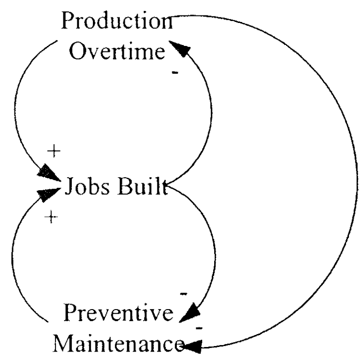

Figure 4. System Dynamics Model for the Production Overtime Policy

On the other hand, DAP Body Shop utilizes the short-term solution policy of scheduling production overtime to make up the lost units each week regardless of having a thorough understanding of the capacity constraining resources (CCRs) at the factory. While the overtime immediately builds the lost units, it further restricts available preventative maintenance (PM) time. The reduced efforts in PM create even lower throughput output during scheduled production because of greater equipment failure frequency. This warrants ever greater production overtime. The fundamental solution of PM is continually reduced while the short-term solution is reinforced. This vicious cycle continues as production works more and more weekends. At DAP Body Shop, it was not uncommon to see production people working in the Body Shop on both Saturday and Sunday. One way for the DAP Body Shop to ultimately increase their throughput is to eliminate overtime production in areas that are not CCRs and start reducing it gradually in CCR areas. During that same period, increase the amount of PM and equipment reliability projects. By stressing the fundamental solution, management can improve the throughput and reduce overall plant overtime.

Unfortunately, the improvements from this solution are not seen immediately. The first effect of this suggested policy is in fact an increase in cost and only after several months do the cost savings start to accumulate.[5] In addition, because of the limited Body Shop human resources, being able to perform all the PM required would probably mean having to increase the maintenance manpower and this would not be considered an effective recommendation at the time. Because of the current financial difficulties and the short life expected for DAP, plant management was unwilling to wait for the longer term solutions and basically was trying to operate the plant as a "cash cow" for the time remaining.

Therefore, it was necessary to come up with a solution that directed limited resources to the areas in the Body Shop that would create the most impact on net system throughput through the Paint Shop.

2.3.1.2 Inventory Policy

Another policy being practiced at DAP's Body Shop was to increase throughput by increasing the amount of inventory stocks in the off-line buffers between the major sub-assembly lines (see Figure 5). By buffering for all potential breakdowns, the Body Shop was able to meet better their daily production during the shift. Unfortunately, because of the large inventory stocks, the maintenance workers have little incentive to fix breakdowns quickly. The complacency of the maintenance worker increases the Mean Time to Repair (MTTR) of each station and reduces the amount of jobs built on the production line. This effect also depletes the jobs in the buffer ultimately affecting throughput. In order to prevent throughput losses from these breakdowns, the off-line buffers are further increased, creating even more complacency in the maintenance worker.

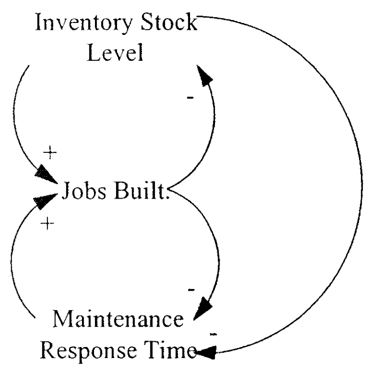

Figure 5. System Dynamics Model for Inventory

The off-line inventory itself can also create throughput problems. For example, the front structures were stored on the floor outside of inventory racks. The parts on the floor in some instances can become bent or damaged. When these damaged parts are re-entered into the assembly process, they do not fit properly in the tabbing station and the machine shuts the skid system down. Again, by stressing the fundamental solution of improving response time and also reducing the amount of inventory in the plant, management can improve the system throughput although, the benefit of these actions will have a delay.

2.3.1.3 Summary

The use of system dynamics archetypes can help management recognize the long term effects of certain policy decisions. DAP has currently been using two short term solution policies in the Body Shop to attain the necessary throughput each day. By shifting their policies toward the long-term solutions, they can ultimately solve their throughput issues and save overtime and inventory holding costs.

Chapter 3: Theory of Constraints and Lean Manufacturing

First, we discuss serial production systems, including a discussion of the blocked and starved states and the importance of buffers and inventory with respect to throughput. Then we describe briefly and compare the Theory of Constraints and the Lean Manufacturing System. At last we state both methods applicability to the Rear Pan Line.

3.1 Serial Production Systems

A serial production system is comprised of manufacturing operations in a sequential order. Buffers storing parts for the following station can exist between operations. Even when most assembly plants do not strictly follow a serial production line as some of the parts may feed into the line from a different subassembly line, the modeling of serial production systems is the basic building block for developing more complicated models.

In coupled stations, one station immediately feeds a part into another station, while in decoupled stations; the two stations are separated by a buffer. There are three states for machines that negatively affect the throughput of an assembly line - failed, blocked, and starved.

When a machine fails, it can affect the state of other operations around it. For example in Figure 6, there are three stations coupled without a buffer. When Station 2 fails, it directly affects the state of the other two stations. Station 1 has finished its job but has no place to put it because Station 2 has failed. Station 1 is blocked. Similarly, Station 3 cannot build because Station 2 is down and is not feeding it parts. Station 3 is waiting, it is considered starved by Station 2.

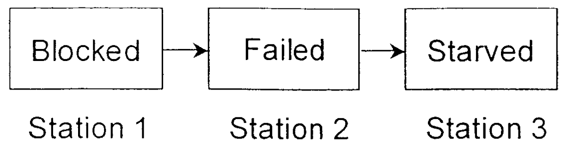

Figure 6. Three Coupled Stations Without a Buffer and their States

When stations are coupled together, one failed station will either block or starve the remaining stations. As a result, any failure within the coupled group will affect the throughput of the last station and therefore the line as a whole.

One solution for increasing throughput is to add buffers to the system. Let us now assume that we place a buffer between Station 2 and Station 3 (Figure 7) and that this buffer contains some work in process (W.I.P.) in it. Now, when Station 2 fails, Station 1 remains blocked but station 3 can still operate because it pulls jobs out of the buffer. Later, if Station 3 breaks down, Stations 1 and 2 can build jobs until the buffer fills up. Previously this would have blocked Stations 1 and 2. Now these stations can build jobs into the buffer until the buffer becomes full.

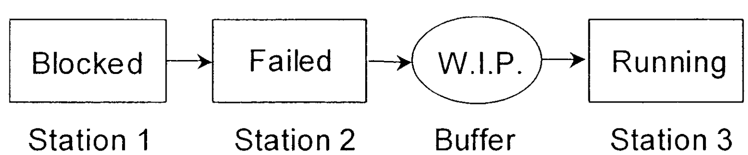

Figure 7. Three Stations with a Buffer and their States (Station 2 & 3 Decoupled)

The purpose of inventory is to cope with the variability of the system. The greater the system's variability, the greater the inventory levels required. Since machines do breakdown occasionally, inventory can compensate for these breakdowns and assist in leveling throughput. The advantage of inventory is clear, yet much has been written about the "evils" of inventory under the Lean

Manufacturing System. One of the Lean Manufacturing System strategies is to eliminate waste by reducing inventory. Among many other disadvantage of having inventory we can mention that there are higher levels of scrap due to damaged parts in inventory, long delays between discovering faults and correcting them, higher inventory holding costs and cost of transportation as well as slower response times of operators and maintenance trades due to high buffer sizes.

To maximize the effectiveness of buffers, one must balance the buffer's disadvantages with its throughput advantages. Having too much buffer results in high costs while having too little buffer also increases costs due to many blocked and starved conditions restricting output. When designing a Body Shop, the engineers must consider these inventory issues to optimize the assembly facility. From a throughput perspective, the best assembly system keeps each station working when it is not in a failure mode. Therefore, no station in the system is blocked or starved due to any other station's failure. Managing these blocked and starved conditions in the real world is critical to improving total system throughput.

3.2 Theory of Constraints

TOC was developed by an Israeli physicist named Eliyahu Goldratt. Dr. Goldratt developed this management philosophy to aid companies in optimizing the overall system, rather than optimizing parts of a system. Its goal of making money can be stated in terms of three metrics: increase throughput while simultaneously reducing both inventory and operating expense.[3] The concept of simultaneity indicates a focus on optimizing the organization as a whole rather than on local optimums.

Thus, at a high level, an organization should be concerned about increasing net profit, while simultaneously increasing both ROI and cash flow.[3] At a plant level, an organization should utilize the following metrics: throughput (rate at which the system generates money through sales), inventory (all the money that the system invests in purchasing things the system intends to sell), and operating expense (all the money the system spends in turning inventory into throughput).[6]

A bottleneck or constraint is the operation with capacity that is equal or less than the demand placed on it,[3] or anything that limits a system from achieving higher performance versus its goal.[7] The Theory of Constraints focuses on finding the location and managing the bottlenecks in any system. A constraint can be any part of the entire system and may be found in the market, materials, capacity, logistical areas, and management or behavioral areas. A bottleneck typically refers to a constraint in the manufacturing process. This research is focused primarily on the entire manufacturing system rather than the system of a corporation as a whole, and therefore the terms bottleneck and system constraint are used interchangeably. A work station can become the manufacturing system's bottleneck due to a wide variety of reasons: low cycle time or high downtime, excessive material blocking the operation of the work station, poor material replenishment systems that cause the work station to starve frequently, etcetera.

A key insight of TOC is that only a few work centers within the factory control the output of the entire factory for each product line. Managing these capacity constraining resources (CCRs) or bottlenecks optimizes the output of the factory.

To increase the throughput, one must have a clear understanding of where it is constrained and an understanding that throughput improvement efforts at points in the system other than at the bottleneck will have no impact on the throughput.

Sometimes the true bottleneck is not the station with the greatest amount of downtime due to the buffers in the system. When this case occurs, much effort tends to be placed by management on the station with the most downtime, resulting in little overall effect on system throughput. Resources focused on a bottleneck are well placed and will have an impact on the system. Resources focused on non-bottleneck processes are not well placed and will likely lead to frustration when it is recognized that the system is not impacted. Another important issue is to never starve the bottleneck. Whenever a bottleneck is starved, the losses in throughput as a result of starving pass directly through the system and affect the system's throughput. Knowledge of the plant's CCRs also provides guidance for future plant investment. The identification of constraints also shows where setup reductions and process improvement efforts should be focused.

The suggestion is to do CCR determination by simply walking through the shop and observing where inventory has piled up[3]. Other sources for insights on the CCR determination are the shop floor personnel, the master scheduler and, in case there is, a list of machines that are candidates for capacity improvement. The initial set of bottlenecks will change as TOC is implemented, so perfect accuracy is not necessary. The Pareto rule is used to determine CCRs, and explore candidates for setup improvement. The 20% most heavily loaded work areas are assessed as potential bottlenecks.

In an automotive assembly plant, one tends to see multiple bottlenecks due to the low reliability of the substations and the balanced designed cycle time of the assembly processes. The design of the tooling tends to equalize the capacity at each machine. Therefore, low equipment reliability at the tooling, stemming from machinery complexity, can produce multiple bottlenecks in the system. These multiple bottlenecks can ultimately affect the throughput of the whole system. The buffering used in the system plays a factor in whether certain stations become one of the bottlenecks.

3.2.1 Measurement Systems

To keep the system in synch with the constraint, TOC develops the concept of Drum-Buffer-Rope (DBR).[6] This essentially involves tying a "rope" from the slowest process in the system to the first process. There will be no dispersion behind the slowest process since those behind it will have the capacity to catch up. The only spreading that will occur will be in front of the slowest process, but the length of the buffer will control that. This gap in front of the slowest hiker is a buffer against the disturbances of the preceding processes. It is apparent that in this method you can avoid the detrimental effects of statistical fluctuations. The slowest process' pace becomes the drumbeat for the entire system. A key to implementing the DBR system is the appropriate sizing of buffers so that the entire plant is protected, not the individual operations. If the actual buffer equals the planned buffer, then the buffer size is too large and should be reduced.[6] The point, though, is to never starve the constraint.

Efficient data management is crucial to the effectiveness of any TOC management system. Understanding where the constraints are and understanding when to release material into the system requires data that is collected for that specific purpose. Data is typically collected for financial reporting purposes and may not provide the exact type of information that is necessary to identify constraints. Systems may need to be developed to enable the implementation of a drum-buffer rope material control system.

3.2.2 Process of Ongoing Improvement

Working from a base of appropriate metrics, bottleneck management, and employing DBR to account for the combination of dependent events and statistical fluctuations, TOC boils down to the following process of ongoing improvement (using the terminology of the system to be improved) [7]:

1. **Identify the system's constraints:** It also means to prioritize them according to their impact on the goal; otherwise many trivialities will sneak into the next step.
2. **Decide how to exploit the system's constraints:** We should manage the system's resources so that everything that the constraints are going to consume will be supplied by the non-constraints.
3. **Subordinate everything else to the above decision.**
4. **Elevate the system's constraints[7]:** we only need to be aware that if we continue to elevate a constraint by increasing its throughput, there must come a time when we break it.
5. **If in the previous steps a constraint has been broken, go back to step 1, but do not allow inertia to cause a system constraint:** Every manager is overwhelmed with problems, or as some would call it opportunities. We all tend to concentrate on taking corrective actions that we know how to take, not necessarily concentrating on the problems we should correct and the actions needed to correct those problems. Thus, if a process of ongoing improvement is to be effective, we must first of all find what to change. In other words, the first ability that we

must require from a manager is the ability to pinpoint the core problems, those problems that, once corrected, will have a major impact, rather than drifting from one small problem to another, fooling ourselves into thinking that we are doing our job.

The following steps are equivalent to the above five steps, but are expressed in the terminology of the improvement process itself[7]:

1. **What to change?** Pinpoint the core problems!
2. **To what to change to?** Construct simple, practical solutions!
3. **How to cause the change?** Induce the appropriate people to invent such solutions!

The process of ongoing improvement acts as a method for eliminating the disruptions that cause the holes in the constraint buffers so that inventory can be reduced.[6] As the buffers are decreased, since they contain the majority of the work-in-process inventory, the competitive edge of the plant is increased.

3.3 Lean Manufacturing

Since the early 1980's, American manufacturing firms have been under close examination. The widespread traditional mass production system used by these firms, find itself in competition with a new set of ideas pioneered by Japanese companies such as Toyota, and grouped under the term "lean production".[8] This new method of manufacturing has been so successful against the world's industrial giants, that many U.S. firms are reengineering their operations to take advantage of these powerful ideas. The Ford Motor Company, whose founder's name is almost synonymous with mass production, is not an exception and started to undertake the change under their Ford Production System.

The differences between mass and lean production are striking. Traditional production systems are designed to manufacture standardized products at very high volumes, using expensive, single-purpose equipment and a low-skilled workforce. Lean production seeks instead to be able to produce a high variety of products using flexible equipment and multi-skilled teams. The focus is on zero defects, zero inventory, and on reducing costs. Toyota is perhaps the best known of the lean producers, and provides Ford with an impressive benchmark for its own production system.

Making money today and in the future is also the motive behind Lean Manufacturing. It is built on the foundation that the market sets the selling price of a good, and the way to increase profits is to reduce costs by the elimination of the seven categories of waste (motion, defects, conveyance, overproduction, waiting, processing and inventory) and provide customer satisfaction.

Lean Manufacturing aims at providing high quality, low cost products with volume and mix flexibility in response to customer requirements. It consists of a set of concepts: all of which are applicable in some environments; some of which are applicable in all environments. Following is a list of some lean manufacturing concepts:

Just In Time (J.I.T.): producing what you need, when you need it, in the quantities you need. Production is triggered or pulled by customer demands.

Jidoka: human-like qualities that equipment must have to ensure that defects are not passed on to subsequent operations.

Pokayoke: "fool-proof" or "error-proof" devices to help prevent defects.

Kaizen: its English translation is improvement. Kaizen is viewed as a never-ending, continuous process.

Standardized Work: defining and following the motions and actions for each operation can reduce variability. Improvements can be made afterwards.

Man/Machine Chart: the chart combines an operator's work and walking times with equipment operating times. By considering different work combinations, efficient Standardized Work can be developed.

Takt Time: the available production time divided by the number of parts required by the customer. It is a key element in the design of a lean manufacturing system since it defines the pace for the production system.

Kanban: its English translation is signboard.* A tool to visually convey information. Kanban are used as a tool for pull systems in JIT operations.

Heijunka: refers to scheduling production loads at a level schedule for each day, week, and month to eliminate peaks and valleys in manufacturing**.

Setup Time Reduction: the time elapsed from the instant that the production of unit A finishes, to the instant that the first good unit of B is produced. Reduction of setup time is a requirement for successful implementation of Lean Manufacturing, and involves the use of techniques such as Shingo's Single Minute Exchange of Dies (SMED). Having predictable, efficient setups allows for better utilization of people and equipment, and better response to changes in customer demand.

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* *(accessed May 28, 2003); available from http://www.courses.fas.harvard.edu/~jlit141/*

** *Cochran, D., Lecture Notes for Mfg. System Design Workshop, Michigan, U.S.A., 2002*

Flow Operations/Cell Layouts: dissimilar machines are grouped into a flow line[9], or cellular layout. The objective is to achieve one-piece flow.

Andon: tools for visual communication. Typically, colored lights that indicate the status of a machine or line.

Worker Involvement: an essential part of lean manufacturing. Improvement potential will be achieved, only by utilizing the experience and abilities of the people who actually perform the work. An environment of continuous improvement is only possible when the workforce is engaged in the concepts of lean manufacturing.

3.4 Theory of Constraints versus Lean Manufacturing

In this section's introduction, TOC and Lean Manufacturing were described as basic philosophies for running a plant. While this is an acceptable frame of reference, we must further identify the similarities and differences between TOC and Lean Manufacturing before we can truly understand their usefulness. The following points are viewed as the most significant similarities and differences.

3.4.1 Similarities

Both systems try to maximize profits. TOC seeks system responsiveness to the customer's needs by providing on time delivery of high quality, low cost products. Lean Manufacturing tries to deliver the right product at the right quantity, at the right time and price (by accepting that the market sets the price).

Both systems view the survival and ability of the organization to make money as being dependent on the process of continuous improvement. TOC calls it "A Process of Ongoing

Improvement" while Kaizen is part of the foundation of Lean Manufacturing.

TOC's concept of the drum as the pace setter is analogous to the Lean Manufacturing concepts of heijunka and takt time while the rope which ensures that operations with excess capacity do not overproduce is equivalent to the kanban. While both systems address pace setting, TOC recognizes the process bottleneck as the controlling factor for pace; Lean Manufacturing recognizes customer demand as the controlling factor for pace.

Like JIT, TOC assumes a stable environment. A plant should have a stable order mix and given resources before implementing.[10] TOC's buffer concept is central to mitigate the effects of combinations of dependent events and statistical fluctuations. Lean Manufacturing makes use of one-piece flow, where at all possible. Besides, its supermarket concept and the allocation of appropriate numbers of kanban between processes serve the purpose of absorbing the effects of disturbances.

At last, both philosophies view worker wages as a sunk cost and worker idle time during production as a sign of efficiency. Goldratt indicates in *The Goal* that "a plant in which everyone is working all the time is very inefficient".[3] Dr. Goldratt distinguishes between 'utilizing' a resource which helps move the system toward the goal and 'activating' a resource which does not.[3] Similarly, Shingo explains that Toyota's basic philosophy is that it is better to allow workers to be idle than to overproduce.[11]

3.4.2 Differences

Within manufacturing, Lean Manufacturing is most useful for the production of medium to high volume repetitive parts or part families, and not so useful in a job shop that makes individual, one-of-a-kind parts. TOC, though, is more flexible and can be effectively utilized in both situations since, regardless of the volumes; there will always be a bottleneck process. Another reason is that TOC is actually less sensitive to changes in the production plan than Lean Manufacturing J.I.T.'s concept. Production plan changes are analyzed in terms of their impact upon the CCR, which highlights any problems. Simulation of the factory can be carried out in the scheduling process.[12,13] Capacity changes in the CCRs can also be simulated. This permits the planner to anticipate impact of changes in demand, schedules or work center capacities. J.I.T., on the other hand, reacts to the actual results of the change.[14] In Lean Manufacturing, a disturbance can immediately shut down the entire system. In TOC the system is protected from disturbances to a certain point.[6]

TOC is a push system downstream from the CCR and a pull system upstream from the CCR. Obviously, if the market is the constraint, then the whole factory is a pull system, as it is for the Lean JIT concept. But TOC is flexible, and the CCR may be located anywhere in the factory.

In terms of process flow, Lean Manufacturing is most applicable to cellular production; whereas, TOC is most easily applied to serial flows. If a process flow is highly serial, bottlenecks can be found with relative ease by analyzing starved, blocked, and downtime data.

The approach to the information flow is drastically different under both philosophies. While Lean Manufacturing is a very visual system, information flow with TOC is somewhat hidden. While the former stresses the need for visual control such that anyone can tell the status of the system at a moment's glance (use of Kanban and andon), the later often relies on a computerized scheduling system to release materials into the plant; thus, information is not accessible to all in the manufacturing environment.

While both philosophies promote reduction of inventories, TOC is more explicit in the need for appropriate buffers until instability is brought under control. Lean Manufacturing is inflexible about the need to strive for one-piece flow and is less forgiving of buffers, although the kanban between processes are, in fact, buffers.

As with any system, implementation is the key. Goldratt deals with it by defining his process of ongoing improvement as well as a set of tools: the Socratic, Effect-Cause-Effect, and Evaporating Clouds methods. Lean Manufacturing is subtler and leans towards the "learn by doing" approach, although Black has done well to codify 10 steps to implement such a system.[9] Goldratt tends to think global in terms of the process of implementation; whereas, Lean Manufacturing lacks the 'how to implement the big picture' and focuses more closely on specific tools and techniques.

3.4.3 Applicability to Rear Pan Line

The Rear Pan Line area is comprised of two styles of manufacturing that come together into one system: an offline Skin cell, merging into a more traditional serial line, Ladder and Automatic

Area. Based on the idea that Toyota developed the Lean Manufacturing system to support its serial process based assembly plants, one might conclude that the application of Lean is ideal. Nonetheless, in this Body Shop environment, we felt that an application of TOC would be more appropriate for the serial portion. TOC ensures a focus on bottlenecks so that limited resources are used on problems that affect the system. Utilizing starved, blocked, and downtime data at the start and system pay-points, bottlenecks is an approach to relatively easy locate the constraint area in the Rear Pan Line.

The Rear Pan Line lacked the appropriate infrastructure and culture to support Lean Manufacturing. However, I felt that the first three manual load stations at the Ladder Area and the Skin Area represented the best opportunity for an application of some of the Lean Manufacturing tools. As cells are the backbone for lean manufacturing systems, it made sense to utilize Lean Manufacturing tools in these areas to help eliminate the waste that could potentially create bottleneck situations in these areas. Our suggestion is not to utilize one system, TOC or Lean Manufacturing, but rather pick and choose tools from both and apply them in a customized fashion that suits the needs of this Body Shop environment.

3.5 Summary

People have their own understanding of Just-in-Time (JIT) and TOC. Yet the philosophies are not miles apart. Implementation of Theory of Constraints does not preclude the implementation of Lean Manufacturing, and the two can be combined to gain the benefits of both. They are, in fact, based on the same fundamental goal and can be complimentary.

In essence, the TOC body of knowledge does not provide the tools for local process improvement like lean does. Rather, DBR points out where to get the most out of JIT and Lean concepts. To compete, today's managers should understand and apply both JIT and TOC. The TOC model of DBR would be used to create the operating system for manufacturing. Application of JIT and other lean tools would increase the throughput velocity of the DBR model.[*]

The Dearborn Assembly Body Shop can use these throughput tools and techniques to assist management in improving the system throughput.

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* *Pitcher, Michael, "Examining Just-In-Time and Theory of Constraints", SME Lean Directions: the e-Newsletter of Lean Manufacturing, March 13, 2003 (accessed March 18, 2003); available from Society of Manufacturing Engineers.*

Chapter 4: Performance Metrics

An important part of the change implementation strategies is shifting the mindset of people and gaining their acceptance. To make improvements, you need current values, target values, and measurement criteria for evaluating the effects of the improvement. Since it is human nature to behave in the way in which one is measured, the choice of performance measurements is critical in determining whether the transition to the new system of production will be successful. Ultimately, information should lead to changes in people's behavior.

4.1 FPS Performance Metrics

Under Ford's vision to develop a "lean" production system, the goal is to establish a common system of manufacturing operations in all regions of the world. Not a centralization of management, but decentralized control of the business using a standard set of performance metrics. The first visible effort is the launch of a common set of manufacturing measurements. The FPS measurements are a set of plant metrics used to evaluate its performance in meeting the goals of FPS and to drive continuous improvement. The FPS measurements were launched at all manufacturing sites at the beginning of 1996, and are used in plant management's performance evaluation and reward structure. The four FPS manufacturing metrics are:

Overall Equipment Effectiveness (OEE): A composite index of the availability, performance efficiency, and quality rate of a given piece of equipment (the constraint operation).

First Time Through (FTT): The percentage of units that complete a process without being scrapped, retested, rerun, returned, or diverted to an off-line repair area.

Dock to Dock (DTD): The elapsed time between the arrival of raw materials and the release of finished goods for shipment, for a particular control part.

Build to Schedule: An index of the percentage of units scheduled for a given day that are produced in the correct sequence on that day.

In developing the metrics, the objective was to find a set which were few in number, emphasize physical instead of financial measures, focus on trends and forecasts, be process-oriented, designed for usage by both plant floor employees and management and be common for all of Ford's manufacturing operations.

The metrics were used at DAP but mainly by plant medium and top management to monitor the performance at the plant level. Line supervisors were not used to dealing with such metrics for their own areas because they did not have the necessary information and knowledge to calculate such indexes. In reality, the above indexes are useful to monitor whether the FPS vision to produce exactly what the customer wants, exactly when it is in demand is being achieved.* Nonetheless, they are complex to understand by the line supervisors, moreover, by the line operators. Besides, in order to be able to calculate the indexes, a great deal of data is required. When the collection systems are not in place, the indexes become almost impossible to calculate, as it was the case at DAP.

4.2 Reliability and Maintainability Metrics

Before addressing Reliability and Maintainability performance metrics the definition of a failure has to be stated. Failure is defined as the event when the equipment is not available to produce

* *Ford Communication Network, "Into the Future," FCN Broadcast Oct. 13, 1995*

parts at specified conditions when scheduled, or is not capable of producing parts or scheduled operations to specifications.*

Because we are most interested in operation dependent failures to determine bottlenecks, we disregard time-dependent failures as anomalies to the system. When calculating downtime, blocked and starved time condition is removed from the calculation.

Mean Time Between Failure (MTBF) is a reliability engineering term that is the average time between failure events that cause operator or skilled trades personnel to return the machined to specified operating conditions. The MTBF is in inverse proportion to the breakdown rate. Higher MTBF figures indicate higher equipment reliability. Increased reliability in turn implies fewer failures and increased uptime and less downtime.*

All machines eventually fail. When they do, the cost and time to repair must be as little as possible. Mean Time to Repair (MTTR) is the average time to restore machinery to its specified conditions per failure incident.

Reliability and Maintainability metrics along with operating cycle time, transfer times and buffer size between stations, allow computer simulations to mimic the behavior of a work station within a production system.

* *Machinery R&M Planning Workshop Notes. DRM Technologies Inc. Dearborn, MI., June 21, 2002*

4.3 Summary

The chapter has introduced the FPS metrics, an approach taken by the Ford company to assist them in their change implementation strategies by shifting the mindset of people and gaining their acceptance through the knowledge of common data. The challenge of having these metrics fully implemented is still present, mainly because the metrics have to be fed by on-time, accurate data. Another difficulty is that the metrics try to include several concepts in one number and that makes it difficult for the line operators to interpret.

At last, reliability concepts, which will be required in the next chapters, were presented and calculations were shown for each of them. These concepts will be used in the constraint analysis in the following chapter.

Chapter 5: Constraint Analysis

The objective of the constraint analysis is to determine the identity of the processes that most restrict productivity, so that limited improvement resources may be focused on these processes. In a serial production system, like the Body Shop at DAP, each process receives its inputs from the preceding process and sends its outputs to the following process. If any process fails for a significant period of time, it may prevent parts from flowing through the line and become the bottleneck of the moment. As processes fail frequently and are repaired, the bottleneck of the moment may shift frequently. While this devised bottleneck may be useful for dispatching maintenance personnel, it shifts too frequently to be used for focusing improvement resources. To focus improvement resources, the primary system bottleneck(s) must be identified. The primary system bottlenecks are those processes that most restrict productivity over a period of weeks or months.

The benefits of implementing analytical tools for bottleneck identification are the proper identification of bottlenecks as well as a achieving a good alignment of improvement teams around the identified bottlenecks.

Section 5.1 will address issues at the Body Shop level. Data obtained from the down time study as well as from the Factory Reporting System (FRS) is analyzed and used along with the results from a discrete-event type computer simulator to determine the bottleneck area in the Body Shop.

After some validation that the Rear Pan Line is the primary bottleneck at the Body Shop, section 5.2 focuses on the Rear Pan Line. Once again, manual and FRS data is analyzed to create average JPH graphs and man/machine maps. A computer simulation of the Rear Pan Line is presented and recommendations are made on how to use it in order to be effective at determining constraints within the area.

5.1 Body Shop Production Level

The first step before starting the Body Shop's constraint analysis was to understand the desired plant's throughput. In contrast to an expected common production level among Ford's Vehicle Operations Division, DAP's plant management, and operators, these were actually all different. Defining the target production level was challenging.

5.1.1 Overspeed Strategy

Whenever a new manufacturing facility is designed, the Vehicle Operations Division has to follow the Stamping and Assembly Plant Tooling Capacity Guidelines. These Guidelines state the overspeed standards. The standards require an up-stream station to run 5% faster than the down-stream station.* The designed capacity of a line is basically its offline chassis rate (the maximum number of units per hour off the end of the final line) times its defined overspeed factor. This number is then increased to take into account the percent of time the tool is available, the relief factor and worker's tea time, where applicable. As plants become older, the uptime or reliability factor of a line changes. After several years it is necessary to reassess the manufacturing facilities production capacity. At DAP, the last reassessment was in 1995.

* *Stamping and Assembly Plant Tooling Capacity Guidelines (Vehicle Operations Ford Motor Company, 10/14/1996)*

At DAP, Vehicle Operations was requiring an offline chassis rate of 40 jobs per hour (JPH). If we were to consider the overspeed, relief factor and, assumed 90% uptime, the Rear Pan Line should have been running at 60 seconds per cycle, or 60 JPH. Nonetheless, plant management was actually setting the production goal at the Rear Pan Line not at 60 but at 50 JPH (72 seconds per cycle). If we do the calculation backwards, considering 50 JPH at the Rear Pan Line, in theory, the plant's capacity should be then set at 33.3 offline chassis rate JPH instead of the 40 required by Vehicle Operations.

In reality, the Rear Pan Line was actually running neither at 60 nor at 72, but at 67 seconds per cycle. This would compute to an estimated offline chassis rate of 35.9 JPH, which was very close to the real plant's offline chassis rate.

In summary, there was a divergence between Vehicle Operations, plant management and line-level personnel concerning the expected JPH of the facility. A standard JPH goal should be defined and the whole organization should be aware of it.

5.1.2 Manual Data Collection

When automatic data collection systems are not in place within a big manufacturing company, the cost of having literally an "army" of data loggers for several weeks or months becomes prohibitive. In the case of the DAP, they outsourced manual data loggers for two weeks (during the day shift). Data loggers filled up downtime sheets that recorded the date, shift, the subassembly line as well as the specific faulted equipment, the type of fault, and the duration of the fault. V.O. had to process the information to determine MTBF's and MTTR's as well as

Pareto charts of the equipment problems. The purpose for collecting the data was (1) to have the necessary information to input it into a computer simulation and allow for bottleneck identification, and (2) understand the top issues affecting those that were believed as the "most constraining" operations.

The are several shortcomings of the manual data collection method:

1) It was clear that all of the downtime data was not being fully recorded by the loggers. By outsourcing the data collection, data loggers did not feel any ownership concerning the accuracy of the data collected since they basically would not be at the plant by the time the decisions, based on this data, were implemented.

2) Some areas of the assembly line did not have any data recorded at all. Because of the limited human resources, plant management had to record data only in those stations that were considered possible bottlenecks. Even for those areas, the data was collected for irregular periods during the downtime study.

3) Breakdowns of less than one minute were not recorded. This potentially overstates the MTTR and understates the MTBF.

4) Errors would occur by data loggers (i.e., forgetting to write the start and end time of the period they logged data for, lunch breaks, etcetera) and by the person entering the data in the computer.

All of these errors in data collection combined to created serious data integrity problems. In fact, the data logging exercise had to be performed for a second time due to the inconsistency of the data. Similar to any analysis tool, the value of the computer simulation is only as good as the data that is entered into the model. Because of these potential errors, we also investigated other possible data available at the Body Shop. The only other data available at DAP was through its Factory Reporting System (FRS).

5.1.3 Factory Reporting System (FRS) Data

Every hour, production supervisors at DAP would log production counts, machine state times and faults into an internal information system. Supervisors were also supposed to log the duration of a state, other than the running state. This is almost impossible to perform especially when supervisors are trying to "fire-fight" the daily problems. Supervisors estimated the durations of the faults and input their best educated guess. At last, the FRS system had a glitch, if the duration of a certain fault or state was longer than one hour, it had to be input into the FRS system as a separate incident for each additional one-hour-block time incurred. Thus, if the line was down for 2-1/2 hours, the FRS system would show there were 3 incidents, two one hour long and one half an hour long. Incident reports at the FRS system were misleading.

In practice, handwritten or manual input data records are rarely reliable. This is because whenever a major breakdown or minor stoppage occurs, the first thing the operator or supervisor does is fix it. Recording it is secondary. As a result, from one-third to one-half of the stoppages go unrecorded. Typically, the supervisor in charge of the recording process will estimate that about one-third of the minor stoppages were not recorded. Often, however, when an automated counter is later introduced, the worker is surprised to find out that about 70 percent of the minor stoppages had actually been omitted.[15]

The FRS system's reporting options were very limited and did not offer a great deal of useful information to the supervisors on the floor concerning operating trends. Basically, the system was a database with limited ability to aggregate data across different time periods and shifts. The system also lacked any type of graphic interface. It did not allow a deductive process for detecting bottlenecks. The process in turn, had to be inductive, meaning that you actually needed to have a certain hypothesis and then use the data to prove it or discard it.

One approach suggested and partially developed by Vehicle Operations was to identify the bottleneck without resorting to an analytical tool and to compute an average production capacity for each major line in the operation. This average production capacity is called the standalone throughput. This measure isolates the system's throughput from upstream and downstream systems by removing starved and blocked, as well as down time, to give a fair representation of its throughput. The average standalone throughput (JPH) for each line within the Body Shop from 06/03/02 thru 10/28/02 is shown in Figure 8. It was calculated by averaging the JPH per hour recorded by the shift 2 line supervisors for each of the lines (Saturdays and Sundays were excluded).

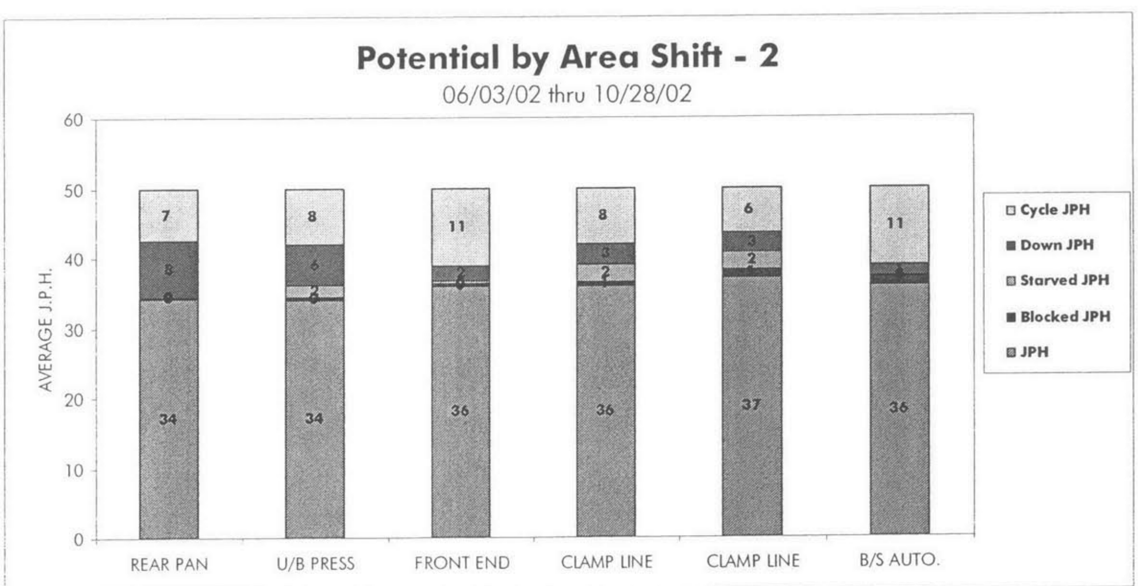

Figure 8. JPH Potential by Area (Shift - 2)

Besides showing the standalone throughput (JPH), Figure 8 shows an average of the down, blocked and starved states. These numbers were calculated by averaging the seconds per hour recorded by the supervisor in which the station was reported to be in any of the above mentioned states. Each of these averages was divided by 72 seconds (50 JPH goal). Thus, these averages translate into the equivalent JPH that was lost during that time state. In theory, if we were to set 50 JPH as the plant management's production goal, adding the standalone throughput to the equivalent JPH for each of the states (down, starved and blocked) should add up to 50 JPH. In reality, this did not add up to 50 JPH due to the lack of accuracy of the data. The difference between these two numbers was accounted as Cycle JPH, or in other words, the average time (expressed in JPH) that supervisors did not account for when logging in the information. It is basically unaccounted time. This cycle time can range anywhere from 12 % to 22% of the total time to be accounted for.

The standalone throughput for the Rear Pan and Underbody Lines are almost the same at 34 JPH. Front End and Clamp Line follow at 36 JPH. The basic difference between the Rear Pan and the Underbody Line is that Rear Pan has an average down time of 8 JPH per hour compared to 6 JPH per hour at the Underbody Line. For the Rear Pan Line this means that in average 17% of the time is down, being the highest among all the other lines. Additionally, the Underbody line is in average starved for 2 cycles per hour, while the Rear Pan Line shows almost no starvation time.

This chart can be taken as a confirmation that the Rear Pan Line is in fact the primary bottleneck. Attempting to identify the primary bottlenecks by comparing the standalone throughput of the operations is prone to failure because, in addition to the low reliability of the data, the comparison does not account for the interaction between the operations. The Underbody line is fed by the Center Pan, Front Structure and the Rear Pan Line. In this case, the downtime at any of these feeding stations causes the Underbody line to starve, but it is hard to predict what percentage of that starved time was actually caused by the downtime in the Rear Pan Line.

A second approach to analyzing the FRS system was to do a visual comparison of the daily production (shift 2 & 3) of rear pans versus the daily production of body-in-whites. Figure 9 show the results of such comparison. The visual analysis suggests that there is a trend showing that the daily production of the body-in-whites mimics the daily production of the rear pans. Nonetheless, there are some times where the rear pan production goes down and the overall BIW production remains at a constant level or actually goes up. Possible causes for such outcomes are that the chart does not take into account weekend production. The data collected during the weekend showed great variability and inconsistency thus, it was taken out of the study. On the other hand, the opposite happened as well, rear pan production goes up without actually increasing the daily production of BIW's, meaning that some other area different than the Rear Pan Line was working as the constraint at that specific time.

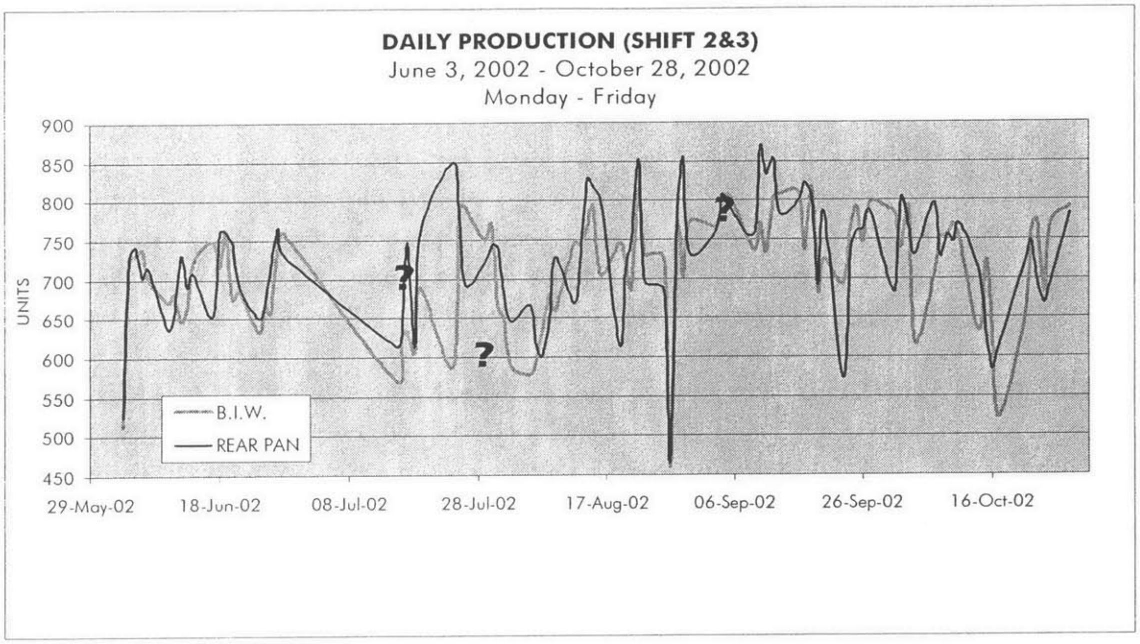

Figure 9. Rear Pan versus B.I.W. Daily Production (Shift 2 & 3)

This chart allows us to state the hypothesis that the Rear Pan Line does have some effect on the final production of the BIW's taking into account some time period exceptions. These exceptions can possibly prove that the Rear Pan Line is in fact the primary constraint but there are other areas that behave as secondary constraints during certain time periods.

5.1.4 Computer Simulation of Automated Flow Lines

Systems such as robot cells, flexible manufacturing systems or automated flow lines, are sometimes too complex to submit to analytic mathematical models. Computer simulation can be used to assess the performance of these complex production systems and to identify their design flaws and operating problems.[16]

Simulation modeling tools can be divided into two categories: (1) simulation languages (e.g. Slam II, S iman, C ML), and s ystem s imulators (such a s e.g. S IMUL8, S imFactory, S imView, Seewhy, Witness, Arena). Simulation languages tend to be flexible and powerful tools, sometimes linked with animation. System simulators tend to be object-oriented/menu-driven. System simulators are easier to master and are user-friendly. Additionally, the implementation of graphics and animation that permits the user to visualize more clearly the operation of the flow line (or other system), as well as built-in statistics' analysis makes them very powerful tools.[17]

Within system simulators, certain types of model classifications have developed. One of these is "continuous versus discrete." A continuous model treats change like a continuously occurring phenomenon, while a discrete model describes changes in the status of the system as occurring only at isolated points in time.[18] A second classification of simulation models is whether a particular model is static or dynamic. A static model portrays the behavior of a system at a single point in time (e.g., end of year profits), whereas a dynamic model describes the behavior of a system throughout time.

The modeling work done for this project were discrete-event type simulation models using SIMUL8 system simulator and contained some static calculations (e.g. JPH per line) and some dynamic ones too (e.g. percentage of station's starved time throughout the simulation).

The benefits of using a system simulator tool are:

- Identification of system bottlenecks is inaccurate based on individual workstation performance (quality rate, availability, etc.) or by analyzing the system based on a one day data point. System simulators provide an approximation by allowing a fast long-term analysis.
- Helps to focus design, production and maintenance activities on those areas that improve throughput most. Thus, indirectly promotes teamwork by making improvements visible.

- Ability to measure effectiveness of process improvement activities and perform "what-if" analyses.
- System simulators allow for the evaluation of several parameters and capture the complex interactions between workstations resulting from blocking and starving.
- Ability to incorporate stochastic distributions of events.

Simulation models do have their drawbacks. Lead times for developing a large, complex simulation can be over 2-3 months or more. Packages such as SIMUL8 require much time to learn before useful models can be developed. Many times, due to the pace of change in plans for a plant and the time required to create a model, when finally completed, does not answer the questions that the planners want to ask. A model can be difficult to update and maintain if the plant is undergoing a fast pace of change. Much of the modeling work was usually done by off-site people. This distance can make the creation of a useful simulation less probable and maintenance of the model, once developed, very improbable. Besides, if recommendations made by the simulation developer are not generated and evaluated for its feasibility along with the plant management, the recommendations for throughput improvements might not be suited to the specific plant conditions or requirements.

The first step to developing the V.O. Body Shop simulation was to obtain cycle times, MTBF's and MTTR's of all the Body Shop stations. The data was obtained through the downtime study performed at the Body Shop. Transfer times between stations and Min/Max buffer quantities between them had to be physically recorded by myself since Industrial Engineering did not have the data available. This data was input into an excel spreadsheet. SIMUL8 imports the data from the spreadsheet and uses it to "warm-up" the simulation by running it for the equivalent of 5 working days (two 10-hour shifts per day). This allows the simulation to achieve its steady operating state. After the "warm-up" period, the simulation is run for an equivalent of 60 working days. The results of the simulation are exported back to the spreadsheet and the output data is inserted in a value stream map format showing the following data per station: min., net and max. JPH, MTBF, MTTR, availability, OEE, percentage of time blocked, down and starved. Figure 10 shows a diagram of the process just described above.

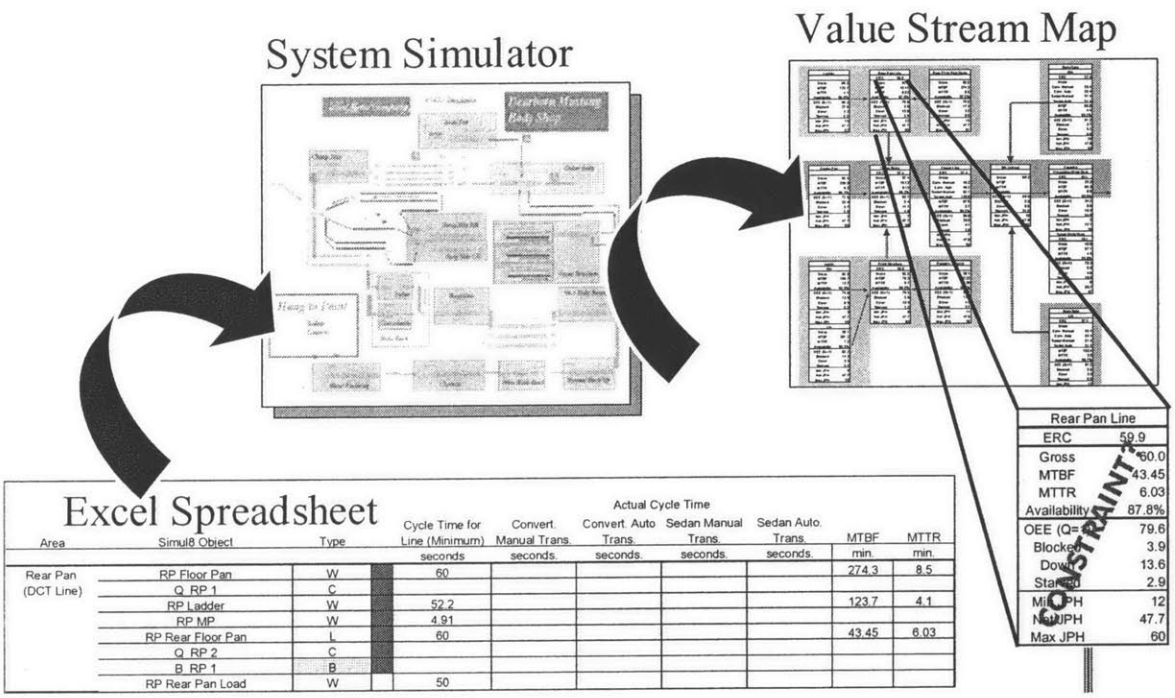

Figure 10. Inputs and Outputs of the System Simulator Using a Spreadsheet Interface

As stated, the real value of the system simulators is to explore "what if" scenarios. Once the simulation was in place, a road map for productivity improvement was developed. The road map proposed a series of steps to increase the plant's throughput 20%. In order to ensure confidentiality, the steps are not listed. The first five recommended improvements were in the Front Structure, Rear Pan and Underbody lines by first suggesting gross cycle time reductions and then improving availability and reducing repair time.

For the project's scope, the main purpose of this exercise was to detect the area with the most potential for improvement, thus the primary system bottleneck. The most important fact realized out of it was that three out of the seven recommended steps dealt with improvements needed at the Rear Pan Line. The throughput improvement roadmap required a larger number of improvements in the Rear Pan Line than in any other of the lines.

5.2 Rear Pan Production Level

The analysis of the FRS data along with the results from the computer simulation allowed us to be at a point that we could make a good hypothesis that the Rear Pan Lines was in fact the primary system constraint at the DAP Body Shop. Because of the lack of accurate data and diagnose time, the project focused on the Rear Pan Line under the premise that it is better to be "almost right than exactly wrong".

5.2.1 Factory Reporting System (FRS) Data

Even though not totally accurate, FRS data once again proved to be useful for calculating and comparing Rear Pan's 10-day moving average JPH and its variability among shifts (weekend days were not considered for the reasons already stated). Figure 11 shows the comparison.

As DAP had two 10-hour work shifts, it made sense to make a comparison of 1st and 2nd shift to note any differences (shift 2 and 3 were the day and the night shift respectively). The variability of the 10 day moving average is reflected as a computed standard deviation per shift of the hourly production for the last 10 days at any point in the chart. This variability is multiplied by 3 deviations and subtracted from the moving average just to have an idea of its confidence interval.

We need to be aware that whenever the hourly production was higher than 50 JPH, the line supervisor would only report 50 jobs. Any excess production would be "saved" and added to the next closest production hour with a production lesser than 50 JPH. This is the reason that adding up the 3 standard deviations to the moving average does not make any sense.

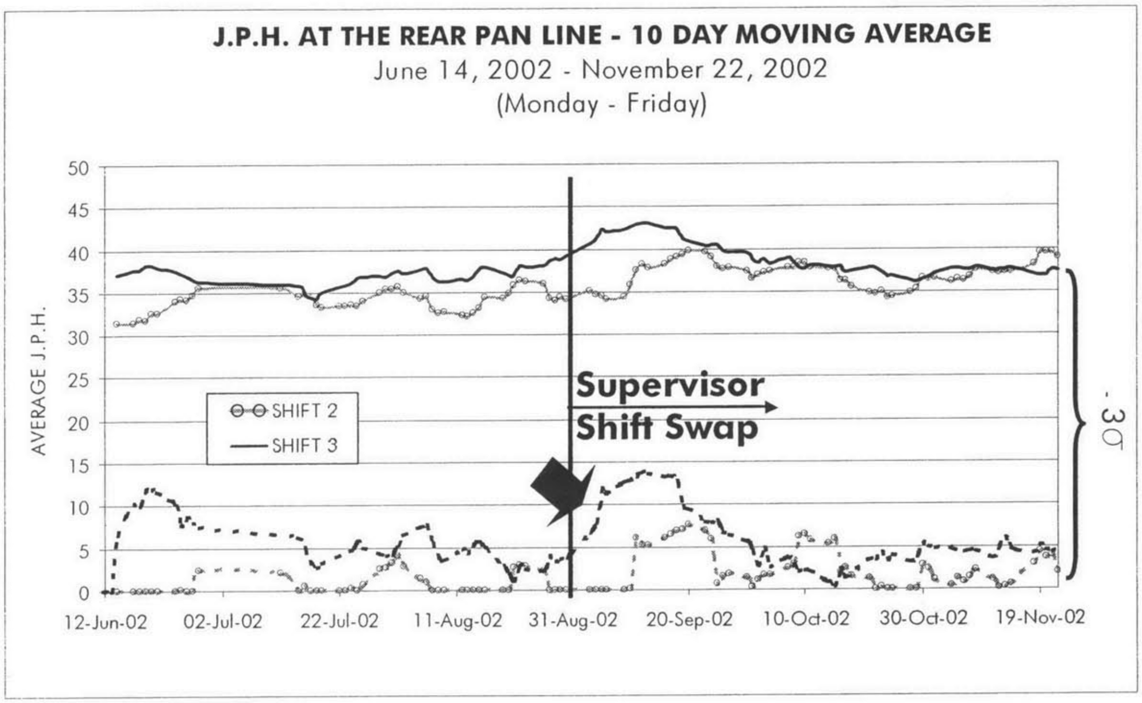

Figure 11. Comparison Between Shifts for the Rear Pan Line's 10-day Moving Average JPH and its Variability

Based on Figure 11 we can notice that up to the end of September, the night shift seemed to always over-perform the day shift. After that period of time, this conclusion does not seem so obvious. Before the end of September, not only did the moving average for shift 3 stayed above the day shifts but also the variability of the production was less as well thus, the probability of not having produced a single part during an hour period was smaller than during the day shift. In fact, the lower limit of the night's shift confidence interval for JPH hits the zero lower limit for the first and only time during mid-October. These differences suggest a possible people issue.

One hypothesis learned from maintenance skill trades for such lower production variability in the night shift is that line operators during the night shift do not rely as much on maintenance skill trades to do quick repairs to the machines when they know how to do them. Night shift employees are more proactive at solving their minor stoppages. Even though the plant had a decentralized maintenance team in place near the Rear Pan Line and their time to respond to a stoppage was fast, there would always be a faster response time by the night shift employees especially if most of the line faults were repetitive minor stoppages quickly fixed by the operators.

Another observation out of such chart is that in general, throughout the time observed, there is no sign of constant and sustainable improvement efforts in the time period observed. Not taking into account the month of September 2002, the JPH moving average seems to be around 35-40 JPH. The importance of such observation is that the lack of information that would enable management to track the performance of the line might make them think that the performance is actually going up while in reality it is not. In reality, it just keeps going up and down in cycles.

September's data, in contrast to all the rest of the period is very interesting. During the month of September, DAP achieved record production levels. If we take a look back at Figure 9 we will notice that during this month, record production levels of rear pans and BIWs were achieved. The 10-day Rear Pan Line production moving average went up to 43 JPH for the first time in the period. At that point in time everything seemed to be just getting better. Unfortunately, things got back to normal during the month of October. Something worth noticing during the month of September is that the standard deviation of the production for the night shift was the lowest ever from July 2, 2002 - November 22, 2002. A standard deviation of 9 for 8 consecutive days versus an standard deviation of 11 for the remaining days in the period is an explaining factor of the better throughput achieved. Faster response time to stoppage seems in fact to be a very effective way to achieve the target throughput. Faster response time to failure as well as better machine performance during the month of September are definitely two hypothesis to consider when analyzing the information.

5.2.2 Man/Machine Mapping

The man/machine mapping procedure, one of the Lean Manufacturing tools, was used to create a graphical representation of the Rear Pan Line system timing. The map enables one to see the effect of the interrelationship of the manual load cells (Ladder Area) on the average cycle time of the Rear Pan Line. By creating a man/machine time map, the analyst develops an intuitive understanding of the system dynamics and is able to separate the people and process issues.

A sample man/machine map is shown in Figure 12 in next page. The map was developed for the Ladder and Automatic Areas only since the throughput of the Skin Area and its availability seemed to be superior than the first two mentioned areas. The timing for both stations was taken by videotaping all the operations for at least 5 cycles, prior authorization of the operators where manual load was involved. When manual load operations were involved, man/machine charts using the longest, average and fastest times were developed. The reason was that by averaging we would loose some important information for the analysis of the map. Some of the conclusions after developing the map are:

- Management's perception that Automatic Stations 1 & 2 were the Rear Pan Line system's CCR disagree with the results obtained. The map shows Station 10 has the longest cycle time at 67

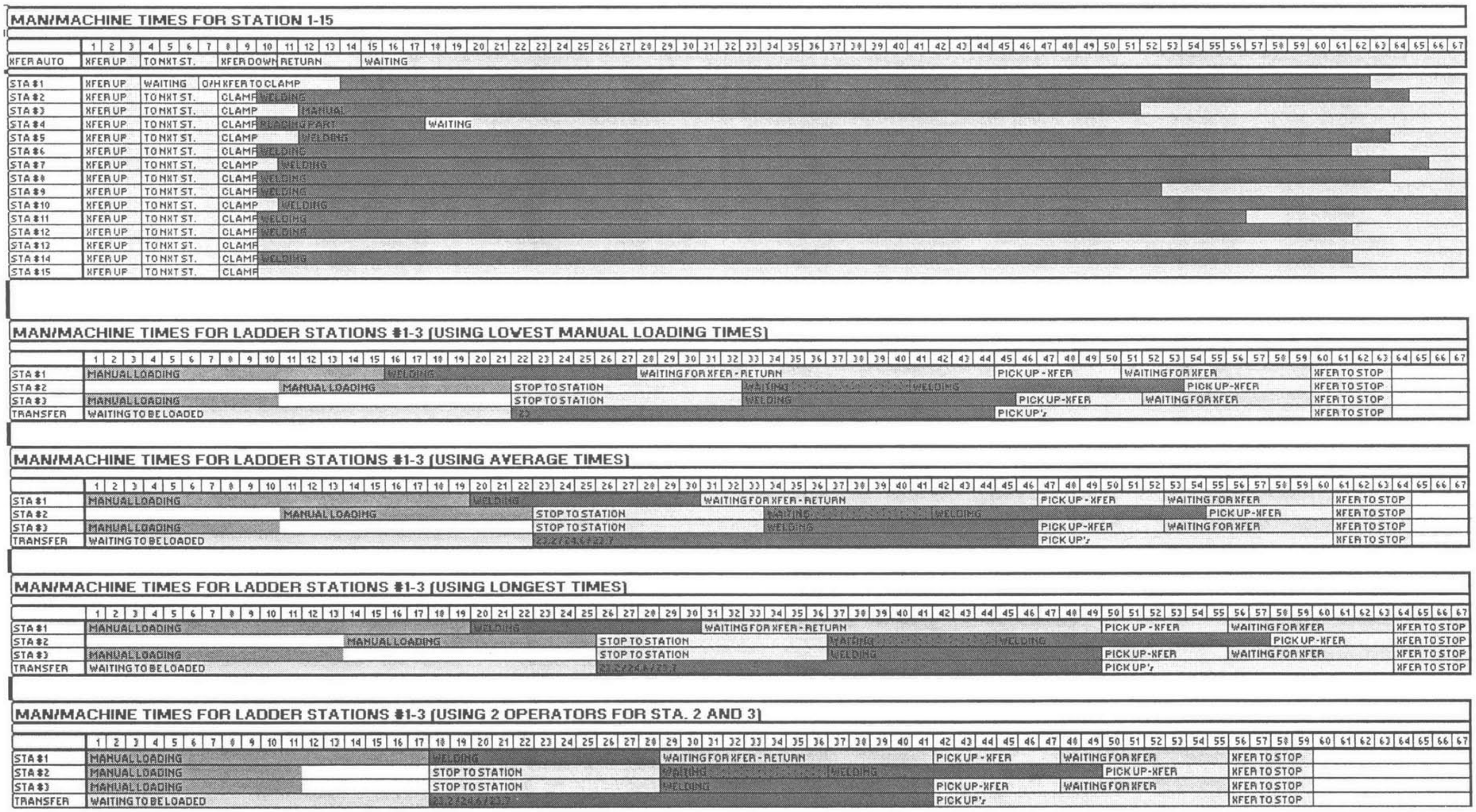

Figure 12. Man/Machine Map for the Rear Pan Line (Ladder and Automatic Areas)

seconds. This cycle time is five and three seconds longer than the ones for Station 1 and 2. Nonetheless, there is the possibility that due to reliability issues, stations 1 and 2 go down so often that they actually become bottleneck at certain points in time. Unfortunately, as already experienced when developing the constraint analysis for the whole Body Shop, such dynamic interactions can only be studied either by long periods of observation and proper data logging and analysis and/or by using analytical tools such as the system simulators.

- The three stations on each side of the Ladder Area were actually loaded by only two operators (one of the operators loads Station 2 and 3). A great variability on the load time was found depending on the operator's experience. When experienced operators were loading the stations, total cycle time would be 63 seconds while, if the operators were rookies or filling up the position for someone else, cycle time could be as long as 67 seconds. This longer cycle time is similar to the 67 second cycle time of Automatic Station 10. Thus, if inexperienced operators are loading the line, the primary constraint (Station 10) can become subordinated to the Ladder Area performance, and thus, becoming a temporary constraint.
- Several years ago there was an initiative at the Ladder Area to reduce from three to two operators on each side. Some time after, the overhead transportation system was overhauled and an eight second delay in station 2 had to be programmed before the welding cycle could actually start. The need for an additional operator was never re-evaluated as the working conditions changed. Based on the man/machine map, we can conclude that by adding an additional operator per side, the total cycle time for the Rear Pan Line can actually be reduced to 60 seconds. As already mentioned, this might

not be necessary to do since Automatic Station 10's cycle time is 72 seconds. Nonetheless, when filling up for one of these positions with a rookie, the supervisor should consider using 3 operators per side instead of 2 in order to avoid the risk of turning this area into a potential constraint for the Rear Pan Line.

- Industrial Engineering's Modular Arrangement of Predetermined Time Standards (MODAPTS) study showed manual cycle times of 16 and 17.93 seconds for the right hand and left hand Ladder Station 1 operations. It also showed manual cycle times of 17.93 and 16.90 seconds for the right hand and left hand Stations 2 and 3. This last calculation did not reflect the new standard practice and needs to be updated since the operation was actually taking from 21-25 seconds. In general, all the MODAPTS time studies had to be updated for the Ladder line since all showed total cycles times below 50 seconds while actually they were 63-67 seconds.

The most important take away from this exercise was to experience that, in order to obtain the data for this little station within the Body Shop, it took almost five days of effort from a single person just to provide, at the end of a day, a snap-shot of the operation, which was already five days old. In fact, the data collection takes so long that there is the risk that maintenance trades re-program cycle times in the mean time and by the time the map is made, the data is already obsolete. The quest for a way to collect the data in a more reliable and efficient way started.

5.2.3 Computer Simulation

The most difficult step about developing a constraint analysis tool for the Rear Pan Line was accumulating accurate data, other than the information available from the FRS system, to be fed into it. Besides not being reliable, the data required for this study required a greater amount of detailed information per station within the Rear Pan Line This information was not being manually logged neither by the supervisors nor the maintenance skill trades. In contrast to the development of the Body Shop's simulation, now there was not a crew of manual data loggers to help determine MTBFs, MTTRs, cycle times and transfer times. TOC builds on data requirements and does not require extreme data accuracy except at points feeding the CCR resource.[19,20] Nonetheless, the CCR and its feeder data must be accurate, or TOC will not work at its best.[10]

The Rear Pan Line had a real time, web-deployed, machine monitoring system that was not being used. I will discuss more about this system in Chapter 6 but, setting it up to obtain the necessary data seemed to be the best solution to not only get a single snap-shot in time of the Rear Pan Line performance but actually be able to obtain a snap-shot at any point in time required. Even though the resources for finishing the set-up of the Visualplant™ software were not released during the course of the project thus, no data was available to be fed to the computer simulation, a template for the Rear Pan Line simulation was programmed by myself in the SIMUL8 software. Figure 13 shows the simulation template developed.

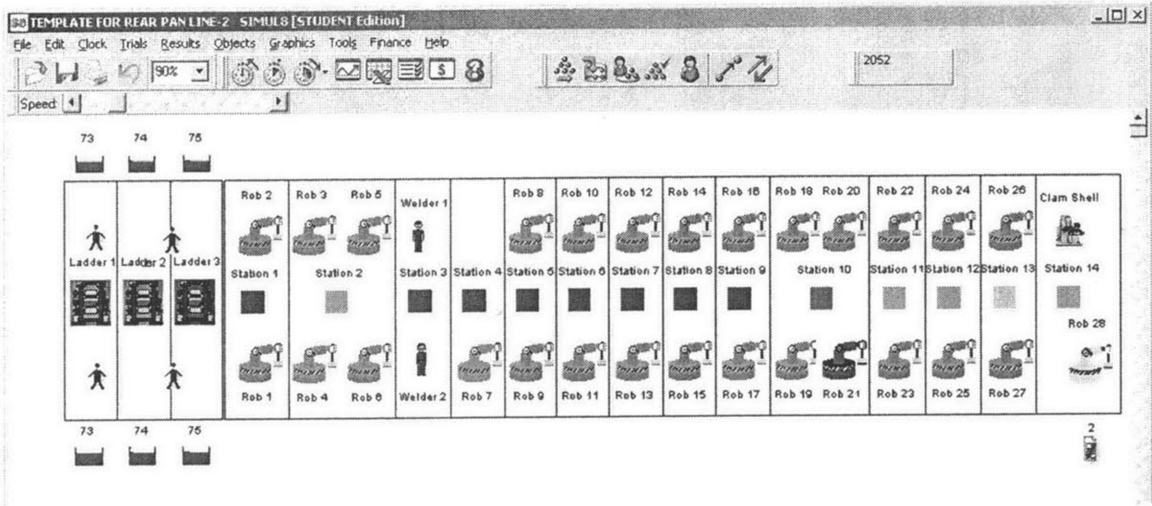

Figure 13. Computer Simulation Template for the Rear Pan Line

In the simulation template, MTBFs, MTTRs and cycle times can be changed per station in the Ladder Area and per robot in the Automatic Area in order to analyze "what if" scenarios. In the Automatic Stations, if at least one of the two or four robots in a station goes down, the whole station goes down until the robot(s) are repaired. The square boxes in between the robots show the station's state: green for working, yellow for waiting, blue for down and red for blocked. At last, operators are assigned to the manual load/weld stations so that the operation in the station cannot be performed if the operator is not available by the machine at the required time. After having input the cycle times per station and arbitrary MTBF's and MTTR's, the simulation delivers the JPH achieved as well as a TimeView report (Figure 14) where the user can relate and track the percentage of the time that a single station was at a certain state during the simulated time period.

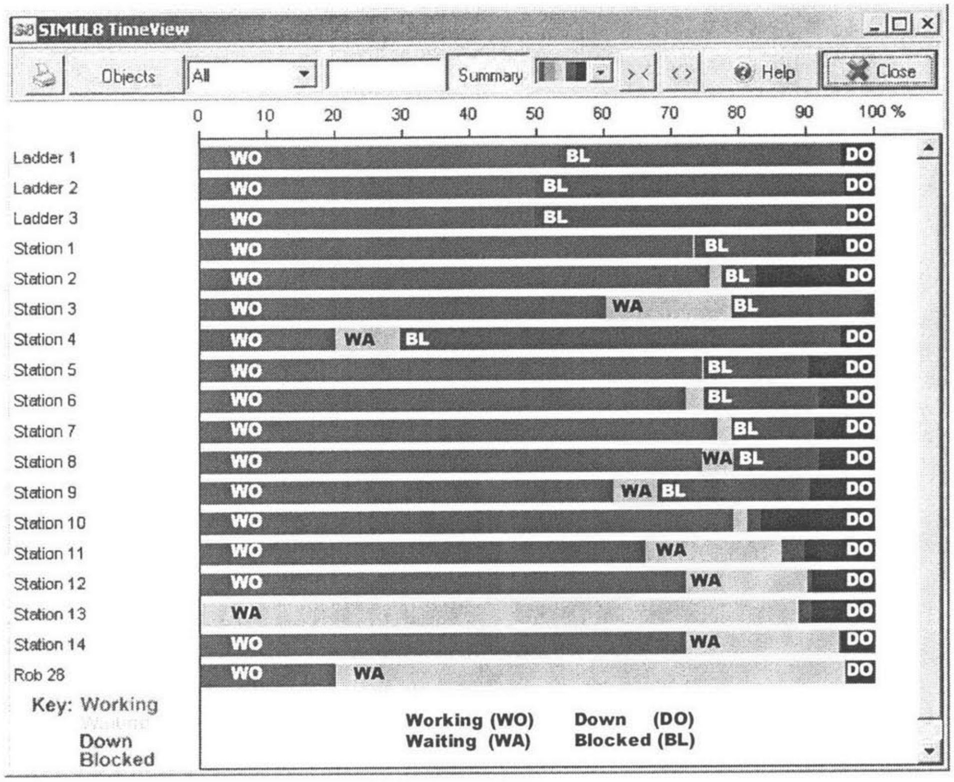

Figure 14. TimeView Report for the Rear Pan Line Simulation

The bar's length is representative of the percentage of time spent in each of the states. In this case, the results are consistent with the data obtained with the man/machine map. Upstream Automatic Station 10, there is a great amount of blocked time while downstream there is almost no blockage. Real accurate data needs to be calculated in order to obtain an accurate result but even by making some assumptions, key learnings from the exercise can be mined. For instance, even when the same MTBFs and MTTRs were assumed for all robots in the Automatic Area, it is noticeable that Automatic Stations 2 and 10 have the most percentage of downtime. The overall reliability rate of those stations is the product of all the reliability rates for each individual machine. Thus, stations 2 and 10, the only two stations with 4 robots have a greater risk of having an overall reliability rate lower than the other stations. Thus, a great deal of attention should be paid to station 10. Besides having the longest cycle time, it also has the potential to have one of the highest chances of being down.

5.3 Summary

Using as much of the information available, several attempts were made to validate the Rear Pan Line as the primary constraint at the Body Shop Level. Similar and new tools were also applied to analyze the Rear Pan Line once this was defined as the system's constraint.

Pros and cons of some of these tools were listed. In general, the tools proved to be very powerful to detect throughput improvements. Nonetheless, we need to be aware of the low reliability of the input data and remember the old saying: "garbage in, garbage out". In order to guarantee sound improvement decisions we need to strive for reliable data.

In the next chapter I will stress the necessity of data driven actions and propose a template on how an on-line monitoring system can be set up to obtain the necessary data.

Chapter 6: Data Driven actions

The shift of the auto industry to raise its automation and high technology systems has increased the complexity of managing a Body Shop. While the implementation of technology has allowed for higher quality and increased consistency, thereby dealing with the old management issues, the technology has also created greater need for information to manage the systems. In order to be effective at improving operations, new throughput tools and different skills that allow data collection and analysis have become a necessity. The old adage, "if you can't measure it, you can't manage it" is particularly relevant. Decreasing time-to-market can only happen in an environment that provides employees with all of the right information they require to make the best possible, fact-based decisions.

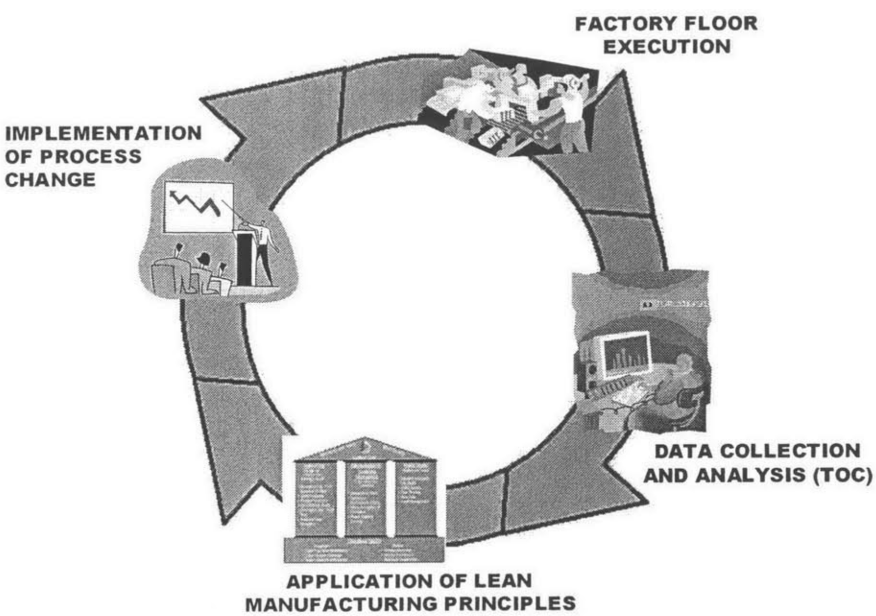

Figure 15. Lean Improvement Cycle Improved by Industrial Information Technology

Shown above in Figure 15 is the standard lean cycle implemented by Boeing. At the top of the cycle is factory floor execution in steady state. Boeing's process engineers collect and analyze data from the shop floor to identify areas of improvement. With this data, they will apply traditional lean principles to redesign select processes. Finally, they will implement that process change, including shared learning techniques. To drive the cycle more efficiently, industrial information technology solutions can be used to measure and analyze factory performance.

While many of these activities appear to be logical strategies to implement, information technology manufacturing projects are often difficult for companies to justify. A significant challenge is that return on investment for these types of implementations can be poorly defined because they typically do not have concrete start and stop dates.* In addition, it is hard to come up with throughput improvement forecasts since most of these systems are people-enablers. They will help the people do their regular job more productive but it is hard to forecast how much beforehand.

Knowing real time asset utilization/capacity, focusing on the major sources of downtime in the plant, identifying and removing constraints and improving product quality are some of the challenges that leave most manufacturing plants still in need of a solution. At the heart of this issue is the absolute necessity not only of collecting the appropriate data, but also of collecting it in a consistent, meaningful context across the plant and throughout the enterprise. Only then can accurate, relevant data be disseminated to, and analyzed by

* *De Jesus, Rafael,. Determining the Value of eManufacturing. (White paper at ABB, 2001).*

the various disciplines within the enterprise. Decisions need to be based upon facts, not upon a combination of gut-feel and outdated and unreliable reports.

6.1 On-line Monitoring System

There has been no shortage of data collection in the past decade. As the phrase 'Islands of Automation' became a familiar one in the early 90's, control system suppliers responded by developing Programmable Logic Controllers (PLCs) that were easily networked. This created the basic infrastructure required to do peer-to-peer communications, remote programming and programmable device support, effectively networking the plant floor for the first time. At the same time, more and more Human Machine Interface (HMI) products were introduced to the market place, with the promise of seeing plant floor data anywhere at any time.

While HMIs have played a significant role in providing a window into the plant floor, the reality is that they were designed as large, monolithic applications to collect and display real time data at the machine or cell level. They keep virtually no historical record of the data they were displaying, and they were not designed to work at the plant/enterprise level. The end result in a typical plant were scores of custom databases scattered throughout the facility – largely inaccessible and, for the most part, meaningless in terms of plant-wide data visibility and analysis.*

* Dyck, John, What is Manufacturing Intelligence? (accessed March 18, 2003); available from http://www.visualplant.com/

The Ford Motor Company has been aware of these issues but in the past has experienced rising costs for internal development of these information technology tools. Ford's new strategy is to utilize Executive Manufacturing Technologies' (EMT) VisualPlant™ software, an off-the-shelf commercial monitoring application, as their standard for their Next Generation Monitoring Systems. In fact, EMT is one out of 20 companies in which Ford Venture Capital Group has invested.[*] Its plan, by choosing an off-the-shelf package, is to leverage the development costs among the other players in and out of the auto industry.

In the auto industry, VisualPlant™, is now installed at five of the six largest automakers with in the world (assembly, powertrain, stamping, and component plants). It is connected to over 12,000 plant floor machines at over 20 original equipment manufacturer (OEM) facilities in the U.S. and Canada.[**]

VisualPlant™ integrates, visualizes, reports and generates user-defined key performance metrics on real-time, historical and calculated data collected from the entire plant and delivers it to plant managers in a web-browser.

6.1.1 Current State

The monitoring process of VisualPlant™ is driven by Programmable Logic Controllers (PLCs) that control the Body Shop production equipment. The PLCs run off PLC code or ladder logic, which is basically Boolean logic. The PLC receives inputs (I/O bits), runs

* *(accessed March 18, 2003); available from http://www.visualplant.com/*

** *Dyck, John, VisualPlant now installed at five of the Big 6 auto makers in North America, December 16, 2002 (accessed March 18, 2003); available from http://www.visualplant.com/*

them through its ladder logic, and then sends outputs (I/O bits). PLC logic is also written for activities such as process monitoring. Code is written to allow the equipment to monitor for line states: in Maintenance, Automatic, Faulted, Bypass, Blocked, Starved and Overcycle, among others. In the ladder logic, a state will be present when the I/O bit is on. Visualplant™ basically maps the bits out of the PLC codes once these are linked through an interface.

In August, 2000, Ford Motor Company made its second purchase of the Visualplant™ for DAP Body Shop along with a two-year maintenance contract through a third party system integrator, JMP Engineering, who was also responsible for the system's installation. At that time, downtime at automotive manufacturing plants was estimated to cost as much as $6,000 to $8,000 a minute.[*] VisualPlant™ was linked to the PLCs of the Rear Pan Line and programmed to monitor for each station: time in auto/manual, fault codes, rejected parts and production count. No state monitoring was programmed.

After making the proper mapping of the PLC bits, the system integrators delivered the system to the Body Shop's Manufacturing Engineering (M.E.) Manager. The data collected never seemed to be right but due to the limited time of the M.E. Manager to validate the information collected, a very time consuming activity, the system never proved to be reliable. The data collected became more inaccurate as time went by and maintenance skill trades would make changes to the PLC ladder logic without properly

[*] *Ford Buys VisualPlant™ for Dearborn Assembly, New Orleans, LA. August 21, 2000 (accessed March 18, 2003); available from Society of Manufacturing Engineers.*

linking the changes to the Visualplant^{TM} mapping. After two years, all of the information monitored, besides good parts count, was erroneous and not comprehensive.

6.1.2 Proposed State

In order to be in a position to collect real-time reliable data, debugging old and poorly documented PLC code, re-mapping the PLC fault bits, making assumptions to determine machine states and validating the collected information was required. This involved a significant amount of time. The only resources allocated to the project was a balance that remained from the 2 year maintenance contract originally bought with the VisualPlant^{TM} package. The funds were enough to set-up only the Skin Area under the proposed state, an area which was probably as complex to set up as the Ladder Area but simpler than the Automatic Area. The streamlined process monitoring data for the Skin Area was validated along with the operators to make sure the right bits were being monitored out of the PLC logic.

Based on this proposal, VisualPlant^{TM} would not only be monitoring the data for which it was programmed initially but also its state. This would allow the user to develop TimeView type charts, similar to the ones generated by the computer simulation software (Figure 14). The most expensive and time consuming approach to monitor the states of each area was to program the states in each area's PLC code. Nonetheless, since resources were limited, states were determined by monitoring several bits that were used for process monitoring and using Boolean logic within VisualPlant^{TM} to determine the state of the area. Figure 16 shows a schematic of the different assumptions made in order to determine the state of the Ladder, Skin and Automatic Areas. By determining Blocked

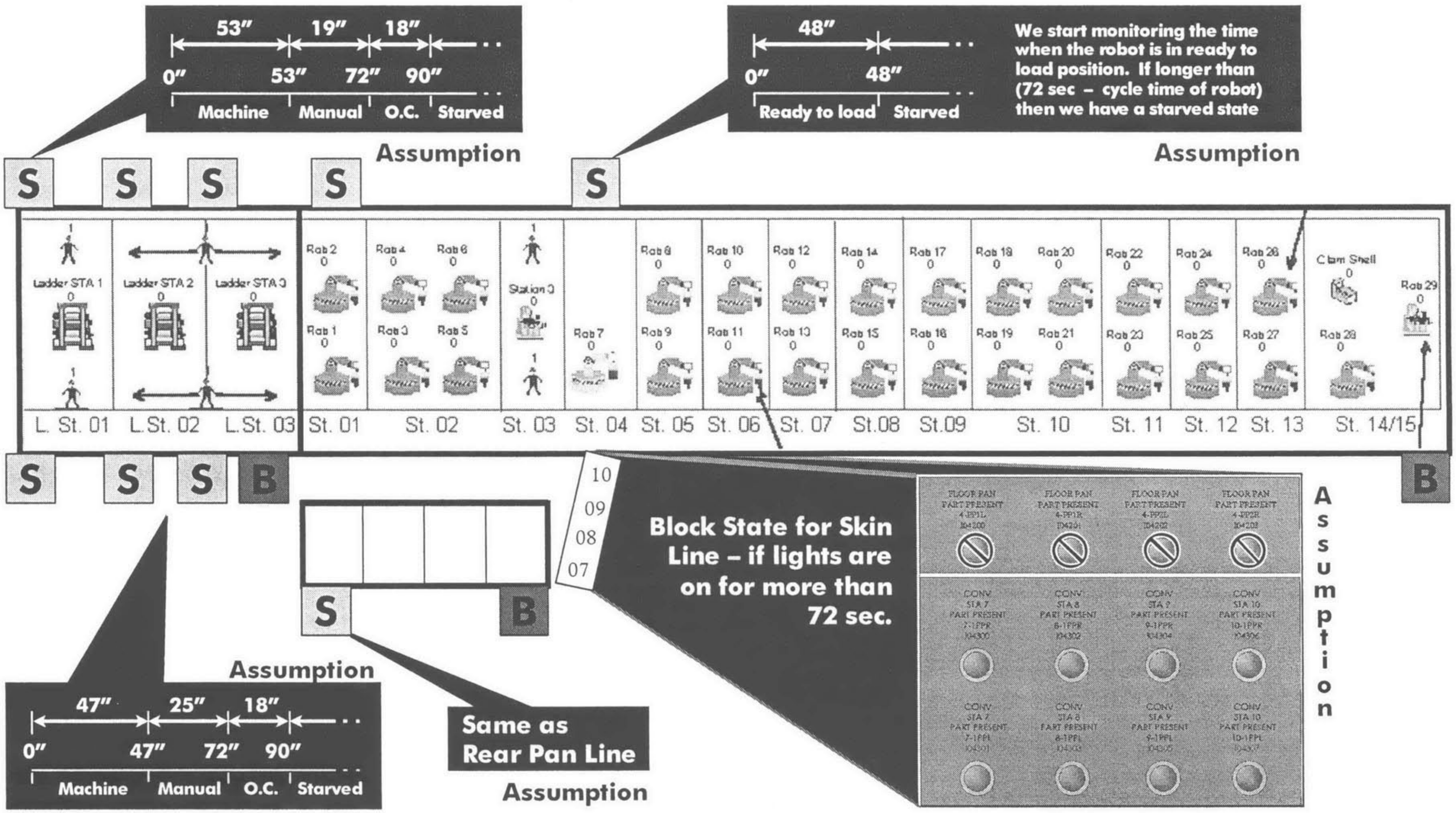

Figure 16. Assumptions to Determine the State of the Ladder, Skin and Automatic Areas

and Starved states at the start or interfaces of the areas, we would be able to determine which area was behaving as the primary constraint during a defined period of time.

The following screen shots are examples of different types of "window views" used to analyze plant floor data under the proposed state. Figure 17 shows a real-time and historical charting/trending environment with sophisticated analysis tools to identify concerns quickly. In addition to trending process variables, you can trend counters, timers and even calculations.

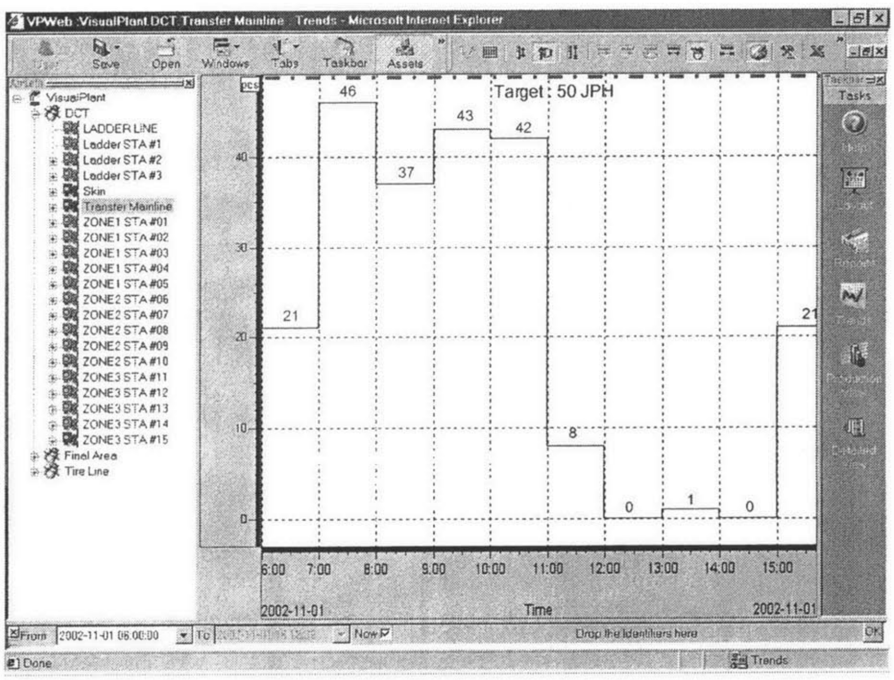

Figure 17. VisualPlant™ Trends Window

Figure 18 shows a numerical, spreadsheet-like environment with rows of data items from the plant, organized in columns of the user's choice – such as time (minutes, hours, shifts, shift periods). Data can be exported to any Microsoft documents with the ease of a click. Microsoft documents can also be accessed and launched within the VisualPlant™ application.

DISCLAIMER

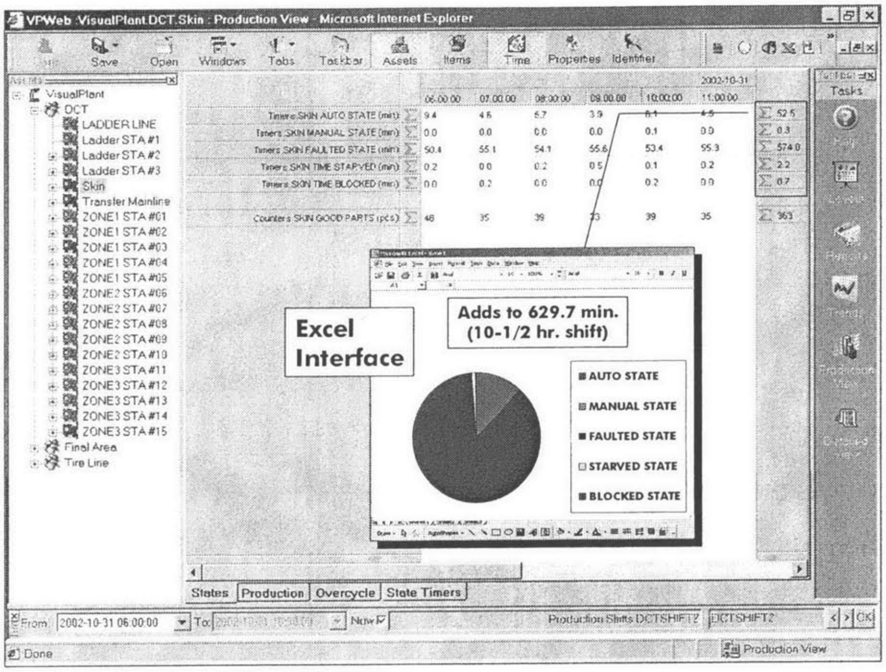

Figure 18. VisualPlant™ Production View Window

The Detailed View (Figure 19) provides a holistic view of the plant floor, including simple ways to monitor machine downtime, i.e.: by fault and/or duration.

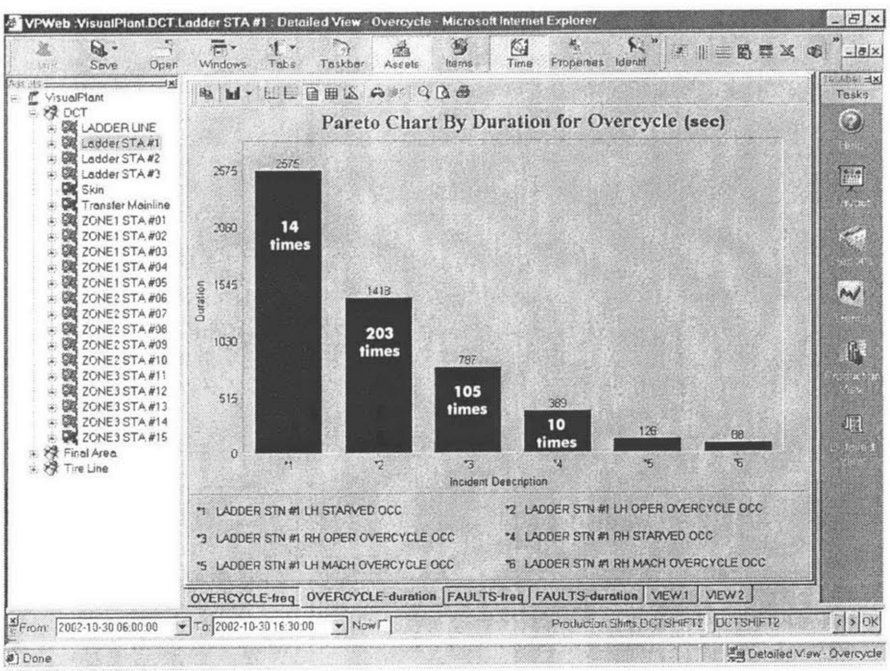

Figure 19. VisualPlant™ Detailed View Window

6.2 Summary

As the auto industry raises its automation and high technology systems, the complexity for applications to aid in collecting accurate and on-time information to allow data driven actions is increasing as well. Being able to link and analyze as a whole all the independent 'Islands of Automation' within a system has become a challenge for the manufacturing companies of the future.

Web deployed on-line monitoring systems such as VisualPlant™ appear as the total solution to the problem. The template suggested for the Rear Pan Line gives us an idea of how powerful these applications are. Unfortunately, on-line monitoring systems are still 'too good to be true' and depend on heavy validation and maintenance procedures. If performed accordingly though, the systems are indeed a great tool for the next generation manufacturing systems.

Chapter 7: Conclusions and Recommendations

This thesis attempted to start with a foundation of TOC and Lean Manufacturing knowledge and discover some of the synergies between the two by working on a throughput improvement project in an automotive assembly plant. Increasing the throughput of a production system is challenging. This challenge arises in part because of 1) complex and subtle interactions that exist among workstations, and 2) lack of timely and accurate data.

In order to be effective in firefighting and continuous improvement arenas, activities need to be data driven. In this way we can move from a reactive mode to a proactive mode. The research effort shows that such a process can be successful, but is largely dependent on 1) developing a model which accurately depicts the shop floor environment, 2) quality data to be used in the models and reports, 3) teamwork and involvement of the people in the process and, 4) a high level of management support

Starting at a plant level, DAP's Body Shop was identified as the macro-level bottleneck. With the use of data from downtime studies and computer simulations, a throughput improvement road map for the Body Shop was developed. The Rear Pan Line showed the highest need of improvement. Data collected hourly by the line supervisor helped determine the Rear Pan Line as the primary bottleneck. The use of man/machine maps and FRS data led to the location of the potential constraining operations within the bottleneck. Trying to obtain data to set up a computer simulation for the Rear Pan Line was difficult. None of the bottleneck identification methods actually tells how to fix a station that is a bottleneck. Root-cause analysis is required to suggest appropriate countermeasures.

Since lack of data kept appearing as a consistent problem throughout the project, part of the project's effort was to set-up a template of how an on-line monitoring system could work at the Rear Pan Line to later be used by other areas.

For the first 4 months of the project, management support for the on-line monitoring system came from the DAP's Body Shop M.E. Manager. He performed as the heavyweight process champion by reducing barriers to process implementation and having enough authority to ensure that resources were dedicated to the project. A reorganization moved him out and another manager in. Even though the new manager seemed to be supportive of the initiative, he was going through the learning curve of managing the Body Shop and did not provide the same level of support to facilitate implementation during the internship time period. Furthermore, recent reorganizations which reduced the size of the departments without reducing the workload, left many, especially maintenance skill trades, feeling overworked and with little time to devote to a new project. Most of the skill trades went to their supervisors for an indication of how much time they should devote to this project.

Taking these experiences into account, if given the opportunity to do it all over again, there would be more upfront work in obtaining the buy-in of upper management. Either, drawing upon success stories of similar systems or, being able to see such a system in place and talking with those who have realized some of the advantages, can achieve this. The actual implementation of such a system, however, would require significant work in obtaining buy-in and infusing the ideas from the workforce who would be the actual users of the system. By incorporating their ideas early in the process, it is more likely that they would take ownership of the process, which would improve chances for success.

7.1 Operational Level

Since most of the project was done at the operational level, most of the recommendations concern the operational domain. Following is a list of recommendations:

- **Set Up VisualPlant™ to monitor Rear Pan Line's performance**. Positive outcomes of having a structured, data–based bottleneck identification process have been covered in the last chapters. An additional benefit for the working team is to learn about and improve the process itself. The results of throughput improvement activities can be compared to the predicted results and differences are subject to further research.

- **Revise MODAPTS calculations for the manual load at the Rear Pan Line.** By performing the calculation, Industrial Engineering will realize the need to either cover an experienced operator loading Ladder Station 2 and 3 with another experienced operator or with 2 rookies. Failing to do so means the possibility of turning this area into the constraint within the Rear Pan Line. Plant's throughput has the risk of being affected in this case.

- **Required performance of each machine should be defined and established at a plant and floor level.** Contrary to management's belief that operators know exactly what they need to do and are just thinking about ways to break the system, my belief is that there is lack of knowledge in the floor regarding the performance required from each piece of equipment. As a result, the cycle times drift out of specification. To allow early detection of this condition, and to prevent loss of production, each operator should be responsible for tracking the cycle times of his/her machines.

  Vehicle Operations and plant management need to define the JPH target for every station and make it common knowledge to every one in the plant. Furthermore, line operators need assistance in their cycle time tracking by providing visible systems to warn them when they are running into the risk of being overcycled. An operator overcycle set of four lights, each one lighting up at 25%, 50%, 75% and 100% of the cycle is suggested. This allows the operator to adjust its speed while in cycle and to avoid the late warning when he/she is already overcycled. If this option is considered expensive due to the specific conditions of the plant, current cycle times and the specified cycle times should be clearly posted in each piece of equipment.

- **Heighten the awareness of bottlenecks and their direct impact on production.** Employees must understand the importance and impact of repairing workstations faster and preventing failures. This could be accomplished through training and by reviewing daily production measures that highlight the cause and effect relationships between key system variables (e.g., repair time and throughput). Inventories of commonly replaced parts should be stored next to the workstations to reduce repair time and facilitate preventative maintenance.

- **Revitalize FTPM.** This program will bring production to stability and allow for TOC and Lean initiatives to be implemented in an easier way. The use of system dynamics archetypes can help management recognize the long-term effects of certain policy decisions. DAP has currently been using two short-term solution policies in the Body Shop to attain the necessary throughput each day. By shifting their policies towards long-term solutions, they can ultimately solve their throughput issues and save overtime and inventory holding costs.

- **Implement Rear Pan Line throughput improvement roadmap.**
    - Reduce Automatic Station 10 cycle time from 67 sec. to 63 sec. by synchronizing robots or sending welds to other stations.
    - Bring the Ladder Area to an average cycle time of 60 sec. from a 64 sec. average cycle time. It is possible by adding one more operator per side.
    - Reduce Automatic Station 7 cycle time from 65 to 63 sec.
    - Re-balance all the welds in the Automatic Stations. Assuming they are perfectly balanced, Automatic Stations 1 and 2 can achieve 64 sec. cycle time (leaving Automatic Stations 3 and 4 for manual back up and unload skin) and Automatic Stations 5 thru 12 at an average cycle time of 63 sec. (leaving Automatic Station 13 idle, as a back up station).
    - Analyze the possibility of having an unload robot at Automatic Station 4 do a 2nd function and pick up some of the welds from the robots downstream.

7.2 Management Level

Management at DAP should be aware that, in order to become a data driven Enterprise, D.A.P. should:

- **Commit the necessary human and financial resources to the monitoring and simulation systems**. Not as an added activity for the Automation Engineer but with its own human resources and funds necessary to gather the data required for an analytical bottleneck identification process.

  As a research intern, I was not directly involved in supporting production. As a result, I had the time to gather some of the data required. Plant personnel on the other hand were working overtime to support the increased production requirement, leaving little time for the development of a data gathering system.

  While management agreed that the objectives were important, there was lack of economic support when it came to the required funds to implement the data collection systems either at the plant level (up to the Body Shop's marriage point or at the Rear Pan Line level. The major hurdles were those discussed in the previous chapter. While the benefits of the project sound great, it was impossible to show a cost/benefit analysis. Even when the cost of the installation project at the Rear Pan Line would be offset by the marginal contribution of only 8 additional units, it was difficult for management to justify the expenditure due to the possible short-life time of the plant during a time of significant cost-cutting provided that there was no "guarantee" of return on investment.

- **Require a Validation Procedure as part of the deliverables of the V.O. Next Generation Manufacturing Committee.** Validation of the information should be performed under regular basis, just like an airplane pilot checks all his controls before taking off*. Validation requires great attention to detail. Validating ALL the information is an overwhelming task. V.O. should prioritize which information to validate. Further investigation on auto-validating systems that check the consistency of the data should be performed. As a benchmark opportunity, nuclear power plants use a system of analytical redundancy to validate their information*

7.3 Labor Relations

Neither analytical tools, software programs nor improvement processes will produce any favorable results and savings on their own. Good, solid labor relations are the foundation for sustainable improvements. Without such relations, no matter what manufacturing philosophy is being followed, progress will be limited. Only through strong teamwork and support can such a process be successful. The major weakness of the throughput effort lay in the realm of labor relations. There is a lack of mechanisms and willingness to engage the work force. There is much untapped potential in the operators, but it will be a long process to exploit this potential. A significant culture change is required.

Manual collection of the data is very expensive and hardly an option for the day-to-day operation. While web-based monitoring systems offer a great deal of flexibility to collect, arrange and present the data, they are still "hard-wired" to PLC code that is subject to

* Dr. Daniel Whitney's comment during his plant visit, October 24, 2002

changes from the operational personnel as well as the maintenance crew. Collection of on-line data within the auto industry is still in an early stage of development and there is still the challenge to guarantee that you can collect real data - free of error from manual entry and manipulation.

The manufacturing systems have grown and, as attractive as on-line data collection looks, management has to realize all it takes to keep it running. It is fragile and not foolproof. Changes to PLC code will alter the information. If care is not taken properly, the system will "get sick" over time and start collecting more and more faulty information, as it happened at DAP's Body Shop for the two subsequent years after the VisualPlant™ initial installation. PLC ladder logic back up systems are a necessity for this new environment in order to avoid the time delay and the consequent collection of faulted information between the time the change was made to the PLC code and the time it was detected and re-mapped to VisualPlant™.

Another argument against the idea that software will solve all the problems is that, even when the data seems to be "invisible" to the operators, they are aware of being monitored and the information being logged. Operators need to be certain that they will be monitored fairly in order to work with the system and use it as a tool for decision making on the floor. We should keep in mind that the system can be altered easily and the data collected can become garbage instantly if not properly maintained by the operators. Just to give a quick example, by failing to properly clean part-present switches and bypassing the PLC ladder logic manually, the collected information can be distorted.

Implementation of on-line monitoring systems must consider the commitment from the people operating and maintaining the equipment. People on the line need to feel the ownership of the data being collected and value its usefulness. They also need to know they are being measured fairly. If any of the above is not taken into account, the data collection system will not have a successful implementation.

One basic requirement for people is an environment of respect and transparency. Improvements will be easier to come by when the adversarial walls come down between union and management. Management can make great strides towards that end by involving the work force in problem solving activities up front. Explain the problems and consequences of throughput, and invite union members to be apart of the team by sharing information on the project. The proof that this approach actually works was the Rear Pan Line operator's willingness to be videotaped so that the information could be validated against the data collected by VisualPlant™.

Union participation was non-existent both at the plant level initiative and at the Vehicle Operations Division level within its cross-functional team. The recommendation is to involve the United Auto Workers Union (UAW) in the implementation of the VisualPlant™ Monitoring System and at the V.O. Next Generation Manufacturing Committee. By including all parties early, their confidence in the process can grow as the project develops. This also prevents anyone from being caught by surprise by the results.

Glossary - Acronyms

BIW:	Body-in-White
CCR:	Capacity Constraining Resource
DAP:	Dearborn Assembly Plant
DBR:	Drum-Buffer-Rope.
EMT:	Executive Manufacturing Technologies
FPS:	Ford Production System
FTPM:	Ford Total Productive Maintenance
HMI:	Human Machine Interface
JPH:	Jobs per hour
ME:	Manufacturing Engineer
MODAPTS:	Modular Arrangement of Predetermined Time Standards
MTBF:	Mean Time Between Failure
MTTR:	Mean Time to Repair
OEM:	Original Equipment Manufacturer
PLC:	Programmable Logic Controllers
PM:	Preventive Maintenance
TOC:	Theory of Constraints
UAW:	United Auto Workers Union
VO:	Ford's Vehicle Operation's Division

Bibliography

1 Hayes R.H., Wheelwright S.C., Clark K.B. *Dynamic manufacturing*. New York: Free Pr., 1988.

2 Dertouzos M.L., Lester R.K., Solow R.M., MIT Commission on Industrial Productivity. *Made in America: Regaining the Productive Edge*. Cambridge: MIT Pr., 1989.

3 Goldratt, E. , Cox, J. *The Goal*. New York: North River Press, 1986.

4 Senge, P. *The Fifth Discipline: The Art and Practice of the Learning Organization*. New York: Currency Doubleday, 1990.

5 Sterman, J. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. U.S.A.: Irwin McGraw Hill, 2000.

6 Goldratt, E., Cox, J. *The Race*. New York: North River Press, 1986.

7 Goldratt, E., *What is this thing called THEORY OF CONSTRAINTS and how should it be implemented?* Grear Barrington: North River Press, 1990.

8 Womack, J.P., Jones, D., Roos, D. *The Machine That Changed the World: the Story of Lean Production*, New York: First HarperPerennial, 1991.

9 Black, J.T. *The Design of the Factory with a Future*. McGraw-Hill, 1991.

10 Jacobs, F. R. *OPT Uncovered: Many Production Planning and Scheduling Concepts Can be Applied With or Without The Software*, Industrial Engineering

11 Shingo, S. *A Study of the Toyota Production System*. Portland, Oregon: Productivity Press, 1989.

12 Plenert, G., Best, T.D. *MRP, JIT, AND OPT: What's best?* Production and Inventory Management, 2nd Quarter 1986.

13 Plenert, G., *MRP, JIT, OPT: A Study of Modern Production Management Systems*. North-Holland: Elsevier Science Publishers B.V., 1987.

14 Lambrecht, M.R., Decaluwe, L. *JIT and Constraints Theory: The Issue of Bottleneck Management*. Production and Inventory Management Journal, 3rd Quarter, 1988.

15 Suehiro, K. *Elimination of Minor Stoppages on Automated Lines*. Productivity Press, 1992.

16 Groover, M.P. *Automation, Production Systems, and Computer-Integrated Manufacturing*. U.S.A.: Prentice Hall, 1980.

17 Brandimarte, P., Villa, A. *Modeling Manufacturing Systems*. Berlin, Germany: Springer-Verlag, 1999.

18 Pegden, C. D. et al. *Introduction to Simulation using SIMAN*. New Jersey: McGraw-Hill, 1990.

19 Ptak, C.A., *MRP, MRP II, OPT, JIT, and CIM - Succession, Evolution, or Necessary Combination*. Production and Inventory Management Journal, 2nd Quarter 1991.

20 Ronen, B., and Starr, M.K., *Synchronized Manufacturing as in OPT: From Practice to Theory*. Computers Ind. Engineering, Vol. 18, No. 4

* Cassidy, M. *Throughput Improvement Initiatives in an Automotive Assembly Plant Body Shop.* Cambridge, MA: MIT Leaders for Manufacturing Thesis.
* George, J. *Applying the TOC in a High Volume Manufacturing System to Increase Throughput and Performance.* Cambridge, MA: MIT Leaders for Manufacturing Thesis, June 1997
* Hoag, M. *Improved Integration of Information in Discrete Part Manufacturing Environments.* Cambridge, MA: MIT Leaders for Manufacturing Thesis, May 2002
* Longcore, J. *Bottleneck Identification in Cycle Time Reduction and Throughput Improvement Efforts in an Automotive Transmission Plant.* Cambridge, MA: MIT Leaders for Manufacturing Thesis, June 1994
* Schulist, J.A. *Micro and Macro Throughput Improvements in an Automotive Assembly Facility.* Cambridge, MA: MIT Leaders for Manufacturing Thesis, June 1997
* Smith, J. *Theory of Constraints and MRP II: From Theory to Results.* Peoria, IL: Bradley University, May 11, 1994
* Stanley, J. *An Evaluation of the Design of Manufacturing Measurables for the FPS.* Cambridge, MA: MIT Leaders for Manufacturing Thesis, June 1996
* Tagawa, J.T. *Implementing TOC in a Job Shop Environment.* Cambridge, MA: MIT Leaders for Manufacturing Thesis, December 1999