Micro and Macro Throughput Improvements in an Automotive Assembly Facility

by
Jason Andrew Schulist

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Signature of Author: ______________________
Department of Electrical Engineering
MIT Sloan School of Management

Certified by: ______________________
Donald B. Rosenfield, Thesis Supervisor
Sloan School of Management

Certified by: ______________________
Al Drake, Thesis Supervisor
Professor of Electrical Engineering

Accepted by: ______________________
Larry Abeln, Director of Master's Program
Sloan School of Management

Accepted by: ______________________
Auther C. Smith, Chairman
Committee on Graduate Students, Electrical Engineering

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Abstract

This thesis, based on a Leaders for Manufacturing internship at an international automotive assembly facility, discusses the use of throughput tools in order to improve both individual throughput performance as well as system throughput performance. This automotive plant had recently switched models from a manual-based body shop to a technical robot based body shop. Because of the need for throughput improvement, these throughput tools and methods were implemented to build lasting change throughout the organization. The improvements in throughput were made both on a micro and macro scale.

The micro throughput improvements in this thesis focus on optimizing individual subassembly lines. Three areas of the body shop are evaluated using micro improvement tools and methods.

1) The Underbody Rear area project utilized cycle time reduction methods and the shifting of non-value added time in its local bottleneck to improve throughput by 15%. A second contribution to these throughput improvements stemmed from transferring learning between plants by setting up plant visits.

2) The Framing 1 area project also used cycle time reduction strategies and learning transfer strategies. In this case a 4% improvement in throughput occurred by adapting the knowledge from a team member's past experience into a solution for the Framing 1 area.

3) The Body Sides area project created throughput improvement by utilizing a pre-existing buffer. Through the use of queueing theory and Markov processes, the thesis calculates throughput results and compares the choice of using the buffer and not using the buffer. Gershwin's manufacturing analysis theory and software (Gershwin 1994)

were used to calculate these efficiency gains. By applying these theories to this automotive assembly application, the plant achieved throughput gains of over 3%.

This thesis also deals with macro throughput issues. From the Theory of Constraints, the best way to optimize a total system is to find and improve the system bottleneck. The internship focused on utilizing a proprietary bottleneck analysis tool developed by the United States affiliate of the company. The thesis describes this first European installation of the throughput software. Typically, the firm has introduced this software to a plant during a major retooling or model change. In this specific plant's case, the software had not been installed during the tooling change, so the team developed a new implementation strategy for the software. The thesis covers three different methods of data collection that helped deal with the implementation strategy. By coupling the software with a developing Management Information System (MIS), the team was able to gain additional benefits that would not have been realized in an earlier installation. Typical plant throughput improvement from implementing this software is 12%. At this point, the actual improvements that will be realized from this specific installation are unclear.

Finally, the thesis describes two policies that can affect throughput and can be explained using systems dynamics. The use of Senge's "Shifting the Burden" archetype describes how short-term policies may have long-term effects. In the overtime model, the scheduling of overtime ultimately reduces throughput. Similarly, in the inventory model, the increase in inventory actually reduces throughput, too. Both of these policies favor short term solutions to throughput problems over the long term solutions of fixing the problems. By changing these policies, the plant can improve their long term throughput.

Thesis Advisors:
Professor Donald Rosenfield, Senior Lecturer, MIT Sloan School of Management
Professor Al Drake, MIT Professor of Electrical Engineering

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Chapter 1 Introduction and Plant Overview

The Vauxhall assembly facility in Luton, England, has recently been experiencing throughput difficulties in the Body Shop as the result of a new model introduction. The introduction of the Vauxhall Vectra, first as a hatchback, and then as a station wagon, necessitated a change from a manual based-body shop to a high-technology Body Shop. In the past, the Body Shop had not been the bottleneck of the plant. With the increasing pressure for units out of the Body Shop, it has become necessary to implement tools that will improve throughput. Micro throughput tools can be used to optimize individual subassembly lines or operations. Macro throughput tools can be used to optimize Body Shop throughput by determining the bottlenecks in the system and allocating the scarce resources to fix these bottlenecks. By continuing to use the throughput tools practiced during the internship, Luton's Body Shop can shift its mindset from a manual Body Shop to an automated Body Shop that is critical for its future success.

The past model (J-car Cavalier) utilized only four robots to assemble the Body in White (sheet metal). Most welding on the vehicle was performed by manual operators wielding manual welding guns. The parts would travel along a simple conveyor controlled by a few electronic switches . The Body Shop management's greatest tasks regarding the old Body Shop dealt with maintaining consistency and quality of product. The throughput issues in the manual Body Shop tended to result from conveyor failures and operator variability. The Body Shop typically was not a bottleneck in an assembly plant.

The new Vectra model, on the other hand, retooled the Body Shop and added over 300 robots as well as many other automated equipment systems. This shift to 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 throughput problems and increased the need for new throughput tools and different skills compared to the manual Body Shops of the past. Since the current model start-up, the Body Shop has been the bottleneck of the Luton plant. Because of the large increase in technology complexity, it is hard to determine the location of the bottlenecks within the Body Shop. The throughput analysis tools used during the internship helped locate these bottlenecks quickly. The shift from a production focus to a more holistic, throughput focus demands different management styles and organizational methods.

My internship attempted to address the issue of throughput on a micro and macro scale. Different tools and concepts were used to improve the throughput of the Body Shop and assist management in shifting its mindset towards a throughput focus. Micro throughput projects were completed on three of the subassembly lines: Underbody Rear, Framing 1, and Body Sides. These projects helped me gain familiarity with the Body Shop equipment and management policies. The projects also introduced manufacturing systems analysis, cycle time reduction, and area optimization. A macro throughput project was also initiated that modeled the entire Body Shop using C-More, a throughput analysis tool. C-More locates system bottlenecks given a system's parameters and quantifies the impact of improvement. This tool can therefore be used to allocate resources efficiently and maximize the impact on throughput.

The thesis consists of six chapters. This first chapter discusses the current situation at the Luton plant and describes the plant history. The plant history gives general background information about the Luton facility to better understand the context of the current throughput problems. The second chapter focuses on general throughput concepts. the chapter presents both throughput optimization and bottleneck analysis to justify the methods and software used during the internship.

Chapter 3 briefly presents an overview of the Body Shop from an operations perspective. It also reviews the most recent organizational structure changes their potential impact on operations. The end of the chapter analyzes two policy decisions with respect to system dynamics principles to demonstrate how changes in these policies may help resolve

Luton's throughput problems. Chapter 4 describes the three micro throughput examples and their ability to produce tangible throughput improvements. The three projects were 1) Underbody Rear optimization of assembly tooling, 2) Body Sides buffer utilization and optimization, and 3) Framing 1 cycle time reduction.

Chapter 5 describes in detail the use of the C-More software program. Chapter 5 surfaces the data collection methods used for obtaining MTTR, MCBF, and cycle time, and each of the method's effectiveness including the data integrity issues. The chapter presents results from C-More in a format to maintain confidentiality but to demonstrate the power and effectiveness of the model. Chapter 6 presents the final conclusions from this thesis as well as other major learning points from the internship. Particular attention will be given towards the learning that can be propagated through General Motors as a whole.

1.1 Luton Plant History

Vauxhall began building automobiles in London in 1903. In 1905, Vauxhall moved its assembly facility to Luton. General Motors acquired Vauxhall in 1925 under the leadership of Alfred Sloan for $2.5 million dollars. The Luton site became General Motors first manufacturing site in Europe. During World War 2 the Luton plant was called upon by the government to design and build a new tank. At this time the normal product development cycle lasted about four years for vehicle design. Vauxhall designed, built, and produced tanks all within a year. The plant also built fuel cans, army helmets, and was involved in the work on the first jet engines and bomber planes.

After the war, Vauxhall grew quickly to become a market leader. By 1957, the Luton area employed around 22,000 people. The 1960's and 1970's saw the increase of competition in the market and the introduction of a second assembly plant in Ellesmere Port, England. In 1975, Vauxhall introduced the Cavalier and concentrated its Luton production to this model. The Cavalier became one of the most successful automobiles in the market. This model (with one major redesign) was ultimately replaced with the Vauxhall Vectra in 1994.

The implementation of the Vectra mandated a $200 million dollar investment program that upgraded most of the equipment in the plant. Each operation and method was scrutinized in order to optimize the plant. According to the Vauxhall brochure, the plan was to switch from the outdated mass-production concept to the new lean production techniques. The Vauxhall Body Shop switched from 35 robots in the old Cavalier to 418 with a high integration of additional sophisticated machinery. By 1996, there were only 4500 employees at the Luton facility.

One can see from this short history that Vauxhall and Luton have been through many changes. The switch from mass production to lean manufacturing has both reduced the workforce and added significant amounts of technology to the plant. The 92 years of plant history can make the switch of production techniques difficult to implement. It is important to understand the throughput problems in the Luton plant in the context of this plant history.

Chapter 2 General Throughput Concepts

There are characteristics of every serial production system that can be investigated in order to improve throughput. These characteristics are described here so the reader can better understand the methodologies behind the micro and macro throughput strategies that were used in the Luton plant during the internship. First, we review the general concepts behind serial production systems. This section includes a discussion of blocking and starving and the importance of buffers and inventory with respect to throughput. Next queuing theory and Markov processes are briefly reviewed, since the bottleneck analysis tools that have been implemented use these mathematical concepts. Finally, this chapter introduces the theory of constraints to stress the importance of bottleneck analysis for throughput improvement.

2.1 Serial Production System General Overview

A serial production system consists of manufacturing operations that follow each other sequentially. In between operations there can be buffers which store parts for the following station. 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. While this may be true, the modeling of serial production systems is the basic building block for developing more complicated models. When one station immediately feeds a part into another station these stations are considered coupled. When the two stations are separated by a buffer, the stations are defined as decoupled. All production systems try to maximize their throughput and build as many jobs as the market desires. Automotive companies tend to build assembly plants with a specific throughput target in mind. Many plants typically receive increases for their daily throughput targets throughout the life cycle of a product. 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 2-1, there are four stations coupled without a buffer. When Station2 fails, it directly affects the status of the other three stations. Station1 has a job that it has finished working on but it has no place to put this job because Station2 has failed. Station 1 is

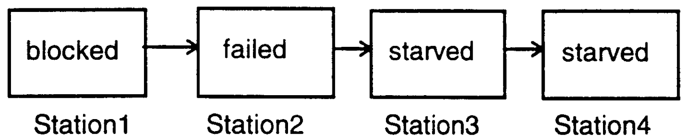


Figure 2-1 Four coupled stations and their states

blocked. Similarly, Station3 and Station4 cannot build because Station2 is not working. Stations 3 and 4 are waiting and considered *starved* by Station 2. 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. In the previous example above, let us now assume that we place a buffer was between Station3 and Station4 (Figure 2-2) and that this buffer contains some jobs in it. Now when Station2 fails, Station1 remains blocked and station 3 remains starved. However, station 4 can still operate because it pulls jobs out of the buffer. Later, when Station4 breaks down, stations 1-3 can build jobs until the buffer fills up. Previously this would have blocked stations 1-3. Now these stations can build jobs into the buffer until the buffer becomes full.

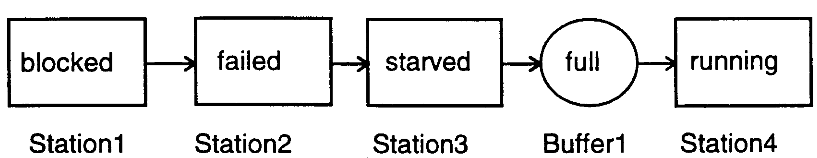


Figure 2-2 Four stations with buffer and their states

The purpose of inventory is to reduce the variability of the system. Since machines do breakdown occasionally, inventory can compensate for these breakdowns and assist in increasing throughput. The advantage of inventory is clear, yet much has been written about the "evils" of inventory. In the Machine That Changed the World, the authors present the Toyota Production System. One of Toyota's strategies is to eliminate waste by reducing inventory. The disadvantage of inventory results from higher levels of scrap due to damaged parts in inventory, long lags between discovering faults and correcting them, higher inventory holding costs due the design of additional transfer devices, conveyors, etc., and slower response times of operators due to high buffer sizes. The lower response time correlated high buffers can also negatively affect throughput (See Chapter 3: Inventory Model) To maximize the effectiveness of buffers, one must balance the a 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.

While the use of buffers to reduce variability may make intuitive sense, one can mathematically analyze these advantages by using Markov processes and queuing theory.

2.2 Mathematical Analysis of Throughput: Markov Processes and Queuing Theory

Markov processes and queuing systems are used to analyze serial production systems. This section briefly introduces these concepts with the context of solving serial production systems mathematically.

A Markov process is a discrete-state random process. The determination of the future states in a Markov process are only based on the current state and no past state. Machines in the Body Shop typically exhibit this type. A machine's chance of failing (or being repaired) is independent of the last time it failed (or the time we have been repairing the machine). Since machines are complex and tend to fail when performing operations, we assume that a machine can be modeled using Markov processes. The states of a Markov process are solved by a set of differential equations. The long-term steady-state probabilities can be solved using a series of linear equations.

A typical Markov process can be used to determine a machine's reliability. (See Gershwin, Manufacturing Systems Engineering p. 26) Any stand-alone machine can be defined by its two possible states, up or down. The machine performs work in a set amount of time. There is a probability p that it fails when working and a probability r that the machine is repaired after having failed. Markov processes are normally diagrammed to show the various states. The following diagram (Figure 2-3) shows the state diagram for the stand-alone machine :

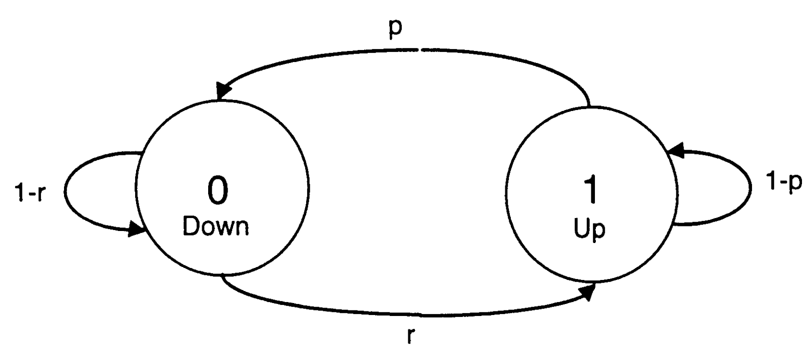


Figure 2-3 State diagram for stand-alone machine

Based on the probability distributions and solution of the differential equations, the probability in steady state of being down is p(0) = p / (r+p). Similarly the probability of being up is p(1) = r / (r+p). (Gershwin p.29).

The M/M/1 queue is also used to describe manufacturing processes. In this case parts arrive at a machine and are serviced by the machine at exponential rates according to a Poisson process. We assume that an infinite buffer can build up before the machine. The exponential service time must be faster than the exponential arrival time in order to process all of the material that could accumulate in the buffer. As the arrival rate approaches the service rate, the jobs in buffer increase and hence the delay before completion of a particular job increases. When one thinks of a buffer that is not infinite, as this arrival rate approaches the service rate, the buffer will remain full and the previous station will remain blocked. The blocking effect will reduce overall throughput. The delay that a part experiences can be approximated by Delay = 1 / (service rate - arrival rate).

The use of queuing theory, Markov processes, and general production concepts is exemplified by Gershwin's Deterministic Two-Machine Line. In this case two machines each behave like Markov processes separated by a buffer (see Figure 2.4). The arrival rate of jobs to the second machine is determined by the buffer size and characteristics of the first machine's reliability (p and r probability rates). Similarly, the first machine may also become blocked by the behavior of the second machine. The deterministic nature (both finish a job at the same deterministic time) of the two machines in this model

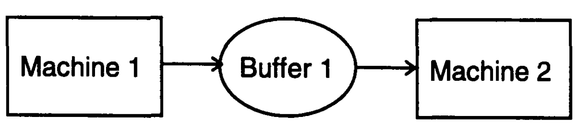


Figure 2.4 Deterministic Two-Machine Model

makes the mathematics for the steady state probabilities easier than in other models (such as exponential or continuous). The Mean Time to Repair (MTTR) and the Mean Time Between Failure (MTBF) data of each machine is used to calculate the p and r of the Markov process. Gershwin uses a solution technique of describing the probability distribution of each event and its boundary conditions. Then the set of equations are solved to find the steady state distribution. From this distribution, throughput from machine 2 can be calculated. For further description of solution technique, refer to Gershwin, Manufacturing Systems Engineering pp. 71-92. These methodologies are the basis for both micro and macro throughput improvement strategies implemented in the Luton plant.

2.3 Theory of Constraints

The Theory of Constraints focuses on finding the location of bottlenecks in any manufacturing system. This theory was developed in the book "The Goal" by Goldratt. A bottleneck is a station that constricts throughput of a system. 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 in a system, much effort tends to be placed by management on the station with the most downtime resulting in little overall effect on system throughput. The result is a frustrated manufacturing workforce that feels it cannot fix the system. When management focuses on improving the bottleneck station(s), throughput increases and management's attitude improves. 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 system throughput. By keeping resources and attention close to a bottleneck, every incremental improvement at the bottleneck increases the system throughput.

In an automotive assembly plant, one tends to see multiple bottlenecks due the large system variation stemming from machine complexity and the balanced designed cycle time of assembly processes. The design of the tooling tends to equalize the capacity at each machine. Therefore equipment reliability at the tooling 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.

C-More utilizes bottleneck analysis to locate the stations that most affect throughput. Since C-More identifies bottlenecks and quantifies the amount of throughput lost at each bottleneck, management can utilize its scarce resources to focus their efforts on these bottlenecks.

2.4 Summary

When looking at manufacturing facilities, management can utilize tools that quantify throughput. Using buffers and improving equipment performance can reduce the blocking and starving of operations that occurs due to system variability. These dynamics of a manufacturing system can be modeled using Markov processes and queuing theory to develop a system of differential equations and steady-state probability equations. Tools such as C-More use these mathematical theories to calculate throughput figures for existing manufacturing systems. The Theory of Constraints helps focus management on optimizing throughput by locating and eliminating bottlenecks in the system. The power of a tool like C-More is that can both accurately model the performance of a existing system and locate its bottlenecks. The Luton Body Shop can use these throughput tools and techniques to assist management in improving the system throughput.

Chapter 3 Vauxhall Body Shop Operations Overview

The Vauxhall Body Shop has built the Vauxhall (Opel) Vectra hatchback and wagon models since 1995. A Body Shop assembles the metal of an automobile together through various welding processes. Some of the welding is used to locate the pieces of sheet metal in the right position while other welds (known as respot) are additional welds added for structural integrity. The shift in operations at Luton from a manual Body Shop to an automated Body Shop has created some throughput issues. This chapter will address the new Body Shop equipment layout, the body unit's organizational chart including recent changes, and the policies used by management as described by system dynamics principles that may explain some of the current throughput problems.

3.1 Body Shop Layout and Equipment

The Body Shop is divided into two distinct areas: the subassembly lines and the skid system. The subassembly lines can further be disaggregated into Body Sides Left, Body Sides Right, Underbody Front, Underbody Rear, Dash, and Framing 1. The skid system can also be segmented into different areas: Framing 1 Respot, Tabbing, Framing 2, Framing 2 Respot, and the Left Over Lines. The additional lines of Roof Drilling, Door Assembly and Gas Tank Painting have been ignored because have a negligible effect on Body Shop system throughput.

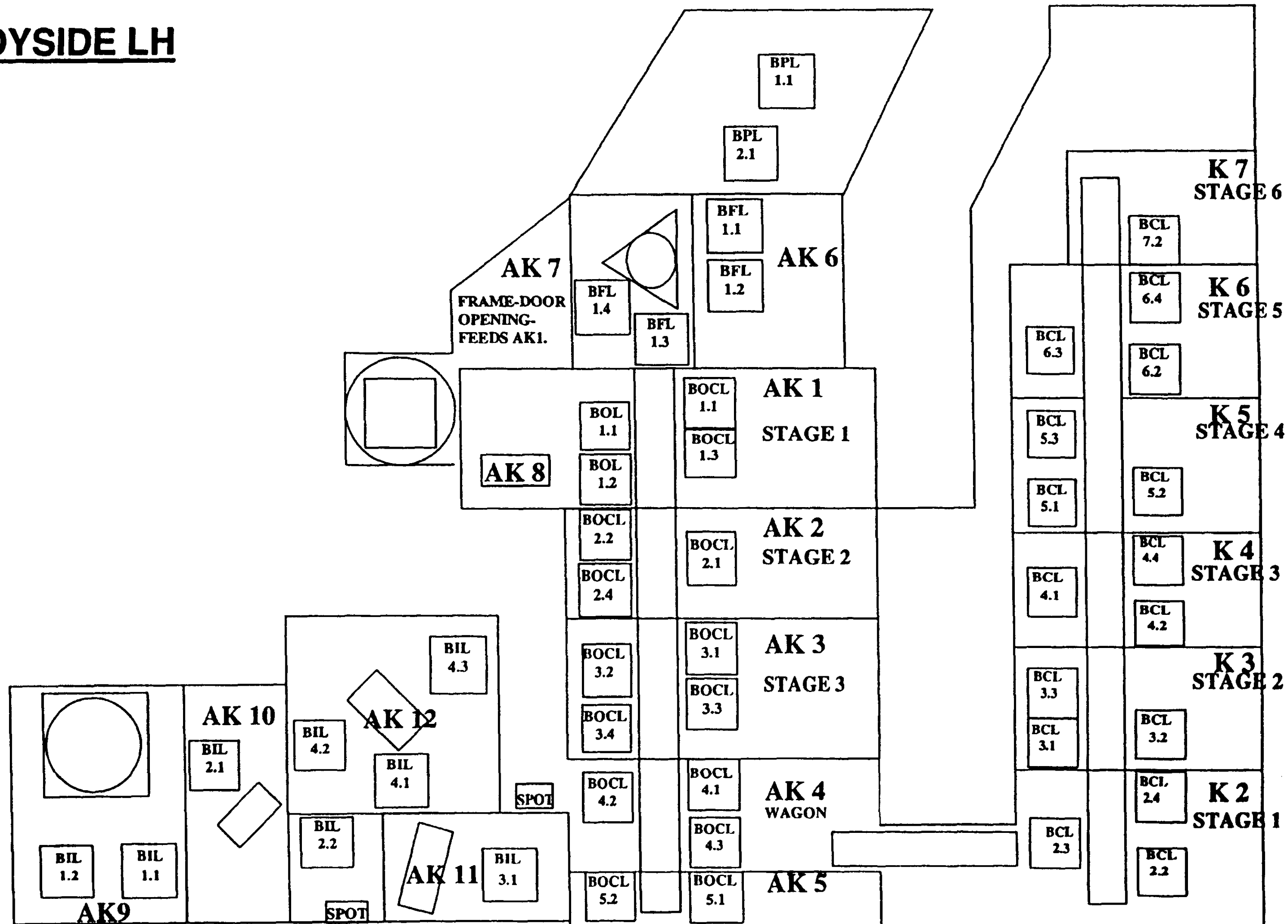
3.1.1 Body Sides Left and Right

The Body Sides Left and Right lines build the sides of the Vectra station wagon and hatchback. Figure3-1 shows the process flow of the Body Sides Left line. A body sides sheet metal subassembly is composed from an inner panel piece and an outer panel piece. The inner panel piece acts as reinforcement and an attaching point to the rest of the car (front and bottom) while the outer panel piece is the part of the car seen by the customer. Within the Body Sides line are inner and outer subassembly lines. The inner subassembly line consists of a turntable and several robots that weld and carry the inner panel from one station to another. The outer subassembly consists of turntables and welding robots. After the turntables the outer panel is placed on a synchronous lift and carry transfer device. Further welding and sealing is performed on this panel prior to marriage with the inner panel piece. The marriage station dimensionally sets the inner panel to the outer panel so that each job is built consistently. After the marriage station, the Body Sides line contains a buffer of six body sides. Finally, there is a final respot area in the Body Sides line. Final respot consists of a second lift and carry transfer device and several respot robots. The finished body sides pieces are then placed on an electrified monorail system and delivered to the Tabbing station.

3.1.2 Underbody Front

The Underbody Front line builds up the bottom front of a vehicle. The underbody front consists of two support rails and a sheet metal bottom. Manual operator loaded stations build up these support rails separately in a set of subassembly areas. Next, welding guns located on a pedestal (pedestal welders) weld each rail using material handling robots to maneuver the rails. There is a buffer between each subassembly area and the rail marriage station. The rails are then married together on a turntable and are placed on a two station lift and carry transfer where the rails marry to the sheet metal bottom in the marriage station. The sheet metal bottom is welded together on two parallel pedestal welding lines. A buffer follows these lines prior to the marriage station. After being married together, an overhead transfer device picks the part up and places it either in a buffer or to another lift and carry transfer. This final lift and carry transfer moves the part to a series of robotic respot welding, stud welding, and sealing stations. Two parallel inspection stations at the end of the line check for missing welds, studs, and sealing patterns. Finally 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 fronts if desired.

BODYSIDE LH



STATIONS AK 9-12 = SIDE PANEL INNER FEEDS TO AK 4

Figure 3-1 Layout of Body Sides Left Line

3.1.3 Underbody Rear

The underbody rear line assembles the bottom rear of the Vectra. Because the hatch and wagon models are different, two different floorpans are assembled on this line. Figure3-2 shows the process flow of the Underbody Rear line. The underbody rear consists of two support rails and a rear sheet metal floorpan. The rear rails are assembled differently than the front rails. More operators are necessary to add parts throughout the process. Therefore the rail stations consist of four cells with an operator load, a few automatic pedestal welders, robotic welding, and a buffer. The buffers are exogenous to the automatic subassembly process and therefore at each cell off-line parts can be stored if desired. The rails are eventually loaded to a turntable where they are married to each other and then married with the floorpan three stations later. Before being married to the floorpan, the rails can be stored in a buffer. The floorpan subassembly line is model specific and is initially loaded to a turntable. A tip-over device transfers the floorpan to a second turntable where additional options are added. Next a robot unloads the floorpan to an area for respot and stud welding. The floor pan is then either placed in a buffer or married to the support rails in the marriage station. After marriage to the rails, a robot places the underbody rear piece on a lift and carry transfer where the wheel well is added and further robotic respot occurs. Two parallel inspection stations at the end of the line similar to the Underbody Front line check for missing welds, studs, and sealing patterns. Finally 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.

3.1.4 Dash

The dash line assembles the front sheet metal dashboard of the car. The dash line consists of four distinct subassembly areas. The first area builds up the basic framework of the dash. Manual operators load parts to the line where robots perform the spot welds. A robot loads to a small buffer area. The next area places the steering column into the dash.

REAR UNDERBODY

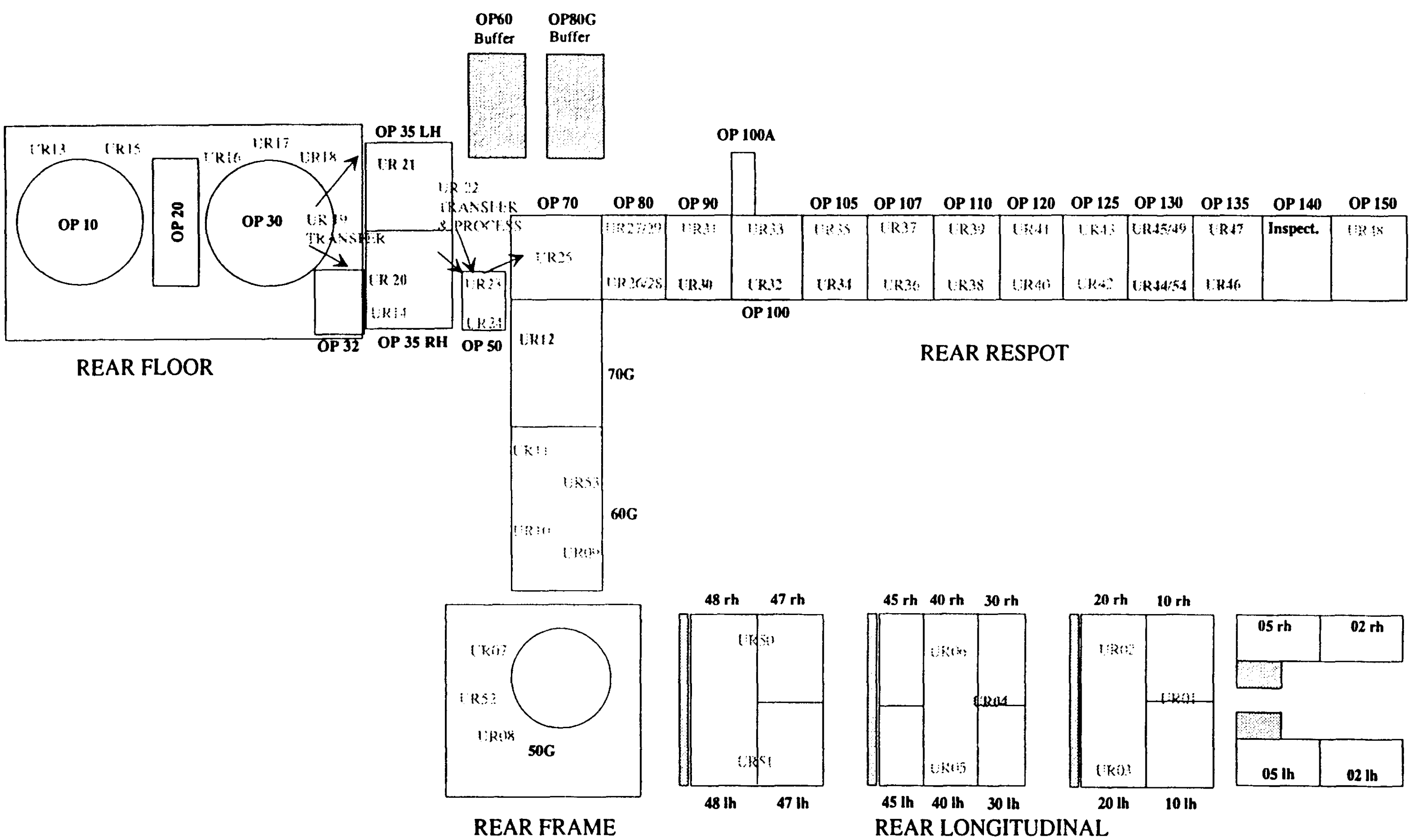


Figure 3-2 Layout of Underbody Rear Line

The steering column can be positioned on either the left or right side of the dash depending on the called out schedule. A material handling robot also determines whether the a/c bracket should be used (option-specific). The third subassembly area adds the sides of the dash (cowl panel) and performs pedestal welding respot on two parallel lines. A large floor buffer stores several of the sequenced dashes. The fourth area adds all of the stud welds on the dash and includes a manual inspection station followed by a second large floor buffer system. The last robot on the line decides whether a job should go to the overhead monorail system, to the floor buffer system or to an additional off-line buffer area.

3.1.5 Framing 1

The Framing 1 area assembles a majority of the subassembly pieces together. In the first station the front and rear underbody pieces are brought together and a manual operator places an ID tag on the job. In the second station, the dash is added to the job and the two underbody pieces as well as the dash are all welded together to set the proper dimensional positioning. The remaining stations in Framing 1 add parts such as the inner wheel wells to the framed sheet metal body and perform some respot welding.

3.1.6 Skid System

After a job leaves the Framing 1 area, it is deposited by an overhead transfer onto a skid. This skid follows the job through the system until paint. At each station where work is performed, the job is raised off the skid by calibrated tooling for positioning, welding, and sealing. The value added part of the skid system has capacity for more than all the skids in the system. Unfortunately, the return side of the skid system has room for only 70% of the skids. If there are too many empty skids in the system, they must be manually backloaded out of the system. There are times when Framing 1 becomes blocked because all of the skids are on the supply side and there are no empty skids available. A skid takes 12 minutes to return from the unload for paint to Framing1 load onto the skids. There are also times when Body Shop can starve paint due to a slow operator response for manually unloading empty skids from the system. If the return line fills up with empty carriers due to this slow response, the carriers on the supply cannot move and they become locked in the system until room is made available in the return system. The management of this system is very important to optimizing throughput in the Body Shop.

3.1.7 Framing 1 Respot

Framing 1 Respot line consists of several robots that pick up the additional framing welds that are not added in the Framing 1 area. The equipment in this area consists of robotic welders and lift stations that lift the job off of the skids.

3.1.8 Tabbing

The Tabbing station accepts the body sides left and right pieces and "tabs" them to the framed job that has finished welding through Framing 1 Respot. The body sides have little sheet metal tabs that fit the side into the dash and underbody. The machine then bends these tabs over to allow the jobs to move to the Framing 2 where they are positioned and welded together.

3.1.9 Framing 2 and Framing 2 Respot

Framing 2 actually positions and welds the sides of the car to the rest of the frame. Three framing stations work in parallel for added flexibility should one framing station fail. All three framing stations are capable of building the wagon or hatch model. The Framing 2 Respot area finishes welding the frame and also attaches the roof to the job. Robots primarily weld the job that is positioned by raising the job off the skid as in Framing 1 Respot.

3.1.10 Left Over Lines

The remaining section of the Body Shop adds the additional parts to the job (known as the attaching parts sheet metal). Here is where the fenders, doors, hood, and trunk are added to the job. Manual operators also sand down the outer exposed sheet metal (finesse) to maintain a smooth consistent outer finish and give the job a better paint appearance. A manual operator also mig-welds the front and rear doors to the car. After all these sheet metal parts are added, a low pressure washer washes the vehicle and the job is sent through a final inspection area prior to being shipped to the paint department.

3.1.11 Summary

The Vauxhall Body Shop has added several new types of equipment since the previous model change including new robots, variable frequency drive packages, and sophisticated control devices. The increase in technology from the previously manually hand welded vehicle has increased the need for throughput tools that can analyze automated production systems.

3.2 Organizational Structure

In June 1996, the Vauxhall Body Shop organization was divided into two areas - Operations and Planning. The operations department was headed by an area manager who had reporting to him production and maintenance departments. The production shift managers directed front line production supervisors and the quality department. The quality department included both weld inspection and coordinated measurement machine (CMM) checks of the body for dimensional consistency. The maintenance manager had maintenance foreman, lead engineers and various support staff reporting to him. The three lead engineers were each responsible for the performance of a dedicated subassembly line area - 1) Underbody Front and Underbody Rear, 2) Dash and Framing 1, and 3) Body Sides Left and Body Sides Right. These engineers tried to troubleshoot the day to day problems that arose in their areas. They also developed long term plans for improving the existing lines. A systems engineer, interns (including me), and various other support employees also reported to the maintenance manager.

The planning department, on the other hand, reported to the Body Shop planning engineering manager. This planning manager had several planning engineers working for him. These engineers had been responsible for implementing the new Body Shop equipment during model change and also included the industrial engineering Body Shop department. As the project ramp-up finished for the Vectra model, these engineers had less responsibility for the daily operations. These daily responsibility duties had been handed over to the lead maintenance engineers. As of June 1996, the long term role of the planning engineers on the existing Vectra project was unclear. The Body Shop planning manager initially maintained his office in a separate building from the plant. This physical separation affected his span of control over his planning engineers who were located in the Body Shop open office. Eventually, the planning manager moved his office into the plant. This improved overall communication between the operations department and the planning department.

In November 1996, the organizational structure of the Body Shop was altered. The planning department now fell under the operations Body Shop unit manager. Therefore, the Body Shop engineering planning manager position was eliminated. Instead, lead planning engineer positions were added for the four major areas. These lead engineers reported directly to the unit manager. Two of the three maintenance lead engineers now became lead planning engineers of their respective subassembly areas and had other planning engineers reporting to them. They did not officially report to the maintenance manager anymore. The advantage of changing to this structure is that the unit manager now had all the necessary resources to make quick decisions when it came to industrial engineering and planning issues. The disadvantage is that the maintenance manager who had the most knowledge about the technical systems in the Body Shop did not have the lead engineer resources reporting to him anymore. This change in control of the lead engineers created a problem in having the best ability to rapidly shift resources as bottlenecks and needs of the Body Shop organization changed.

3.3 Policy Decisions that Affect Throughput

At the Vauxhall Motors plant, there are two policy decisions that negatively affect throughput. Peter Senge's book *The Fifth Discipline* (1990) 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 Vauxhall plant that demonstrate this shifting the burden archetype are the production overtime policy and the inventory policy.

3.3.1 Production Overtime Policy

In the Production Overtime policy case (see Figure 3-3), the Vauxhall 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. Many times the improvements from this solution are not seen immediately. On the other hand,

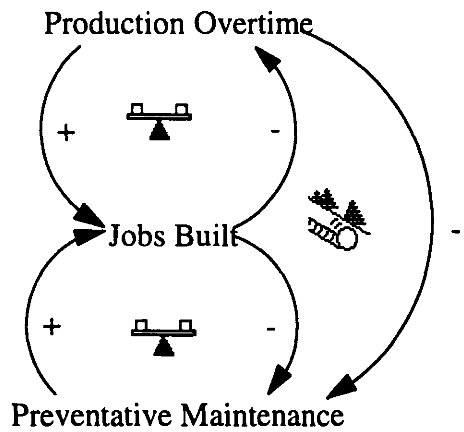


Figure 3-3 Systems Dynamics Model for Overtime

Vauxhall utilizes the short term solution policy of scheduling production overtime to make up the lost units each week. 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 Luton, it is not uncommon to see production working in the Body Shop on both Saturday and Sunday. One way for the Vauxhall plant to ultimately increase their throughput is to reduce production overtime and increase the amount of PM and equipment reliability projects. By stressing the fundamental solution, management can improve the throughput and reduce overall plant overtime.

3.3.2 Inventory Policy

A second way to increase throughput at the Vauxhall Body Shop is by increasing the amount of inventory stocks between the major sub-assembly lines by using the off-line buffers (See Figure 3-4). By buffering for all potential breakdowns, the Body Shop is able make their daily production during the shift. Unfortunately, because of the large inventory stocks, the maintenance workers have little incentive to fix breakdowns quickly. The

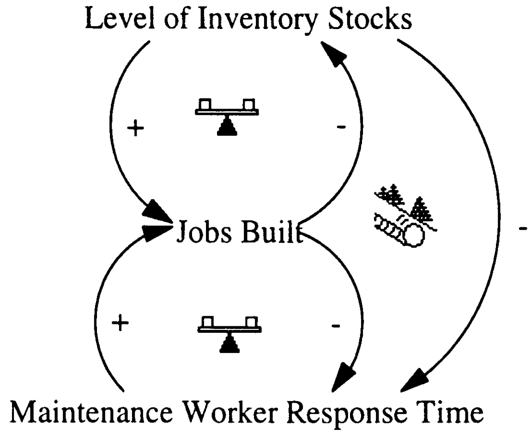


Figure 3-4 Systems Dynamics Model for Inventory

complacency of the maintenance worker increases the 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 these breakdowns, the off-line buffers are further increased, creating even more complacency in the maintenance worker. The off-line inventory itself can also create throughput problems. For example, on the Body Sides line, some of the parts are 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. In "The Race" (p.52), Goldratt and Cox also describe the connection between inventory policy and the overtime policy in order to get desired throughput. For example in the Luton plant, a significant portion of the scheduled overtime has been used to fill up the off-line buffers.

3.3.3 Summary of Policies

The use of system dynamics archetypes can help management recognize the long term effects of certain policy decisions. Vauxhall 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 4 - Micro Improvements in Throughput

Early in my internship experience, I needed to gain familiarity with the Body Shop systems in the plant. Due to the throughput issues plaguing the Body Shop, I decided to focus on "micro" throughput optimization. Each study presented in this chapter centers on an individual sub-assembly line located in the Body Shop. While bottleneck analysis of the entire Body Shop system will be covered in Chapter 5, this chapter locates a throughput constriction point on the various sub-assembly lines studied and proposes a solution to improve the smaller system throughput. According to the Theory of Constraints, managers should direct a large proportion of their human resources to the system bottleneck. These initiatives may sub-optimize total system throughput gains, but were developed as a framework to both understand the current tooling systems, and to familiarize the organization with methods that can be used to attack real bottlenecks.

4.1 Underbody Rear Optimization of Assembly Tooling

The Underbody Rear line is responsible for sub-assembling the lower rear sheet metal of a Vauxhall (Opel) Vectra. One may also refer to Chapter Three for further explanation of the Underbody Rear line and review Figure3-2 for reference. Two longitudinal rails (left and right) are subassembled (cell a) in semi-automatic machines with operators feeding parts into these machines. At the same time, a subassembly cell (cell b) adds parts to the rear underbody sheet metal for seat anchors, seat belt anchors, etc. Additionally, cell b includes stud welding and resistance welding robots. Option content in cell b varies depending on whether a hatchback or a station wagon is scheduled. There are two LIFO inventory banks after cell b for 11 hatch back underbodies and 11 station wagon underbodies. Underbodies and longitudinal rails are then married in Operation 70. After Operation 70, there are two additional LIFO inventory banks of 11 (wagon and hatch). The remainder of the line includes resistance welding respot and the spare-tire hub installation in the rear underbody panel. The underbody rear line utilizes an in-line buffer of 90 jobs and an off-line buffer of about 500. The off-line buffer consists of storage racks that can offload or backload parts in and out of the system at the end of the respot area. These underbodies are also shipped to Plant B that does not have a rear underbody line and are fed as a finished rear underbody into Plant B's Body Shop.

The bottleneck of the Underbody Rear line was located by observing the buffers. While the bottleneck may change from day to day based on the distribution of breakdowns, long-term bottlenecks can be located by observing which buffers tend to be empty and which buffers are full over long periods of time. After one week of observation, it was clear that the buffer after cell b was consistently empty and the buffer after operation 70 was partially full. This means that the bottleneck for the Underbody Rear line was located in cell b since cell b's buffer is empty. The remaining stations in the Underbody Rear line must wait for assembled parts from cell b if it is to build any jobs. Because the buffer from operation 70 was partially full and the buffer after respot leading to the Framing 1 line was also normally 60% full, it is clear that the Underbody Rear line was not the Body Shop's system bottleneck. Had the underbody rear truly been the system bottleneck and cell b the bottleneck within underbody rear, all buffers after cell b would be empty in the Underbody Rear line (and throughout the rest of the Body Shop system process after Underbody Rear). Since this was not the case, the true bottleneck of the Body Shop system was not in the underbody rear area.

However, since the task was to improve throughput in Underbody Rear line, we must direct our focus on the throughput of cell b. Cell b consists of 10 operations (See Figure 3-2). From observing cell b, it was clear that the bottleneck stemmed from the interaction of the first 6 stations. The first three stations involve the use of a two position turntable (two tooling mounts on a turntable). In operation 1, a manual operator loads the rear floorpan and some seat brackets to the line. A physical safety gate closes prior to any movement of the turntable. This turntable then rotates 180 degrees to a robotic resistance welding station (operation2). Once this is finished, the turntable rotates and additional 90 degrees where a tip-up (operation3) picks the part out of the turntable and flips the part over into operation 5. A variable frequency drive and an encoder controls the tip-up's movement. The encoder controls the drive's stop and acceleration/deceleration parameters. Operations 4-6 utilize a second two-position turntable. Operation 4 is also a manual operation where 9 parts are loaded to a machine with a physical safety gate closing before operation of the turntable. These parts then rotate 90 degrees to receive the flipped over floorpan from operation 3. Next the part rotates 90 degrees again to a robotic resistance welding station. Finally, the part rotates an additional 90 degrees for unload by a material handling robot. Operations 7-10 consist of resistance and stud welding robots. These final four operations of cell b do not break down regularly and build jobs within cycle time. They were not part of the bottleneck problem.

When examining this area, I noticed a variance in cycle time when a part left operation 6 and entered operation 7. A typical range for cycle time in this area varied from 54 to 96 seconds. The tip-up at operation 3 was not synchronized between the two turntables. After the operator loaded at OP1, (s)he had to wait for the tip-up to unload the part at OP3 before the table rotated again and the next set of parts were loaded. At the same time the tip-up at OP3 was forced to wait until the operator at OP4 loaded the parts. This operator then waited for both the tip-up to load and the material robot (OP6) to unload before the turntable could rotate clockwise to its operator load position. The two operators were effectively coupled by the tip-up. For example, if the OP1 operator was slow in loading parts, the OP3 tip-up had to wait the extra time thus slowing down the OP5 load and the OP4 parts loader. Alternatively, if the OP4 operator was slow in loading parts, the OP3 tip-up could not unload its part on time and this ultimately delayed OP1.

The coupling can be most easily seen from the timing diagram below. Each box represents a time slot for the cycle of a part OP1, OP3, or OP5. Each x is a guaranteed part of the cycle time of that operation. Each y on the chart is the additional cycle time that may occur due to a slow operator at OP5 or tip-up at OP3. Similarly each z on the chart is the extra cycle time that may occur due to a slow operator at OP5.

Operation action	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14
OP1 Load parts	x													
OP1 safety gate close		x												
Turntable rotate			x											
Wait for unload by tip up				x				y	y	y	y	y		
Turntable rotate					x									
OP1 Safety gate open						x								
OP3 Tip up unload from turntable				x										
OP3 Tip up move to load position							x							
Tip up wait for turntable OP4										y	y	y		
Tip up load to OP4								x						
TIp up return to unload position									x					
Tip up wait for turntable OP1	z	z	z											
OP5 load parts										x				
OP5 close safety gate											x			
Rotate turntable2												x		
Wait for tip up to load part at OP4	z	z	z	z			z	x						
Rotate turntable2													x	
OP5 Open safety gate														x

Figure 4-1 Chart of Operations 1,4 and 5 and their potential cycle time variability

In order to reduce the cycle time leaving OP6, there were three possibilities:

a) Reduce the x's or intrinsic cycle time of each station

b) Reduce the load time and variation at OP5 and OP3 (eliminate y's)

c) Reduce the load time and variation at OP1 and OP3 (eliminate z's)

4.1.1 Reducing the x's

Each station was originally designed to a 48 second cycle time. Unfortunately this tooling was designed in Germany exactly the same for three plants in three different countries with three different safety standards. The original design utilized light screens to prevent machine operation. A light screen consists of several beams of light connected to a relay. When an object (such as a person) breaks the light beam, the relay trips out which is connected to the main output coil that powers the machine movement. In England, these light screens do not meet the plant's safety standards. In order to comply with these safety standards, a physical guard was retrofitted on each of the tooling stations with an operator interface. These guards must be completely closed before the tool is allowed to operate. The retrofit has added 6-7 seconds of cycle time to each operator stand. The initial design of 48 seconds now has a design minimum of 54 seconds at operations 1 and 5. To reach the target of 48 seconds, each machine's movement must be optimized. It is also important to maximize the operator load time window to account for any operator variability. By maximizing the window for operator load, both "x's" could be reduced and "y's" could be eliminated.

4.1.2 Eliminate the y's

Initially operation 1 had a 22 second load time and 26 seconds of non value added time for the operator, such as waiting for tip-up to return and the turntable to turn. Exchanging the two-position turntable for a three-position one in the original design stage for both turntables would have eliminated the problem with operator wait time. The operator then would have had the entire cycle time to perform the parts loading. Because the redesign was cost prohibitive at this stage, it was necessary to optimize the existing tooling so that the operator could increase her window of load time. The objective was to "bury" as much tooling motion during the non value added time. The following elements of the machine's operation were buried in OP1:

1) OP1 turntable clamps were opened early during the rotation of the turntable instead of after rotation of turntable was complete.
2) OP1 locating pin was retracted early during the rotation of turntable.
3) OP2 robot cycle times were optimized.
4) OP1 safety gate was sped up by reducing friction between wheel and rail

5) OP3 tip-up was optimized by altering parameters in variable frequency drive package

The optimization of the OP3 tip-up produced the greatest throughput improvement. We discovered that the parameters had been changed after a previous breakdown in an attempt to repair the tip-up. While the root cause had been determined to be a relay failure unrelated to the parameters, these parameters were never adjusted back to their original values. By adjusting the drive parameters to their original state and further optimizing these parameters by adjusting acceleration values, our team was able to gain about 3 seconds of cycle time in operation 10. The above 5 changes resulted in a change of operator non-loading time (wait time) from 26 seconds to 18 seconds in operation 1. This allowed the operator a 30 second window to load parts. The operator could presently load parts in 33 seconds leaving 3 seconds of time to reduce by optimizing the operator load station design. A recommendation was made to have a industrial engineering study of the operator work area to improve both ergonomics and operator efficiency.

4.1.3 Eliminating the z's

Not only did the tip-up drive parameter optimization create a greater load window for the OP1 operator, it also gave the operator at OP5 more time to load his parts. Since the tip-up now accelerated faster to its load position, the OP5 operator did not need to wait as long for the tip-up to load, and this saved about 3.5 seconds of cycle time.

Another source of eliminating cycle time at OP5 dealt with adding an additional operator. OP5 consisted of an operator loading 9 parts to the turntable. First, the operator loaded parts on the left side of the turntable. Then she needed to walk back to her parts bins and pick up more parts that were loaded to the right side of the turntable. Finally the safety gate came down. The operator waited for the turntable to turn and receive the tip-up's underbody, the turntable to turn again, and the safety gate to rise (See Figure 4-1). In addition, 2 more parts would be added to this station during the next model change. Since it was very difficult to perform this job in 30 seconds, we investigated our sister plant's operations to determined how they had solved their cycle time issue. We found that although they did not have the same safety gates (5-6 additional seconds of cycle time in England) nor the extra upcoming 2 part model content, the sister plant was already using an additional operator. When Luton utilized the additional operator, OP5 was easily loaded in 25 seconds.

4.1.4 Summary

The optimization of the underbody line to improve throughput utilized various strategies. The location of the bottleneck was determined by observing the buffer levels within the line. Once this bottleneck was located and a synchronization problem observed, two strategies were used to eliminate the problem. Efforts were made to reduce non-value added operator wait time and therefore reduce total station cycle time. Through the optimization of a drive package, the elimination of redundant steps, and communication with a similar plant, the underbody bottleneck was eliminated increasing overall throughput on the line by approximately 15%.

4.2 Framing 1 cycle time optimization

In order to gain more familiarity with the plant, I moved from the Rear Underbody line to the Framing 1 area to investigate potential throughput improvements in this area. The Framing 1 area assembles the two underbodies and the dash panel together. First, the front and rear underbody are presented to a loader on their own electrified monorail carrier. The loader drops from the overhead buffer area onto a lift and carry transfer system. The lift and carry system is a seven station line. The first station utilizes an operator to load an ID tag on the vehicle for option and scheduling information throughout the Body Shop. The second station welds the front underbody, the rear underbody, and the dash together for dimensional positioning, while the third through the fifth stations attaches the inner wheelhouses and also performs some resistance welding respot on the vehicle.

After the Framing 1 system, the remaining section of the Body Shop utilizes a skid system where a unloader loads the body of the vehicle to a skid that travels with the body to each operation until it is loaded to the paint conveyor. It is critical to load a body frame from Framing 1 to the skid system every time a skid is available since a delay at this station can ultimately reduce Body Shop system throughput. For example, if Framing 1 is consistently slow relative to the skid system, a backlog of skids can develop in the return buffer. Since the return buffer's capacity is smaller than the number of skids in the system, it is possible that the return skid buffer can fill up and available bodies for paint cannot be shipped to paint because there is no room to put the empty skid. Therefore, loading jobs from Framing 1 to the skid system is very important to the overall throughput of the Body Shop.

The cycle time of Framing 1 was designed for 75 jobs an hour. Based on data collected, the current cycle time of the system was 72 jobs and hour. This data excluded downtime, blocked, and starved conditions on the line. Improving the cycle time on the line to its design level or better would allow for an increase in throughput out of Framing 1. The cycle time of Framing 1 can be divided into two segments: the cycle time of each individual station on the line and the cycle time of the lift and carry transfer device. Each station waits for the lift and carry transfer to raise the job, shift it to the next station, lower the job, and return the transfer rail to the home position. Then each station performs its individual operation such as the ID load by operator in Station 1, or the load and resistance welding of the dash to the underbody in Station 3. The cycle time for each station is:

Cycle time of station = cycle time of individual operation + cycle time of transfer

When observing Framing 1's individual operations, we noticed that 3 of the stations on the line had the highest cycle time of 37 seconds. The transfer cycle time was 13 seconds leaving a total cycle time for the line of 50 seconds which yields a rate of 72 jobs an hour. In order to reach the design cycle time of 75 jobs per hour, at least two seconds had to be reduced out of the total cycle time. This reduction either had to be achieved by reducing two seconds out of the three 37 second stations or by reducing two seconds out of the transfer cycle time. Since reducing the time out of the transfer device would reduce the cycle time of every station in the line, I focused on the transfer first.

The transfer device utilized 13 seconds of each cycle time in Framing 1. After each station's cycle complete, the transfer returned, then raised the jobs up, shifted the six jobs forward to stations 2 through 7, and finally lowered the jobs down. The stations then clamped up each job, welded the job in its proper position, and unclamped the job for each cycle. Similar to the Underbody Rear line problem described above, the Framing 1 transfer time can be considered as non-value added time or set-up time for each station. In accordance with lean manufacturing principles, reducing waste can be accomplished by reducing set-up times and improves the system throughput. Any optimization in the transfer time would reduce the cycle time of each station in Framing 1, and hence increase the throughput.

From the Framing 1 system, there were two possibilities for optimizing the transfer time. First, we could try to speed up the transfer drive motion. Second, we could try to "bury" a portion of the transfer time into the cycle time of each station. After investigating the drive parameters of the transfer line, it was determined that for the drive's loading capacity, no additional acceleration could occur without potentially reducing the rated life of the drive. Therefore, we investigated "burying" the transfer time.

When looking at the transfer time, two and a half components of the transfer time are impossible to bury. The first element of each station's cycle entailed clamping the body in the station. This could not occur until the transfer had raised, advanced, and lowered onto the locating pins of each station. Therefore, only the second half of the lowering stroke of the transfer and the return of the transfer had any potential for being eliminated from the total cycle time of Framing 1.

As the transfer lowered during its second half of stroke, clamps could be closed early to start the cycle earlier than before. This would save about 0.5 seconds for every station. Resistance welding robots could be moved to a "pounce position" thereby engaging the robot drives saving another 0.5 seconds in the four stations with robots and the three press welding machines could also be moved to their lowered position further burying transfer time (unmeasured savings). Since the second half of the stroke to lower only encompassed about 1.0 seconds, this was the maximum allowable transfer time that could be buried during the transfer lowering.

The transfer return time offered a potential cycle time savings of 4.5 seconds. Presently, the transfer returned after all operations were completed at every station. When further inspecting the Framing 1 assembly line, only Station 1 had an interference with the transfer during its cycle.

Station 1 loads the two underbodies from the overhead buffer to the line. The loader's steelwork when completely lowered physically interfered with the lift and carry return rails. I had seen a similar problem with a loader and a lift and carry interference in my previous job at a truck assembly Body Shop. We had solved the original problem by raising the details of the station higher in order to load at a higher position and prevent the interference with the return rails from occurring. The same concept could be transferred to the Luton Body Shop Framing 1 assembly line. Three pedestals in station 1 contain all of the locating pins and clamps. By building 20 inch spacers under each pedestal to raise the entire station up, the loader would not interfere with the returning rails and the two processes could operate independently. The ramp on which the operator loads the ID tag also would need to be raised up to prevent any ergonomic burden to the operator. When this solution is implemented to Framing 1, the cycle time of the entire line will be reduced by 4 seconds.

4.2.1 Summary

Framing 1 utilizes equipment strategies that are similar in many automotive Body Shop facilities. One important aspect of the Luton Body Shop system relates to not starving the skid system that ultimately feeds the paint department. One way to achieve improved throughput at Framing 1 is to optimize its cycle time. By transferring learning from a similar situation in a different plant into a new plant, low-cost alternatives for throughput improvement can occur.

4.3 Body Sides Buffer Use

A third area of the Body Shop in need of throughput improvements was the Body Sides area. This subassembly area built the left and right sides of a car. Once the two body sides parts are subassembled, they are stored in a electrified monorail buffer that feeds the Tabbing area. The Tabbing area, located on the skid system, attaches the body sides onto the underbody/dash from Framing 1 in order to position the sides in the Framing 2 area. Because the Body Sides are attached late into the process and are coupled to the skid system, the throughput of the Body Sides line can quickly affect the system throughput to paint.

The Body Side line consists of 30 distinct stations (See Figure 3-1). These stations assemble the inner and outer body sides. The outer line consists of 11 stations while the inner line also consists of 11 stations. The inner and outer are then married and welded together in the next two stations. After the part marriage the body sides are placed in a buffer of 5 jobs. Because this buffer follows the marriage station, both the inners and outers sub-assembly stations are effectively coupled to each other. If any part of the inners breaks down, the outer area must also stop. Finally the remaining respot welds are added to the body sides pieces in the last 6 stations. A material handling robot loads jobs onto the electrified monorail system as a buffer to the Tabbing area.

After observing the Body Sides line, I noticed that the buffer in the middle of the line was not being used. The buffer always had 5 parts in it. This additional WIP would not empty out if any one of the previous 24 stations in the Inner and Outer sub-assembly broke down. After inquiring into the reason why this buffer was never emptied, an engineer told me about the story of a "Japanese guru" who told the plant to never empty the buffer so that management could quickly locate which station had a problem. Likewise, this buffer could never be refilled after a breakdown on the respot line since the buffer was never lower than the maximum 5 jobs. Because the buffer was not used, all 30 stations on the Body Sides line were coupled together. The electrified monorail buffer at the end of the line does decouple the Body Sides line from the Tabbing station, though.

In order to analyze the expected efficiency, I consulted the lead engineer for the line to determine his estimates on mean time to repair (MTTR) and mean time between failures (MTBF). The inner and outer area was treated as one area (M1) and the respot area as another area (M2). We assumed that the MTTR and MTBF data had an exponential distribution.

M1 Data:	MTTR 4 minutes
	MTBF 11 minutes
M2 Data:	MTTR 2 minutes
	MTBF 22 minutes

From this data, the failure rate (p1, p2) can be calculated as 1 / MTBF. Similarly the repair rate (r1, r2) is calculated as 1 / MTTR.

r1 = 0.25 r2 = 0.50

p1 = 0.0909 p2 = 0.0455

the isolated efficiency of an area can be approximated using the formula e = r / (r+p) (Gershwin, *Manufacturing Systems Engineering,* 1994). Therefore, e1=73.3% and e2=91.7%. The designed efficiency for the line was rated at 80%. Based on this data, the current maximum efficiency of the line as a whole is 73.3% since this is the smaller efficiency of the two areas. We assume an infinite buffer between area 1 and area 2 to decouple the effects of the M2 on M1.

In order to analyze this data, certain assumptions must be made. Because the cycle time of the line is effectively the same for almost all stations, we can think of this aggregated line as a deterministic two machine line with a buffer in between. According to Gershwin (*Manufacturing Systems Engineering*, 1994), deterministic processing time considers that the length of time that a part is in a machine is fixed, is the same for all machines and is known in advance. The first 24 inner and outer stations did not have any buffers between stations. We assume that the cycle time of each station one minute per cycle. The second six stations also have a cycle time of 1 minute and are separated from the first 24 stations by the unused buffer.

By utilizing this buffer, we would increase the Body Sides and overall system throughput. I wanted to quantify the magnitude of this gain by comparing the case using the data without the buffer with the case of using the full buffer capacity.

4.3.1 Case 1: No buffer

The case of no buffer effectively couples all 30 stations together. As soon as any machine fails, all stations in this area fail. While there is a remote possibility that more than one machine could fail at the same time in this area, the effect of this is quite small and rare (second-order dT squared effects). Failures are also considered operation dependent in that the station only fails while operating. In most cases on the assembly line at the plant this is the case. Other anomalies such as utility failure to larger areas of the assembly line are neglected since we are only trying to compare the effect of a buffer on total line efficiency. According to Gershwin (1994), the efficiency of the line for many stations that all have the same r and p can be approximated by:

$$e = 1 / (1 + n(p/r))$$ where n is the number of stations (Equation 1)

Looking at our first 24 stations, we assume that each station has the same r and p value. By plugging .733 in for e and 24 into n, the p/r ratio can be determined as $p/r = (1/e - 1) / n$ or 0.01515. Then the same r1 is chosen for each machine because on the average each station is repaired in 4 minutes. This gives a p of .00378 and an e for each station of .985. Therefore, from the calculations, each of the 24 stations on the average has a utilization efficiency of 98.5%.

Next the 6 respot stations were analyzed to determine their individual utilization. Similarly, plugging in .917 for e and 6 into n, the p/r ratio is 0.01517. This results in an e of .985 meaning that on the average each of the six stations has a utilization efficiency of 98.5%.

Effectively, all 30 stations have individual utilizations that are the same. Since each station utilizes similar electrical and mechanical equipment, the assumption of similar individual utilization makes intuitive sense. There are few reasons as to why on the average a machine would fail more often than another within the body sides area.

Making the assumption for all 30 stations of a similar utilization allows for the reiteration of Equation 1 above with n = 30. We choose a p and r that creates an individual e of .985 for each station (r=.25, p=.0038). The overall efficiency of the body sides line without the use of the buffer is 68.8%. At the time of this calculation, the Body sides line was producing about 41 jobs per hour out of a designed 60 jobs per hour excluding blocked and starved data. The actual efficiency of the line from this data is 41 / 60 or an efficiency of 68.3%. From this data, it is safe to say that the calculated efficiency approximates the observed efficiency. Next we calculated the effect of using the buffer on the utilization of the assembly line.

4.3.2 Case 2: Buffer

When considering the buffer, the body sides line effectively becomes divided into two stations with a potential buffer of 5 units. As described earlier these 2 areas have the following characteristics:

r1	= 0.25	r2	= 0.50
p1	= 0.0909	p2	= 0.0455

Because the cycle time of each station is approximately 60 seconds, we will treat the system as deterministic. The characteristics of the system were entered into a program designed by Dr. Gershwin called det2line. This program analyzes the differential equations needed to calculate overall efficiencies of any two-machine deterministic assembly line. Boundary equations of the system are also characterized based on the r, p, and n (buffer size) variables. (For a detailed explanation, see Gershwin, *Manufacturing Systems Engineering,* 1994, Chapter 3). To determine whether using this model is acceptable, we must compare how its assumptions relate to the Body Sides system.

4.3.2.1 Relevant assumptions of Gershwin Model in relation to Body Sides

1) The first machine is never starved of material and the second machine is never blocked. For comparison with Body Sides, the blocked and starved data was removed. The first station became starved when material shortage occurred and the last station became blocked in the rare occurrence when the Body Sides line buffer of over 200 parts was full due to upstream breakdowns. The blocked data was manually accumulated by

front line supervisors from timers on the programmable logic controller (PLC) and the man-machine interface (MMI).

2) All machines have the same cycle times. The model describes the cycle time in terms of the time unit for the model. To get actual output, the results from the model can be scaled by the actual cycle time. As described above, the cycle times of each station in the Body Sides were nearly the same.

3) The buffer can gain or lose only one job in a time period. This is valid for the Body Sides design.

4) A machine's failure and repair time have a geometrical distribution. This means that when a machine is operating there is a probability at each time cycle that it may fail. This distribution is memoryless, meaning that a previous failure does not affect any future failure. While no data was accumulated for the Body Sides to determine whether the repair time or failure time was geometrically distributed, previous work in reliability theory has shown that assembly equipment approximates this curve over long periods of time (McCormick, *Reliability and Risk Analysis,* 1981).

5) Operation Dependent failures: As described above, the Luton Body Shop is not concerned with time dependent failures due to their rare occurrence. The wear and tear on equipment as well as most breakdowns (poor location of metal, failing switch, etc.) are based on the machine actually operating.

6) There is no scrap as a result of processing. On the Body sides line, the scrap rate was negligible and was ignored for the purposes of the model.

7) The model looks at steady state analysis. The body sides line did have some slight changes in cycle time at operator stations depending on different times of the shift. These effects are also neglected in the model as short-term effects.

Based on evaluating the Body Sides line against the underlying assumptions of the Gershwin model, one may feel comfortable with the validity of the model's output.

Using the Det2line program with a buffer size of 5, we find an efficiency for the whole line at 72.2%. It is clear that utilizing this buffer increases the utilization of the Body Sides line. Since the line operates at 60 jobs per hour, the overall throughput gain from this change is:

(72.2% - 68.8%) * 60 JPH = 2.04 JPH

Both the Left and Right Body Sides can implement this change to make the in-line buffer functional.

4.3.3 Summary

The Body Sides Line is a classic case of utilizing buffers to increase throughput. When too many stations are coupled together without a buffer, even if each individual station has a high utilization, the overall throughput of the line can suffer. Using C-More (see Chapter 5), another throughput measurement and analysis tool, more buffers were hypothetically added to this line to decouple the body side inners and body side outers. These buffers also increased the total throughput of the line. When I inquired into the feasibility of adding these buffers, I found that a buffer between the inner panel and the marriage station was originally planned but eliminated due to space requirements.

4.4 Summary

In most Body Shops, one can find several strategies to optimize throughput at the micro level. While optimizing on various individual lines may neglect the larger system bottleneck approach, it is an effective kaizen (continuous improvement) initiative that also allows employees to gain greater familiarity with the Body Shop equipment and process flow. Many of the projects at the micro throughput level gained theoretical significant increases in output.

Project	original JPH	improved JPH
Underbody bottleneck optimization	48	55
Framing 1 cycle time optimization	72	75
Body Sides buffer utilization	60	62

Figure 4.2 Table of Micro Throughput Projects and their Improvements

A large issue in these improvements depends on the execution of the above plans. Unfortunately, the last two projects, while identified in the early parts of the internship, had not been implemented as of the end of the internship. Due to the high pressure on improving performance, managers had a difficult time prioritizing and organizing which projects would afford the greatest system throughput. Limited technical resources also played an important factor in completing the above proposed work. Because of these limited managerial and technical resources, the Luton plant must primarily focus on macro throughput issues that can identify bottlenecks of the entire Body Shop system and maximize the impact of the resources. From these micro throughput improvements, I turned to C-More, a bottleneck analysis tool that can determine system bottlenecks and the impact of improving these bottlenecks. This is the focus of the Chapter 5.

Chapter 5 Macro Throughput Improvements

As discussed in Chapter 4, the Luton plant afforded several opportunities for optimizing individual subassembly lines. Unfortunately, the plant was experiencing significant throughput problems in the Body Shop during its ramp-up phase. These problems could not be easily identified with the existing methods. Initially, most of the breakdowns in the start-up mode were major equipment failures or learning curve experiences. For example, in my first tour of the Body Shop prior to my internship, the tip-up that I optimized in the Underbody Rear line had an 8 hour breakdown. While many solutions were explored for repairing the tip up such as rebuilding the drive unit and changing the drive parameters, the root cause came down to some faulty relays. The management team has become experienced and comfortable in the firefighting and problem solving mode. As production started to ramp up, the solutions to problems were less obvious and the breakdown durations were much shorter.

A second factor in maintaining throughput stems from Luton's limited Body Shop resources. Because the plant staffs less engineers and maintenance workers than other similar GM European plants (Antwerp), resources can not be allocated to every area in the Body Shop at the necessary level of detail. Therefore, it is necessary to come up with a solution that directs resources to the areas in the Body Shop that will create the most impact on net system throughout to the Paint Shop. I proposed using a software program named C-More. This chapter discusses the C-More analysis tool in detail from its history and a general technical overview, to C-More's applicable functionality in the Luton plant and the software's needs with respect to Luton's current and developing information technology (IT) systems. This chapter also presents Luton's current bottleneck strategy, as well as the understanding and results that C-More has already produced in the Luton Body Shop.

5.1 C-More

C-More is a bottleneck analysis tool developed by the GM Research Center for use in GM assembly plants. This proprietary software predicts where bottlenecks occur in a system and the impact to total system throughput of improving the bottleneck stations. C-More also allows management to experiment with improvement strategies and buffer analysis through "what-if" scenarios. This chapter does not present the details of the C-More model due to proprietary reasons; rather, this chapter describes C-More on a general level. However, we discuss C-More in greater depth as it relates to the application of the software in the Luton Body Shop. Finally, this chapter presents both data issues and organizational mindframe as they relate to C-More.

5.1.1 History and Background of C-More

The General Motors Research Operating Sciences Department in 1987 originally developed C-More under the name "C-Thru". Collaborators on the project included Dr. Steven Graves of MIT. As of February 1996, GM had distributed 1500 copies of C-More to 850 officially trained users. GM utilizes C-More in many phases of the product development cycle. In facility design, engineers use C-More to design buffer sizes based on the rated design specifications of the specified equipment. In facility operation, C-More becomes more powerful by analyzing actual data and locating real bottlenecks in the system. Some plants have used C-More to justify new equipment purchases and schedule needed overtime.

General Motors first tested C-More at the GM Truck Linden plant. Since then, C-More has been utilized in parts plants throughout Delphi and Delco (see George, LFM '97 thesis), and in many General Motors North American Assembly plants including Saturn. The C-More installation in Luton is the first plant use of C-More in General Motors' International Operations. While most managers have never heard of the C-More product, the Vice President of Manufacturing who previously managed an assembly plant in the

United States strongly advocates the software. Some of C-More's successes in % improvement for plant throughput are as follows:

Saturn	12.3%
AC Rochester	45.6%
Lake Orion Assembly	12.9%

While these plants implemented C-More throughout the entire plant, I planned to implement C-More only in the Luton Body Shop since this area was the plant bottleneck and integration problems between three departments might not produce results. After a complete installation of the C-More system in the Luton plant, I would expect at least a 10% overall improvement in throughput.

The C-More product aligns the Luton plant with General Motors' long term lean manufacturing strategy by helping to reduce variation of processes, by providing focus on preventative maintenance issues, and by locating the areas to increase machine and process capability.

5.1.2 General Technical Analysis of C-More

C-More utilizes mathematical analysis to perform the calculation of throughput. Unlike simulation that can take many iterations and long periods of time to run, C-More's calculations result in quick quantifiable results. C-More is based on Markov processes and queuing theory. The theory is very similar to the two-machine deterministic processing model described briefly in Chapter 2. The power of C-More is that C-More emphasizes the analysis of a complete system that deals with the interactions of the blocking and starving of several workstations. The buffer sizes and the system parameters determine the effect of these blocking and starving interactions. C-More looks at multiple stations (versus just 2) by aggregating performance parameters around each buffer in the system. Each station's performance is calculated by performing a series of iterations on the model until a feasible solution results. The performance data shows the location of bottlenecks and their impact on the system throughput. Coupling C-More's data with a management focus that embraces the theory of constraints can create a significant, quantifiable improvement in system throughput.

5.2 Current Luton Plant Situation and Prioritization Strategy

In General Motors, a typical assembly plant contains many similar elements. Luton plant is no exception. After the start-up phase, most automotive assembly plants typically plateau in vehicle output with a high throughput variability. Luton's production numbers for the Body Shop were flat over a 16 week period last spring and summer. Similar to other GM plants, Luton's throughput was 25% below its designed rate and this loss in production was made up by scheduled overtime. There was also much finger pointing in the Body Shop between maintenance, production, and planning engineering as the reason for some of the throughput problems (instead of blaming the system). Failure and repair data on some of the machines was collected but not really used (or accurate).

When arriving at my internship, there was no formal process for production monitoring or breakdowns resolution. My first assignment was as a member of a "throughput" action team on the Underbody Rear line. This first attempt at solving bottlenecks involved three maintenance operators and myself investigating the assumed bottleneck, the Underbody Rear and Front lines. Each team member watched the line and proposed improvements to the system as well as investigated existing suggestions for the area. Data was manually acquired by the team members. My micro throughput project on the Underbody Rear line (see Chap 4) stemmed from the work on this team. While this team produced results on the Underbody Rear line, another idea for tackling throughput issues resulted from the Antwerp plant system.

In GM's Antwerp, Belgium Body Shop (for more information on the Antwerp Body Shop, see Kramer LFM '97 thesis), data on equipment is collected and ranked by the number of fault occurrences in each subassembly line. (See Figure 5.1 for an example of Luton's performance report.) Luton's Body Shop implemented the Antwerp model. For example, on the Body Sides line, maintenance team leaders collect data for each station. A student intern collates this data using a Microsoft Access program. The program then creates a Pareto chart that orders faults by the number of occurrences. Next, the lead engineer on each line prioritizes the five stations on the chart that he believes need the most focus. Typically, the engineer selects the first five stations on the chart. Throughout the week, the people who work on the respective line, focus their efforts on these stations during PM, redesign, etc. Unfortunately, this approach has three fundamental problems.

1) Some of the long duration breakdown items may not occur very often, yet these breakdowns may have tremendous impact on throughput. For example, on Figure 5.1. BOCL 3.3 collected the second most repair time, although it scored on the far right of the chart. There is a high chance that the lead engineer may not focus his resources on that direction even though the station had accumulated high downtime.

2) This method neglects in-process inventory. If an area, BIL4.2 for example, has a large buffer between it and the next station, the frequency and total breakdown time may not affect the throughput of the Body Sides at all.

3) Using this method focuses people on every sub-assembly line. It is highly likely that the committed resources on the Underbody Front line may not be fixing a system bottleneck at all. While these people may be working on their individual Underbody Front issues, their effect on system throughput may be negligible. In the case of Luton Body Shop, with its serious throughput issues, management must commit resources only to the areas that maximize total throughput to paint.

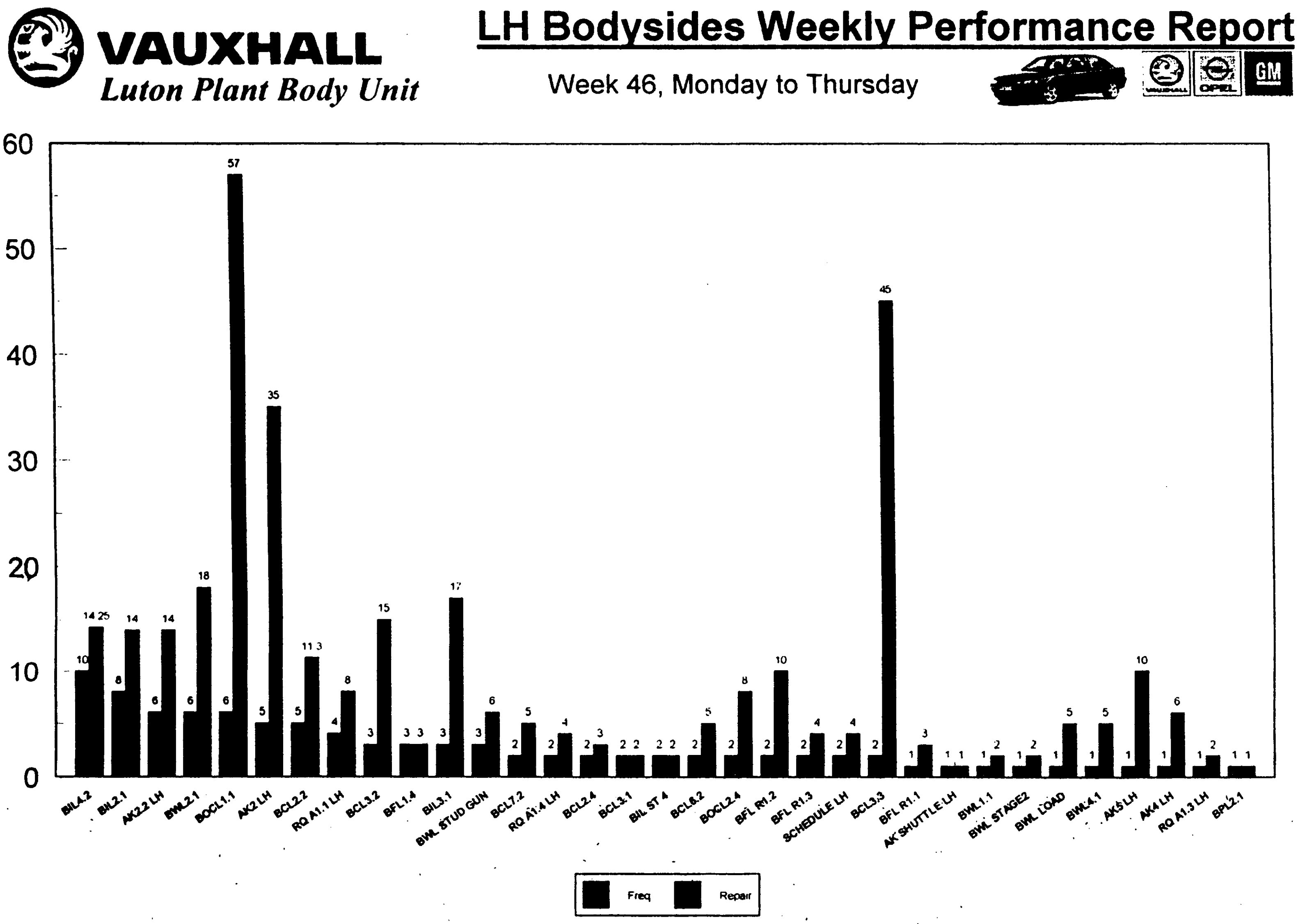


Figure 5.1 Example of typical Luton Performance Report

Another issue (which will be discussed in detail later) is the availability of good data. At the onset of my internship, there was no MIS system. The Body Shop manager's only reliable source of data was a dry erase board with hourly output figures and total units in buffers. The physical layout of the Body Shop does not allow a person to be in one location and determine which subassembly lines are in failure mode. When the Body Shop had converted to the new model, a decision was made not to develop a facilities monitoring system. As a result, the Body Shop systems engineer has been developing a management information system (MIS). Maintenance team leaders currently write manual data down by pencil and paper. This process creates delay and error in information processing. The new MIS system will automatically capture the repair and breakdown data as well as many other features like current buffer sizes, hourly production rates and the visual states of each subassembly line. I proposed utilizing and ordering the data that will be polled by the MIS in such a way that would be useful to the department. After further investigation, I proposed that C-More should be developed with an eventual connection to the automatic data collection feature of the MIS.

5.3 C-More Software Functionality and Needs

The C-More software essentially is used for three purposes in a plant.

1) C-More estimates plant performance by calculating throughput in JPH and its variability. C-More also calculates each workstation's utilization efficiency and the work in process (WIP) in the total system.

2) C-More locates the bottlenecks in the system. These bottlenecks are ranked by the amount of JPH that can be gained through improving the bottleneck. The calculated JPH improvement is also displayed as well as each bottleneck's utilization efficiency. (For a sample C-More output page please see Fig. 5.2)

MACH-2 v3.00 GM Restricted Page 1

Process: C_More System Performance Analysis 12/17/96 11:23AM

Data Description: Body Sides Right Main

SYSTEM THROUGHPUT CAPACITY SUMMARY

	- Hourly Throughput -				- Daily Throughput -		
Average	Minimum	Maximum	Std Dev	Average	Minimum	Maximum	Std Dev
54.31	16.12	69.00	11.32	1,017.59	869.52	1,155.79	51.02

DEMAND, CAPACITY & PRODUCTION SUMMARY

	Annual (parts/yr)	Daily (parts/day)	
Demand	180,715	769	
Designed Capacity	264,206	1,124	
Throughput Capacity	239,133	1,018	
Actual Production	180,715	769	
Excess Capacity	58,418	249	(32 %)

MANUFACTURING LEAD TIME SUMMARY

Loading time (minutes) that parts spend:

Average WIP Inventory (% of cap)	(parts)	Waiting in In-Process Floats	Having Value Added	Total Manufacturing Lead Time
19.94	18.14	2.66	17.39	20.05

Figure 5.2 Sample C-More Output Page

3) C-More can perform "what-if" analyses taking into account increasing buffer sizes or maintenance policies of improving the bottleneck. These analyses calculate JPH improvement from the proposed policies.

In order to perform all of these calculations, C-More requires several inputs into the model.

5.3.1 C-More model Inputs

The C-More model's data requirements fall into three categories: Characteristics, Scheduled Production and Workstations. The characteristics input data allows the user to describe the system being modeled, to enter in the demand and to input the gross line speed of the designed system. This data allows for model outputs to be compared to the plant's target figures. The scheduled production data consists of parameters that scale the throughput data on a daily, weekly or monthly timeframe. Some input categories in scheduled production are: production days per year, shifts per day, overtime percentage, and mass relief time. C-More uses the workstation input data to calculate the throughput of the system. Because this project focuses on throughput improvements and bottleneck analysis, the workstation input data requirements and their relation to the Luton Body Shop are investigated thoroughly in the next sections.

5.3.1.1 Workstation Input Data

The workstation input data for C-More requires several pieces of information from the actual plant system. First, the system must be divided into individual workstations. Then all of the following information must be gathered or calculated for each station: scrap rate, # of parallel machines, cycle time, buffer sizes, MTTR and MCBF. Finally this data must be entered into the model for calculation and analysis. In order to better understand the functioning of the C-More model, each input characteristic will be defined in terms of its relevance to the Luton body unit.

5.3.1.2 Workstation Partitioning.

C-More defines its model in terms based on a set of serial workstations. Each station consists of several defining characteristics such as cycle time, MTTF, etc. An easy area to model in C-More is the Framing 1 line. In Framing 1, the lift and carry transfer links every station together. Therefore, each station's cycle time begins at the same time. All seven areas of the Framing 1 line have individual tooling stations. C-More divides Framing 1 into seven stations. On the other hand, the Body Sides line is much more difficult to model. One difficult area stems from the inner subassembly. First, an operator loads three reinforcement parts to stationery tooling. Next a material handling robot picks the three parts up and places two of these parts in a second tooling fixture where the robot rotates its end effector to present a weld gun to the fixture. This same robot welds the pieces in place, rotates its end effector again and subsequently loads the third part into a different station. From the example, it is evident that the body sides has a complex process flow and does not use a synchronous transfer device between stations. While one may be tempted to aggregate the Body Sides Inner subassembly operations into one big station, this method neglects the cycle times of the process flow needed to achieve throughput targets. I ultimately partitioned this process flow into four stations for the C-More model.

We considered two more issues when dividing up the Body Shop into operations. First, we made every attempt to not split up a robot into two separate operations, since each robot uses an internal timer to measure its cycle time. Second, because of the linearity assumption of C-More, the Luton model uses feeder lines to deal with parallel process flow. A feeder line aggregates several stations into one station. For example, the Body Sides lines feed into the skid system via the Tabbing station. Since the Body Sides line becomes a parallel process, it is modeled as a feeder line into the main Body Shop model. While the Body Sides line consists of 33 stations, the feeder line aggregates its effect into one station with one set of parameter for use in the main model. Similarly, due to parallel processing of Body Sides Inner and Outer subassembly, the Body Sides model also consists of three internal feeder lines.

5.3.1.3 Scrap Rate and Number of Parallel Machines

The C-More model utilizes a scrap rate at each station to factor in any losses attributed to scrap. Because scrap rates are low in the Body Shop relative to fault time, the scrap rates are neglected in the Luton facility. As the model is further developed, these scrap rates may be added at a later time. The number of parallel machines parameter allows a modeler to define situations where multiple machines perform the same operation in parallel. While it is perfectly acceptable to model each of these cases as feeder lines, C-More provides this option for parallel machines. In the Luton Body Shop, there were three parallel stations in Framing 2. This function is also used in the Underbody Front model where there are two parallel robotic respot areas.

5.3.1.4 Cycle Time

Each station in C-More must have its own cycle time. I developed a spreadsheet (GM Proprietary) that lists each C-More workstation and its corresponding operations for cycle time. Because of issues with non-synchronous transfer devices (see Body Sides Inners subassembly discussion above), it is necessary to capture all the critical cycle times that can affect throughput. One difficulty arises from the measurement of these cycle times. In the case of Framing 1, where stations can be easily defined, the man-machine interface (MMI) already captures cycle times. Operators can record these cycle times off the screen manually each day and input them into the C-More model. On the other hand, the Body Sides line where stations are not easily defined, the MMI does not accurately capture the cycle times as defined in the spreadsheet. Therefore, industrial engineers must time these cycle times by hand and then input this data into the model.

The team developed one solution to overcome the tedious collection of cycle times. Instead of manual data collection, C-More would be linked to a currently developing management information system (MIS) in the Body Shop. A Body Shop systems engineer had developed a prototype MIS as a tool for both real-time decision making (by indicating the current status of the Body Shop equipment) and trend analysis (by capturing failure and cycle time data). There are two ways to capture the cycle time of each station in the MIS.

I had originally designed the workstation cycle time spreadsheet as a basis for building timers in the programmable logic controllers (PLC). The PLC would sum these timers accordingly and each workstation would have one dedicated cycle time timer that would be sent up to the data server. A project appropriation was approved by management to accomplish this task. We needed five PLC programmers for eight weeks to enter in each station's cycle time timer and work on MTTR and MCBF data from the PLC perspective (see below). This method of cycle time collection involved high project management integration and large memory allocation in the PLC. Due to limited memory in the current PLC network design and the use of the VIDIS (see below) specification, we developed an alternate means for capturing workstation cycle time.

The present PLC software design in Luton is called VIDIS. VIDIS is a method of using a fault matrix as the driver for both diagnostic display of faults to the MMI system and as a way to form a logical sequence of events. VIDIS divides the assembly line into its own set of operations (dissimilar to the C-More operations). Each operation is further divided into sequences of events. For example an operation OP40 may have sequences such as clamp tooling, weld with robot 62, weld with robot 63, and unclamp tool. A sequence is further subdivided into steps. Each step looks to see whether certain faults occurred in the VIDIS matrix. If these faults did not occur after a certain time then the PLC moves to the next step in a sequence. Within this specification, VIDIS times each sequence. Because of the limited memory space in the PLC, we proposed that the MIS would use these sequence timers to calculate cycle times. The PLC can indirectly address these existing timers and place each one in a memory allocation area that would be polled by the MIS system. When comparing the existing sequence data for the Body Shop with the C-More operation cycle time spreadsheet, we found no sequence that was divided between two C-More operations. Therefore, each C-More operation is defined as the sum of multiple VIDIS operations. Because the computer power and memory availability is greater in the MIS server than in the existing PLC design, the MIS server stores an operation's cycle time. Then an algorithm that aggregates the sequences according to the C-More cycle time spreadsheet will produce the cycle time for each C-More operation.

5.3.1.5 Mean Time To Repair (MTTR), Mean Cycles Between Failure (MCBF)

The final two pieces of workstation data needed by C-More are the MTTR and MCBF. Three additional observable data points are needed to produce MTTR and MCBF. MTTR can be calculated from the total breakdown time divided by the number of breakdown occurrences. MCBF can be calculated from the total jobs built divided by the number of breakdown occurrences. Therefore, each station needs data for jobs built, number of breakdowns, and total breakdown time.

Because we are most interested in operation dependent failures to determine bottlenecks, we disregard time-dependent failures as anomalies to the system. Reliability theory has also shown that manufacturing equipment typically demonstrates negative exponential distributions for MTTR and MCBF (McCormick, 1981, Reliability and Risk Analysis). When calculating downtime, blocked and starved conditions for the job in station are removed from the calculation. Typical downtime events included are machine failures, carrier return blocked and starves, blocks due to no carriers available, overcycles, and station delay due to operators and lack of material.

5.3.2 Data Collection

It is important to collect reliable data for C-More if it is to produce effective results. We investigated three possibilities for data collection.

1) We considered manual data collected on the plant floor by maintenance team leaders.
2) We investigated the automatic data collection function on the MMI.
3) We developed a long term strategy for integrating C-More with the developing MIS system.

5.3.2.1 Manual Data Collection of MTTR and MCBF

Because of the increased throughput problems in the Vauxhall Body Shop, management requires the maintenance team leaders to log all occurrences of downtime over 1 minute. The team leaders log these downtimes on a pocket sized downtime sheets that recorded the date, shift, and subassembly line as well as the specific equipment, the type of fault, and the duration of the fault. Each day the team leader is supposed to hand in the sheet at the end of his shift. The following day, a student intern enters this information into a Microsoft Access relational database that prints out weekly performance reports by subassembly line with a Pareto of the equipment problems. C-More can use this information if it is reformatted to calculate MTTR and MCBF. By adding an additional table in Microsoft Access that links equipment to C-More operations, the data entered into the database could be collated by C-More operation. We designed a report that showed the number of downtime occurrences and the total downtime for each C-More operation. This, coupled with the jobs built data per subassembly line, gave a MTTR and a MCBF for each C-More station. Most of the analysis we performed with C-More utilized much of the available data from the manual data collection process.

The are many shortcomings of the manual data collection method.

1) It was clear that all of the downtime data is not fully being recorded by the team leaders. One part of the PLC program sums the total downtime for each subassembly line. When this sum is compared to the team leaders sum, the PLC sum was always higher. This implies that not all breakdowns are being recorded by the team leaders.

2) Some areas of the assembly line, such as Tabbing, do not have any data recorded by the team leaders at all. Initially, only the subassembly lines were recorded manually (Underbody Front and Rear, Body Sides Left and Right, Dash) since management assumed them to be the bottlenecks. As a result, only the accumulated PLC downtime could be used in the areas with poor manual data collection. This accumulated PLC downtime was uniformly distributed between each C-More operation on the PLC.

3) Breakdowns of less than one minute are not recorded by the maintenance team leaders. This potentially overstates the MTTR and understates the MCBF.

4) The data acquired from the Access database has to be entered into the C-More model manually. If the Access database is redesigned with the C-More operation as a basic field (as compared to an aggregate field), Access could generate an automatic input file for C-More.

5) Operator errors occur by both the team leaders and by the student intern when taking and entering in data. There have been several instances where a 1.5 minute breakdown was entered in as 15 minutes or a station written by the team leader was illegible. All of these errors in data collection combine to created serious data integrity problems. Similar to any analysis tool, the value of the C-More analysis is only as good as the data that is entered into the model.

Because of these potential errors, we also investigated the use of the MMI automatic data collection.

5.3.2.2 MMI Automatic data collection.

Each PLC has at least one man-machine interface (MMI) called a MACH unit that allows the maintenance worker to interface with the tooling. One of the MMI's capabilities automatically records any faults that occur in the VIDIS fault matrix. Faults in the VIDIS matrix are arranged by three dimensions: sequence, line, and lamp. The line and lamp dimensions are called so because of the old troubleshooting methods used in relay logic that utilized lamps for finding faults. Within the MACH unit, the automatic data collected the time of the occurrence, the sequence, line, and lamp of the fault, the state of the occurrence either ALM (alarm) or CLR (clear), and various reference and message data. (see Figure 5.3 for a sample of automatic output). From Figure 5.3, it is clear that the output from the MACH unit must be further formatted for use with C-More. Since the output is aligned in rows, the data is imported to an Excel spreadsheet for sorting. Each fault logged in this data has an ALM and a CLR event. These CLR events are subtracted from the ALM event to calculate each fault's duration. The easiest way to achieve the end result is to sort by each sequence, line, and lamp. The sums the similar sequenced CLR's and subtracts the similar sequenced ALM's to get a total fault time by sequence. The total amount of CLR's (or ALM's) by sequence results in the number of fault occurrences. Finally, these sequences are correlated to the C-More operations similar to the manual data collection using a sequence to C-More operation conversion table (see Figure 5.4 for an example of this table). This data is coupled with the jobs built on each subassembly line to calculate each station's MTTR and MCBF.

TIME	SYSTEM	NODE	STATE	SEQ	LINE	LAMP	REFERENCE	MESSAGE	
02:24:28	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
02:24:37	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:13:16	CP21AB	01	ALM	02	70	12	STN 1 LOAD	CUTTER PART CONTROL (ONLY RHD) I/P 10189 ON, I/P 10141 ON	
07:13:37	CP21AB	01	CLR	02	70	12	STN 1 LOAD	CUTTER PART CONTROL (ONLY RHD) I/P 10189 ON, I/P 10141 ON	
07:14:10	CP21AB	01	ALM	10	50	04	STN 34 LOAD	SWIVEL UNIT 105.2 BACK I/P 10916 ON, O/P 00592	PG03S10
07:14:21	CP21AB	01	CLR	10	50	04	STN 34 LOAD	SWIVEL UNIT 105.2 BACK I/P 10916 ON, O/P 00592	PG03S10
07:17:29	CP21AB	01	ALM	02	70	12	STN 1 LOAD	CUTTER PART CONTROL (ONLY RHD) I/P 10189 ON, I/P 10141 ON	
07:17:35	CP21AB	01	ALM	10	50	04	STN 34 LOAD	SWIVEL UNIT 105.2 BACK I/P 10916 ON, O/P 00592	PG03S10
07:17:48	CP21AB	01	CLR	10	50	04	STN 34 LOAD	SWIVEL UNIT 105.2 BACK I/P 10916 ON, O/P 00592	PG03S10
07:18:17	CP21AB	01	CLR	02	70	12	STN 1 LOAD	CUTTER PART CONTROL (ONLY RHD) I/P 10189 ON, I/P 10141 ON	
07:19:06	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:19:07	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:20:04	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:20:13	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:20:51	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:21:01	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:21:47	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:21:56	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:23:07	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:23:17	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:24:09	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:24:12	CP21AB	01	ALM	02	60	01	STN 1 LOAD	LOCATION UNIT 107.1 FORWARD I/P 10119 I/P 10119 ON. O/P 00107	PG02 S01
07:24:19	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:24:22	CP21AB	01	CLR	02	60	01	STN 1 LOAD	LOCATION UNIT 107.1 FORWARD I/P 10119 I/P 10119 ON. O/P 00107	PG02 S01
07:24:51	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:25:00	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:25:49	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:25:58	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:26:38	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:26:47	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:27:50	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:27:59	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:28:42	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:28:52	CP21AB	01	CLR	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03
07:30:05	CP21AB	01	ALM	11	64	02	STN 34 WELD	CLAMP UNIT 104.7 FORWARD I/P 10967, TIMER REG 48040 , O/P 00609	PG02S03

Figure 5.3 Automatically Generated VIDIS (MMI) Output

PLC	Sequence	Description	Workstation in C-More Code
42	03	TT R1 Movement	BSRH12
42	04	TT R1 Tooling R1.1	BSRH12
42	05	TT R1 Tooling R1.2	BSRH13
42	06	TT R1 Tooling R1.3	BSRH14
42	07	Robot BFL 1.1	BSRH14
42	08	Robot BFL 1.2	BSRH15
42	09	Robot BFL 1.3	BSRH13
42	10	Robot BFL 1.4	BSRH13
47	03	ST A1 TT	BSRH16
47	04	ST A1 Tooling A1.1 HB	BSRH16
47	05	ST A1 Tooling A1.2 KF	BSRH16
47	06	ST A1 Tooling A1.3 HB	BSRH17
47	07	ST A1 Tooling A1.4 KF	BSRH17
47	08	ST A1 Robot BOL1.1	BSRH18
47	09	ST A1 Robot BOL1.2	BSRH17

Figure 5.4 Conversion of PLC Sequences to C-More Workstations

This MACH unit automatic data collection method also creates problems.

1) The automatic data collection is only consistently operational on the Dash line. Every other line needs PLC modifications in order to use this automatic data collection feature.

2) The automatic MMI data collection method records redundant faults within the same PLC. For example, if a clamp faults on a station, the VIDIS specification also logs a fault for the adjacent robot waiting to pick the part out of the station. Therefore, two faults are logged where only one fault actually occurs. Another typical example of the multiple fault takes place when a safety gate for a zone is opened. While this individual fault

shows up in VIDIS (open safety gate), each sequence also has a similar fault (Seq. 14 safety gate open). Due to this multiple registering of faults when only one fault occurs, all additional faults resulting from the first fault must be removed from the data. Each additional fault also has a CLR signal that needs to be removed from the data.

3) The automatic MMI collection records redundant faults across PLCs. This becomes a major problem as each raw output file is saved every day by separate PLC. If a robot in one PLC is waiting for a faulty station in another PLC, both faults will be registered in separate files. When sorting the data, each file's data is compiled separately. Due to this redundancy problem it would be necessary to combine multiple PLC files and run the sorting report stripping out redundant cross-PLC faults. The current sorting technique takes 5 minutes to aggregate (without the fault stripping feature) and each MMI output file contains about 333kb of memory for each day. On subassembly lines with 7 PLCs it would be necessary to compile 3.5MB of data in the sorting program or about 700 Excel pages of data per day per subassembly.

4) Some redundant faults really are not redundant according to C-More. Any simultaneous fault separated by a buffer should be included in C-More operation fault time. The conditional removal of some redundant time faults and not others is difficult to accomplish with the current Excel sorter. As a result, we would need to write an Access program that conditionally blocks out certain combinations of simultaneous faults.

5) The current Excel sorter for data does not produce an automatic export file for C-More. Therefore, this data must be typed into the model by hand. One could also write this into any new developed Access relational database, but these additional features add cost and development time.

In summary, the automatic MMI data collection was never intended to be used with the C-More analysis tool. Several manipulations and removal of redundant faults need to be added to the programming to allow C-More to receive valid data. Since the MMI method requires many resources and a redesign of the sorter, the alternate solution of collecting data using the developing MIS system was investigated next.

5.3.2.3 Automatic Data Collection using Developing MIS

As described earlier, the Body Shop systems engineer is developing a new MIS system for both on-line status of the Body Shop as well as trend analysis of fault data. Since fault data is already tracked using the MIS system, there is a tremendous opportunity to customize this system to account for the C-More's needs. Because the MIS system had not been fully developed as of the beginning of the internship, the C-More operations are integrated into the MIS design. Each PLC records all the VIDIS faults to the MIS. The MIS has the sufficient computing power to only record in its database the first fault that occurs in between any set of buffers. This design of the first-up fault fulfills C-More's model assumptions. The MIS also has the capability to overcome many of the shortcomings of the previous two data collection strategies.

Since the MIS is being developed for the entire Body Shop, the MIS is C-More workstation centric by design. The development of MIS started in the subassembly lines and later will encompass the skid system. By developing in this order, the MMI automatic data and the manual data collection was compared to the MIS data collection. As expected, the MIS collected more data than the manual data collection and sorted through the redundant data produced by the MMI. Since all of the data is recorded in the same relational database file, cross PLC fault redundancies are also eliminated by the MIS. Because this data collection strategy is also integrated into the design, transcription error is minimized by reducing multiple operator entry. The MIS can also create export files to C-More that prevent manual entry (and further transcription error) into the C-More software. Finally, due to issues such as automatic cycle time collection with the MIS (see above), PLC programming resources are already committed to work on the MIS project and can coordinate fault data transmission from the PLC to the MIS.

5.3.2.4 Summary of Data Collection Methods

Based on the three methods, the MIS data collection solution offers the best opportunity for the most accurate data. Since resources are already allocated to this project, this most critical issue is the timeframe implementation. The rollout of the MIS system will take months to implement. Therefore, it is necessary to utilize the manual data collection method in the short term. Management currently places a greater emphasis on collecting this data than using the MMI data. Team leaders have been reinstructed in the importance of recording the data and more areas of the Body Shop have started the manual data collection program. While this data is not complete, it allows for the focus on the some areas of the Body Shop. The data has assisted the Luton Body Shop in locating some of its bottlenecks.

5.3.3 Additional C-More Issue: Feeder Lines

The C-More throughput analysis tool treats any model as a serial production system. The Luton Body Shop is not a completely serial line. For example, the subassembly lines (Dash, Underbody Front and Rear, Body Sides) all work in parallel and join together at Framing 1 and Tabbing. In order to account for parallel lines, C-More must use feeder lines.

Feeder lines are separate models within the larger C-More model. Each feeder line is modeled within a separate DOS file. The aggregate effect of each feeder line is placed into the larger model as a single station for system analysis. Thus, fifty stations can be aggregated into one. An example of feeder lines can be best demonstrated by the Body Sides subassembly line. In the master model, each Body Sides subassembly line (left and right) feeds into the tabbing station area. These body sides lines are modeled in separate files. The aggregate cycle time, MCBF, and MTTR are used as the parameters of a station in the master model. At the same time, Body Sides Left line also utilizes three feeder lines within its model file. The Body Sides Inner panel and Outer panel are built up separately and married together in the middle of the Body Sides line. Therefore, the Body Sides Inner is modeled as a feeder line. Similarly, since there are two separate subassembly operations in the body sides outer area, these operations are also modeled as feeder lines.

Feeder lines do create the following limitations to the model.

1) When two feeder lines follow each other in the master model, it is difficult to precisely pinpoint bottlenecks. In the master model, output from C-More may show that a feeder line is the greatest bottleneck and would have the most impact if fixed. Since this subassembly line may consist of 50 stations that are aggregated as one station in the master model, there may actually be one station on the main line that has a greater effect on throughput than any of the individual 50 stations on the subassembly line.

2) When two lines feed into the same station (e.g. Body Sides Left and Right feeding into Tabbing), the order that these stations are placed into the model can affect the bottleneck results of the model. The reason this occurs stems from the serial assumption of the C-More model. If one feeder is placed before the other, the C-More model effectively starves the second feeder line in the model when the first feeder line fails. In the case of the Body Sides Left and Right lines feeding into Tabbing, when Body Sides Left is placed first in the model, it starves Body Sides Right. In the real world, when Body Sides Left fails and drains its buffer to Tabbing, Body Sides Right has an opportunity to fill its buffer to the Tabbing station. Body Sides Right never is starved in the real world by Body Sides Left; it can only be blocked if Body Sides Right's buffer is full. Because of this limitation in the C-More model, sensitivity analysis of the model must be performed to compare how the bottlenecks change depending on the model formulation. Figure 5.6 shows some sensitivity analysis on week 48 Body Shop data. This data displays a list of the top bottlenecks in the system and the impact of repairing these bottlenecks. Depending on whether Body Sides Left or Right is placed first in the model, different

output occurs. Notice in both cases that the total system throughput is approximately the same.

Week 48

Scenario 1:

Body Sides Right Before Body Sides Left in C-More model

Base Throughput 39.68 JPH

Bottlenecks:

Body Sides Right	10.53 JPH
Body Sides Left	3.56 JPH
Perceptron / Tabbing	0.72 JPH
Framing1 / UB / Dash	0.52 JPH

Scenario 2:

Body Sides Left Before Body Sides Right in C-More Model

Base Throughput 39.63 JPH

Bottlenecks:

Body Sides Right	9.47 JPH
Body Sides Left	4.99 JPH
Perceptron / Tabbing	1.16 JPH
Framing 1 / UB / Dash	0.73 JPH

Figure 5.5: The effects on bottleneck output by switching Body Sides Left and Right in C-More Model.

5.4 Output Results:

C-More tool has been utilized in the Luton Body Shop to verify system design, to perform what-if analysis for Body Sides project proposals, and to locate system bottlenecks.

Some of the data discussed in this section has been altered to maintain General Motors' confidentiality.

5.4.1 System Design Verification

GM engineers initial specifications designed the Luton Body Shop to produce 57 jobs per hour to the Paint department. Body Shop planning engineers were concerned that the individual specifications of each assembly line prevented a final throughput of 57 jobs per hour from occurring given the current in-line buffer systems. Each main line (11 main lines: e.g. Body Sides Left, Dash, Framing 1, etc.) had been designed for 85% uptime with a 75 or 90 JPH rate. Based on these assumptions and a further assumption that the average MTTR is 5 minutes, the MTBF for each major line is calculated as 28.33 minutes.

In the C-More model, I entered the eleven main lines as eleven individual workstations. I also entered the parameters of cycle time, buffers, MTTR, and MTBF for each station. Based on these parameters, C-More calculated the average throughput as 57.84 JPH. The intended design meets the specifications.

These results surfaced two issues. First, these results surprised some of the managers and engineers in the Body Shop. Management had attributed some of the Luton Body Shop throughput problems to the design of the system. Some people had claimed that reaching the throughput target could not be achieved because the system had not been specified properly. The results of the analysis demonstrated that this was not the case.

The second issue from this result stemmed from the close proximity between the design specification and the target throughput. In order to reach throughput at Luton's Body Shop, each assembly line in the Body Shop must perform at 85% uptime with 75 (or 90) JPH. The most recent throughput data shows some of the assembly lines with an uptime of only 60%. Therefore, these results surfaced the type of performance needed on a macro scale if throughput objectives for the Body Shop were to be reached.

5.4.2 What-If Analysis

During one part of the internship, throughput on the Body Sides was a critical issue. Overtime was continually scheduled on these lines to meet the production of the rest of the of the Body Shop. Many different ideas were proposed to increase throughput. One of these ideas involved adding more in line buffers to the Body Sides line. The Body Sides original design buffered the inners from the marriage station. This buffer was removed in the later stages of implementation due to space restrictions in the Luton plant. As discussed in Chapter 4, even the buffer between marriage and respot was not being used. One major advantage of the C-More analysis tool is its capability of quantifying the improvements of different buffer scenarios. Based on the inputted workstation parameters and existing buffers, C-More can calculate the best location for additional buffer spaces in the system in order to improve throughput.

In the case of the Body Sides, we ran the C-More Body Sides model with Week49 data looking at the proposed buffer scenarios and optimal buffer scenarios. Management had proposed some of the buffer locations based on their accessibility and low implementation costs. These buffer sizes were entered into C-More using the same Week49 manual downtime data. The three proposed buffer possibilities were:

1) 20 job buffer between inners and marriage - Scenario A
2) 5 job buffer between rear quarter and outer line - Scenario B
3) 5 job buffer between frame door opening turntable and the outer line - Scenario C

Every combination of these buffers was analyzed using C-More. The percentage throughput improvement from each scenario is captured in the following graph:

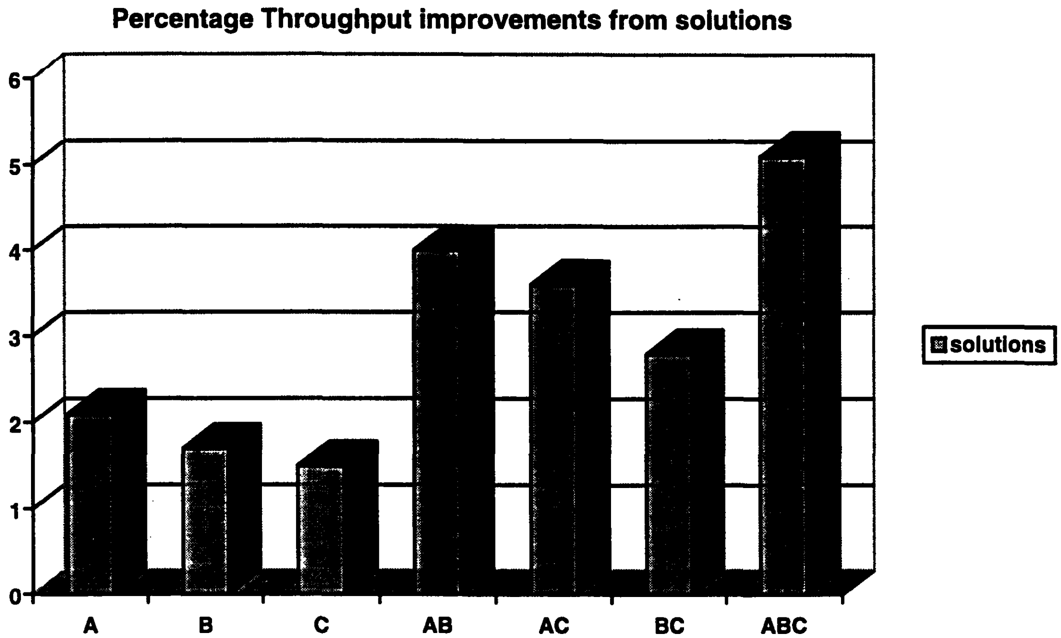


Figure 5.6 Percentage Throughput Improvement from 3 "What-If" Buffer Scenarios on the Body Sides Line Using C-More

From the chart above it is clear that solution A gives the single greatest throughput impact. The managers reviewing this data were surprised at how small of an overall throughput improvement would occur based on these buffers. The reason that these buffers do not have as great of an impact as expected stems from the breakdown characteristics of the body sides line. The data on the Body Sides line calculated the bottleneck to be in the Body Sides Outer area. Many of the workstations in the outers had frequent long breakdowns compared to the rest of the line. When the optimal buffer locations were predicted by C-More (5 buffer spaces at a time, 5 iterations) the greatest improvement came from buffering the outers at stage 3 from the marriage station (3% improvement), then from buffering the outers at stage 2 from stage 3, then the side feed panel subassembly from the outers, etc. No buffer at body sides inners (solution A above) was even mentioned. Therefore, while some buffers may be easier to implement, they may not create the necessary desired throughput increases. Since the solutions predicted by C-More were not initially proposed solutions by management, C-More created greater insight into how the Body Sides line operated.

5.4.3 Total System Bottleneck Identification

The main objective for C-More is to model the entire Body Shop system and locate the system bottlenecks. While the data for the complete Body Shop was not complete at the end of the internship, many estimates were taken of main line performance and these estimates were equally distributed among the individual main line operations. The areas that collected sufficient manual data used this data in the C-More model. Manual data was collected over a two week time period. A two week sliding average window was used to calculate MTTR and MCBF. Cycle times for all operations were timed manually. Initially only the Body Sides line system had enough relevant manual data to model, but by the final few weeks of the internship, the Dash, Underbody Rear, Underbody Front, Body Sides Left, Body Sides Right, Framing 2, and the Framing 2 Respot area all utilized manual data collection. The remaining areas of Framing 1, Tabbing, and the Left Over lines still were in the process of implementing manual data collection.

Based on Week 49 data, the following bottlenecks and their loss of throughput in JPH from the macro model were determined:

Body Sides Right	8.19 JPH
Body Sides Left	4.02 JPH
Tabbing Area	1.18 JPH
Framing 1 (and feeders of UB and Dash)	0.73 JPH

Figure 5.7 Week 49 Bottlenecks in Luton Plant

Notice that more than one bottleneck is located by C-More. Because of the high variability in the Body Shop stations and the complexity of the system, more than one station/area can ultimately affect the throughput of the system. In the macro model, most subassembly lines reveal themselves as feeder files. While noticing that Body sides right loses 8.19 JPH to paint, this line is actually composed of 33 distinct operations. To maximize the focus of resources on the individual bottleneck operations, the feeder lines must also be individually analyzed to disaggregate the JPH figure. When this was completed for week 49, the following bottlenecks and their effects on throughput were as follows:

Body Sides Right Inner Load station	1.31 JPH
Tabbing Station	1.18 JPH
Body Sides Right Stage 3 Side Outer Complete station	0.84 JPH
Body Sides Right Frame Door Outer Tack station	0.67 JPH
Framing 1 Respot #2 station	0.51 JPH
Body Sides Right Stage 1 Side Outer Complete station	0.43 JPH
Body Sides Right Frame Door Load station	0.43 JPH
Body Sides Left Final Load and Scheduling station	0.36 JPH
Body Sides Left Post Marriage station	0.33 JPH

Figure 5.8 Micro Bottlenecks for Luton Plant - Week 49

From this list, one notices that the allocation of job per hour losses are not always impacted by any particular station. In body sides left line only 0.69 JPH of the 4.02 is focused on any one station. The remaining JPH loss is coming from the interactions of the remaining 31 stations. This further signals that the cumulative effect of these individual stations each play a greater role in system throughput because they are not decoupled by any buffers. Similarly 3.68 of the 8.19 JPH on Body Sides Left can be accounted for in bottleneck stations. This also demonstrates the need to use the decoupling buffer on the Body Sides line.

Another surprising conclusion is how critical the Body Sides Lines are Body Shop system throughput. According to the theory of constraints, the organization must allocate more resources to the Body Sides lines to eliminate these bottlenecks. The rest of the Body Shop has a much smaller effect on the throughput of the Body Shop as of Week 49.

The Body Shop must continue to use the C-More bottleneck analysis tool for locating bottlenecks if it is to maximize its effect on overall Body Shop throughput.

5.5 Summary

C-More is an effective tool for locating bottlenecks and performing what-if scenarios in a current Body Shop environment. When implementing C-More into an existing plant, it is important to divide the system into workstations where a cycle time, MTTF, and MCBF can be measured. The Luton plant has three methodologies of collecting data. The manual technique which is being used for C-More input today has many shortfalls as does the MMI automatic data collection technique. The best methodology for collecting data blends the needs of C-More with a developing MIS system for use in the Body Shop. When this MIS becomes fully operational, the C-More model will receive much better data and therefore produce better output results. By integrating C-More into the MIS specification, C-More will have the data automatically generated and the C-More output will be easy for many people to obtain. This shift in focus will assist Luton plant with tackling their current throughput problems.

Chapter 6 Summary and Relevant Learning

There are many approaches to improving throughput in an automotive assembly plant. Throughput can be improved on both a micro and macro scale. When looking at micro-throughput issues, one must be careful to understand the details of the system.

6.1 Micro Throughput Methods and Tools

Micro-throughput involves the following methods and tools:

- Cycle time reduction improves throughput. To reduce cycle time, one can focus on speeding up existing movements and actions, one can eliminate movements and actions, and one can "bury" or parallel process some movements and actions to reduce an operations cycle time. Both the Underbody Rear optimization and the Framing one cycle time reduction are examples of reducing cycle time in order to increase throughput. In both of these cases, careful observation of the details resulted in throughput improvements of 15-20%.

- Using buffers between stations can improve throughput. When buffers are implemented in an assembly plant, it can reduce the effects of variability on overall throughput. Many operations in a row without the separation by a buffer can have serious ramifications on throughput. In the Body Sides case, a designed system buffer was not being used. By using this buffer, throughput could be improved by 5%. Placing additional small buffers in the right locations could improve throughput even more. The estimation of these throughput increases stem from manufacturing systems analysis techniques developed by Gershwin. This non-linear differential equation technique is able to estimate throughput quickly and only once compared to simulations where multiple runs are necessary. These throughput estimations were also confirmed with C-More, a throughput analysis tool based on differential equation and steady-state analysis. This tool uses linear programming to solve for throughput numbers. The correlation of answers from the two models shows that most likely either method of throughput analysis can be used to show the effects of buffers on a system.

- Transferring learning from one plant to another is possible and important. The importance of communication between plants cannot be overstressed. In the Underbody Rear example, another plant with the same equipment had experienced similar problems on their Underbody Rear line. We used the learning of the other plant to optimize our own subassembly line and modify both equipment and assembly processing. In the Framing 1 example, I was able to transfer learning from my past automotive assembly experience to take a solution in one plant and implement a similar solution in a second plant.

6.2 Macro Throughput Methods and Tools

Macro-throughput issues deal with larger system issues. When investigating large systems, one attempts optimize the system as a whole. One must locate the bottlenecks in the system and allocate resources expediently. The following tools and methods were used for macro-throughput improvement:

- The C-More bottleneck analysis tool is effective at macro-throughput issues. C-More locates and quantifies bottlenecks such that management can dedicate resources to the most important problems. Improving the bottleneck directly improves the throughput of the system as a whole (Goldratt, *The Goal,* 1992). Additionally C-More can perform what-if analysis to optimize buffer locations and determine the best maintenance policy decisions. The use of C-More in some plants has improved throughput up to 45%. Typical throughput improvement for a plant tends to be about 12%. By developing C-More alongside a newly designed MIS system, the MIS can collect information and format it for C-More's needs. C-More's most critical issue is receiving valid breakdown data from the system. Three methods of data collection were investigated in the Luton plant. The developing MIS data collection methodology is the only robust solution. Two other significant issues with C-More are:

1) dividing up a system into components that can capture the MTTF, MCBF, and cycle time data

2) There is difficulty in capturing the cycle time data given the current Luton system. In order to satisfy these issues, the plant has appropriated money to install a solution after the fact. C-More and the MIS needed implementation at the beginning of the model change instead of two years later. An earlier implementation in a new plant model change saves costs and removes throughput losses earlier n the process.

- Systems dynamics can quickly model behavioral loops that demonstrate how different policies affect throughput. The use of Senge's Shifting the Burden archetype (Senge, *The Fifth Discipline*, 1990) describes how short-term policies may have long-term effects. In the overtime model, the scheduling of overtime places additional pressure on the time available to perform preventative maintenance. The lack of time for PM further affects throughput. While potentially counterintuitive, reducing overtime can increase throughput. Similarly, in the inventory case, the increase of inventory reduces the response time of the maintenance worker and therefore negatively affects throughput. Due to low output and the low amount of jobs in buffers, more inventory is built up (many times scheduled as overtime). The solution of reducing inventory can speed up the response of maintenance, focus the worker on efficiency, and ultimately increase throughput. Both of these policies favor short term solutions to throughput problems over the long term solutions of fixing the problems. Using system dynamics on other assembly policies may also produce similar insights.

The Luton Body Shop has many improvement strategies in process to improve their throughput. By utilizing some of the tools described above as well as continuing its hard work and management strategies, Luton will overcome its current throughput difficulties.

6.3 Relevant General Learning

Several broader conclusions can also be reached from the internship experience and this thesis:

- Micro-throughput projects are an effective way to familiarize employees with tooling. Since micro-throughput initiatives tend to be detail oriented, employees gain familiarity with the detail of the area. Every employee should be a part of a throughput improvement team in their area of work on the plant floor. Not only will people understand the equipment and processes better, they will also become "throughput-focused". The tools of cycle time reduction, uptime maximization, and buffer utilization can get every employee involved with improving the process. Involving the operators and the entire organization in the decision-making process reinforces principles such as the theory of constraints and lean manufacturing principles.

- Learning from one plant can significantly improve the processes of another. GM should promote cross-communication between plants by sponsoring "exchange days". I used to do this in a previous job in a previous plant. The accessibility for an engineer, employee, supervisor, etc. to see a different plant for even one day can contribute to significant learning and diffusion of knowledge between plants. The learning from a similar plant in the micro throughput underbody situation helped improve the throughput of the Luton Underbody Rear subassembly line. A second way of diffusing learning between plants is to transfer employees between plants more frequently. I was able to transfer learning from an implemented solution in one plant to the Luton Framing 1 line. The experiences at one plant can be significantly different from another and can add to the cross-learning. Research supports the development of communication and a flexible, agile workforce (Senge, *The Fifth Discipline Fieldbook*; 1990; Peters, *Liberation Management,* 1994; Gozdz, *Community Building*, 1995).

- Every GM assembly facility should use C-More, the throughput analysis tool developed by GM Research. While this tool is often used in GM North America, the Luton facility is GM Europe's first installation of C-More. The VP in Manufacturing of Europe has great interest in implementing C-More throughput GM Europe. C-More should be part of each specification for new major model changes. With support at the top for this software, the effort to implement C-More GM-Europe wide should not be difficult.

- System dynamics should be used to map out various policy decisions in plants. The system dynamics loops described in this thesis are relatively straightforward and simple. These simple loops can create learning in the organization on how some policies can affect throughput. Making books such as *The Fifth Discipline* by Peter Senge available to employees cultivates the use of system dynamics throughout the organization. Several computer flight-simulators for businesses are also available for teaching these concepts.

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