1996 Taurus/Sable and Mystique/Contour Bumper Production Planning

by

Russell D. Crawford

B. S. Chemical Engineering, Stanford University, 1992

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

Master of Science in Management
and
Master of Science in Materials Science and Engineering

at the
Massachusetts Institute of Technology
May 6, 1994

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Abstract

Numerous individuals have examined the problems of capacity allocation, scheduling, and inventory management in a manufacturing setting. In many cases, however, traditional manufacturing wisdom has failed companies of the United States in their efforts to maintain or regain their competitiveness vis a vis foreign competitors, particularly those located in Asia. This has led to new ideas regarding capacity allocation, scheduling, and inventory management.

In this thesis, a general paradigm for making capacity allocation decisions based on an examination of traditional line-balancing activities and an unbalanced, Theory of Constraints-based system is developed. Then, the resulting paradigm is applied to the capacity allocation decisions of the Milan Plastics Plant as it makes plans to introduce new products (the new Taurus/Sable and Mystique/Contour bumpers), and scheduling and inventory management procedures consistent with the capacity allocation decisions are developed. In the course of developing the general paradigm, several simple models are used to demonstrate the effects of different capacity allocations on line throughput in the presence of cycle time fluctuations. To assess the scheduling and inventory management procedures developed for the real facility and to figure out how many wire frames the plant should purchase for in-process inventories, a complex, detailed simulation effort was begun in conjunction with Rapistan Demag. Unfortunately, the simulation was not completed before the conclusion of the internship. The likely effects on the plant's production system of the introduction of a new bumper raw material, thermoplastic olefin (TPO), in the place of Xenoy, are also discussed.

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Acknowledgments:

The author wishes to acknowledge the Leaders for Manufacturing Program for its support of this work.

I owe a great deal of thanks to the people who follow, for I never could have survived the internship, let alone write this thesis, without their assistance.

Ford Motor Company - Mark Blair, Roy Schlegel, Lori Friese-Baker, the Bumper Scheduling Office (Dan Innes, Bob Barrett, Jim Dudley, Mike DeFran, Kim Behen, Amy Cline, and Genories Dunbar), Roy Davis, Alan Heneveld, Sheldon Kerper, Dan Himebaugh, Rose Ryntz, Don Toeppe, Ron Clemons, Chad Jones, Mike "Robcad Master" Mott, Kevin Vliet, Scott McCormick, Dave Bucklin, Larry Clore, Joe Jelics, and everyone else at Milan who helped out in one way or another. Special thanks also to Dave Esser, Fred Gamber, and Ron Horton from Saline and Pat Mulrooney and Pete Dragich from PTPD Staff.

Technology Systems Corporation - Paul Henderson and Keith Krenz for making the "Jonah" Theory of Constraints class an amazing experience.

Finally, thanks to the Leland Stanford Junior University Marching Band for providing me with the most amazing four years anyone could ask for, Steven Williams, without whom I never would have survived Ch. E., Kathleen Findley, the high school chemistry teacher who started it all, the Lupines for Manufacturing of the Class of '94, and my parents, who didn't complain about the phone bills.

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Introduction

Numerous individuals have examined the problems of capacity allocation, scheduling, and inventory management in a manufacturing setting. In many cases, however, traditional manufacturing wisdom has failed companies of the United States in their efforts to maintain or regain their competitiveness vis a vis foreign competitors, particularly those located in Asia. This has led to new ideas regarding capacity allocation, scheduling, and inventory management.

One of the most popular of these, which many companies use, or have tried to use, is Just-In-Time (JIT), a system originally developed in Japan. This system maintains extremely low in-process inventories and a high degree of responsiveness, but also requires a degree of process control, if it is to be successful, that is extremely difficult to develop and practically unheard of in most U. S. companies. Unfortunately, most U. S. companies that have tried JIT simply pushed inventories onto their suppliers rather than truly eliminating them.

However, even if JIT implementation is successful, it often takes many years to develop the necessary understanding and control of the processes involved. With the recent rise in the value of the yen, U. S. manufacturers have had more time than they appeared to have in the mid-eighties to better understand their processes and improve them. But, many companies either lack the time or the desire to spend the money and effort required since the bottom line-driven need for improvement has diminished with the reappearance of acceptable levels of profit.

Realization that U. S. manufacturers are unlikely to be willing to go through the rigors of getting control of every single process led Mr. Eliyahu Goldratt, an Israeli physicist turned management consultant, to develop Theory of Constraints (TOC). Notably different from JIT, it requires a high level of process control only over the constraint, or bottleneck process, and buffers other statistical fluctuations present in the system through inventory and excess capacity. The use of excess capacity as a type of buffer differs from traditional line-balancing activities whose goal is to minimize the total line's idle time, preferably by minimizing the idle time at each station. The goal in a Theory of Constraints system is to run the processes upstream and downstream of the constraint in such a way that it is never starved and never blocked. Thus, upstream processes produce only what the bottleneck can use, and downstream operations remove parts from the system as they are produced by the bottleneck as quickly as possible. As long as the constraint is never starved or blocked, the other resources should be idle or producing goods that will not interfere with the constraint's operations. As a result, the majority of in-process inventory resides in front of the constraint. Mr. Goldratt's plant unbalancing approach can be successful in reducing overall in-process inventory below the amount present in a traditional balanced-line, thereby improving the system's responsiveness, and can provide the plant's throughput with greater protection against statistical fluctuations than JIT does.

Where this document fits in

Since there are a variety of different paradigms in existence that deal with capacity allocation, scheduling, and inventory management, a great deal of confusion exists as to which one is most appropriate for a given situation. The particular situation I considered was that of Ford Motor Company's Milan Plastics Plant, where it was clear from the outset that the degree of process control required for JIT was unlikely to be achieved because of a combination of limited engineering resources, large fluctuations in equipment operations, and equipment set-up requirements. Thus, I decided to investigate the appropriate usage of both balanced lines and unbalanced lines based on the Theory of Constraints since the plant's management had recently developed an interest in the use of TOC.

In this thesis, I develop a general paradigm for making capacity allocation decisions based on an examination of traditional line-balancing activities and an unbalanced, Theory of Constraints-based system. Then, I apply the resulting paradigm to the capacity allocation decisions of the Milan Plastics Plant as it makes plans to introduce new products (the new Taurus/Sable and Mystique/Contour bumpers), and I develop scheduling and inventory management procedures consistent with the capacity allocation decisions. In the course of developing the general paradigm, several simple models are used to demonstrate the effects of different capacity allocations on line throughput in the presence of cycle time fluctuations. To assess the scheduling and inventory management procedures developed for the real facility and to figure out how many wire frames the plant should purchase for in-process inventories, a complex, detailed simulation effort was begun in conjunction with Rapistan Demag, a material-handling equipment vendor. Unfortunately, the simulation was not completed before the conclusion of the internship. I also discuss the likely effects on the plant's production system of the introduction of a new bumper raw material, thermoplastic olefin (TPO), in the place of Xenoy.

Chapter 1

The Manufacturing Facility

The Milan Plastics Plant makes a variety of injection molded and blow molded parts for Ford Motor Company, most notably fuel tanks and bumpers. Bumper production was selected for evaluation for several reasons: bumpers are the plant's most profitable product, the plant has had difficulty meeting customer demand with the current production system, and the new products and material coming in 1995 create the need for significant amounts of change.

The Current System of Production

The process flow for bumpers is fairly simple in that each part passes through at most four operations; however, there are many possible flows depending on part type (Figure 1). The bumpers begin as Xenoy plastic pellets which are injection molded into fascias and subassemblies. The subassemblies are joined to the fascia via an adhesive bonding or a linear welding operation. Then, the parts are painted the appropriate color on the monoplane paint system and prepared for shipment through either a packout cell, Selective II (a secondary paint and assembly station), or directly from the paint system depending on the type of product Once the bumpers have been placed on an end-item rack, the racks are loaded into either a truck or rail car to make the trip to one of the assembly plants. Parts whose paint job is unsatisfactory can usually be repaired through the Selective I operation and then repainted on the monoplane.

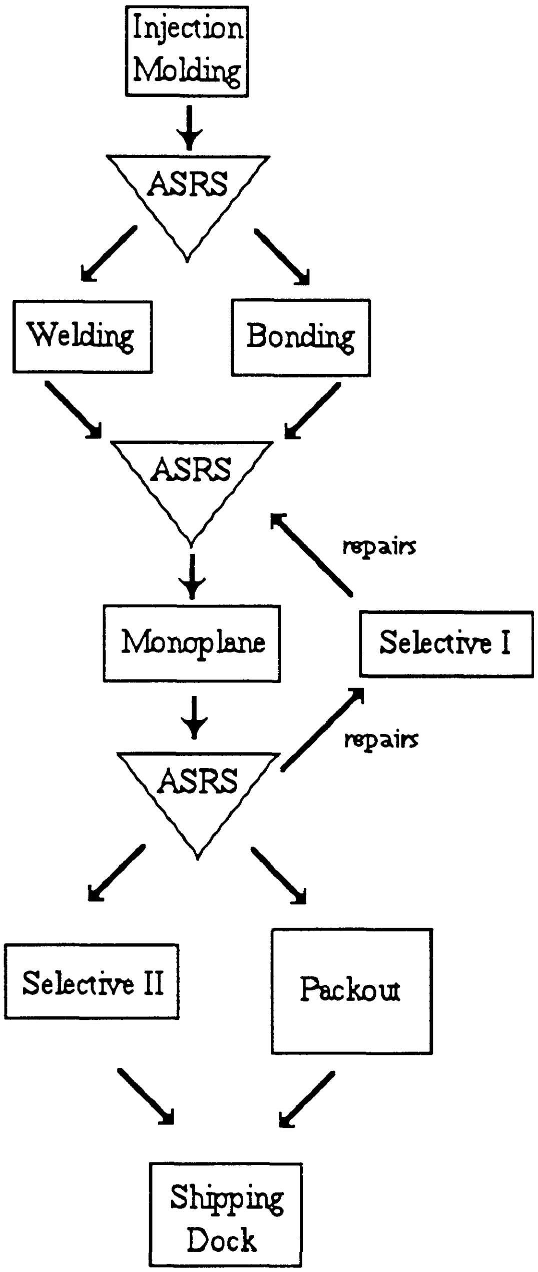

Figure 1: Major process flows as of June 1993

The bumpers travel through the system, with a few minor exceptions between molding and bonding, on in-process racks. These racks have space for ten bumpers each and are carried by Automated Guided Vehicles (AGVs) or an overhead Monorail system. All in-process inventory which is not being worked on or in-transit is contained in the Automated Storage and Retrieval System (ASRS). As a result, the total in-process inventory in the plant is controlled by the capacity of the ASRS, but the mix of products contained in the ASRS can vary widely throughout the day. If for some reason the ASRS fills up, then some combination of molding and bonding/welding equipment that loads from the floor must be shut down until parts can be removed from the ASRS for shipment or are scrapped, thereby freeing up in-process racks.

The Future System

The system required for the 1995 products is different in a number of respects, mostly because of the use of TPO instead of Xenoy as the raw material (Figure 2).

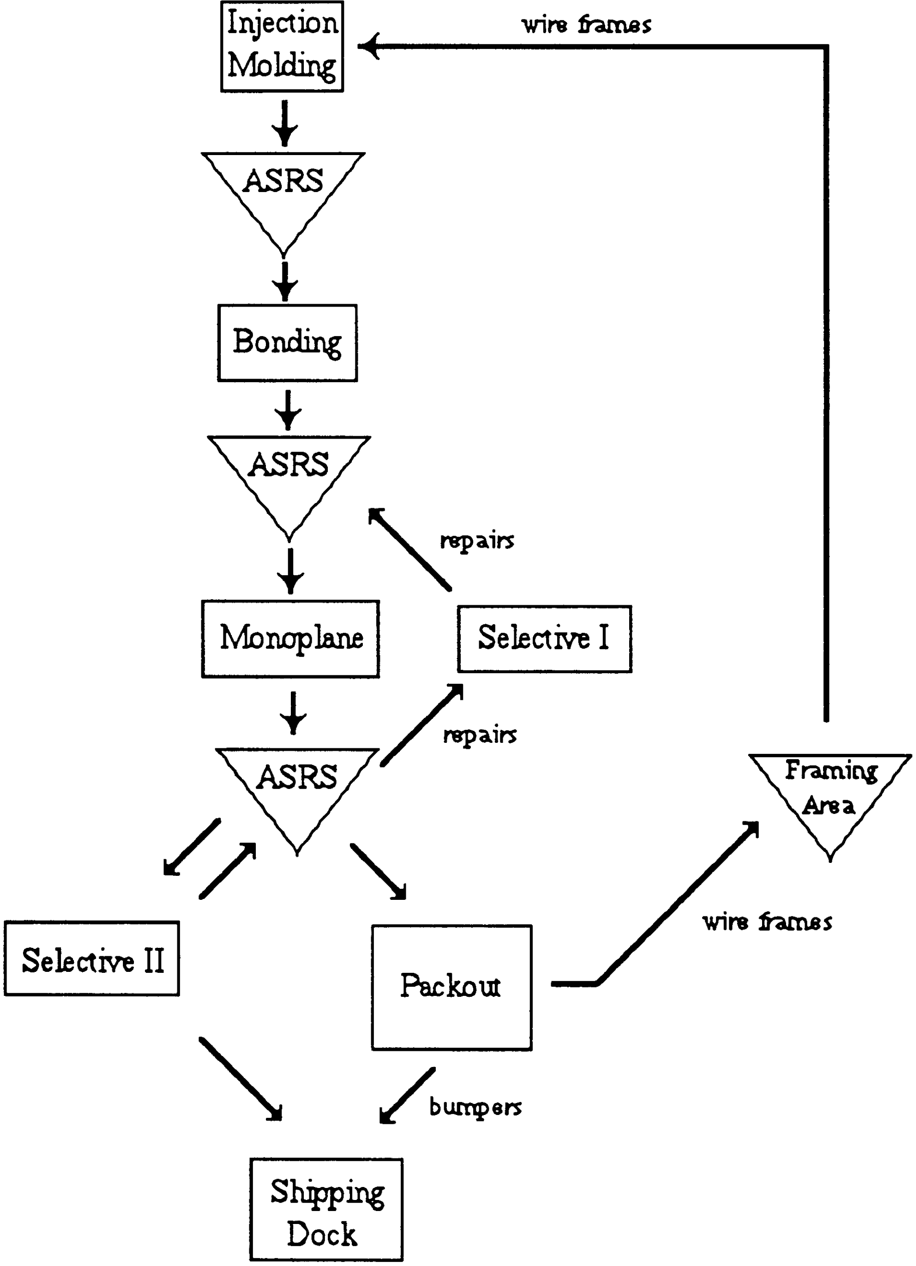

Figure 2: Future process flows

The most significant change is that neither bonding nor welding is required on the majority of the products the plant will be making (the ones made of TPO). However, a number of new difficulties exist. First, the racks for the new products can only hold six parts for the high volume TPO parts and eight for the lower volume Xenoy parts because of the parts' increased size. This decreases the capacity of the ASRS by about 20%, depending on the mix of parts in the ASRS at any given time, in spite of the addition of three crane bays which were built in 1993. Second, TPO parts are very soft and flexible compared to current bumpers because of the material's properties and because the TPO parts do not have subassemblies bonded or welded to them to provide them with rigidity. As a result, wire frames are required to support the parts while they are in-process. Thus, not only must an in-process rack be available for a part to be transported by the Automated Material Handling System, but the correct wire frame must be present as well. This requirement complicates the scheduling problem, and creates the need for the framing area, where the frames a rack is carrying can be exchanged for other kinds as needed. Third, all of the future parts require substantially more assembly than they do today, so parts will no longer be shipped directly from the paint system, and the Sable Rear Sedan bumper requires processing by both Selective II, for additional painting, and a Packout cell for assembly and preparation for shipment.

A more in-depth analysis of current and future system characteristics can be found in Chapters 3, 4, and 5. Table 1 provides a list of the types and quantities of equipment that are used now and will be used in the future. The decreased in-process rack storage density has a strong effect on the number of AGVs, ASRS Crane Bays, and ASRS In-process Racks.

Type of Equipment	Current System	Future System
Injection Molding Presses:	19	17
Adhesive Bonders:	7	5
Linear and Sonic Welders:	8	2
Monoplane Paint Systems:	1	1
Packout Cells:	4	5
Selective Decorating II:	1	1
Selective I (Repair):	1	1
AGVs:	23	29
ASRS Crane Bays:	10	13
ASRS In-process Racks:	2100	2800

Table 1: Selected system characteristics

Chapter 2

To Balance or Unbalance

A basic question that must be asked when setting up a production system is how capacity should be allocated. Since I hoped to apply the results of my analysis of this problem to Milan, I limited myself to those paradigms which I thought had the best chance of being successfully applied there. Those paradigms were the traditional balanced line and the unbalanced line advocated by Theory of Constraints.

The Balanced Line

Nahmias[1] provides a description of the assembly line balancing problem and procedures for solving it. The problem is a set of i distinct tasks that have to be completed on each product. The required time for each task is a known constant t_i. The objective is to group the tasks at a series of workstations so that all workstations have the same cycle time. In most real-world applications, the goal is to arrive at a minimum total idle time for all workstations given a target cycle time based on the production rate. An iterative approach based on varying the target cycle time and number of stations allows the total idle time to be established at most any desired level. However, the cost of the stations and the indivisible nature of some processes generally limits how close to zero the idle time can get. Nahmias provides examples of numerous procedures that have been developed to solve the line-balancing problem.

However, some question exists as to whether the goal of minimizing idle time really has the equivalent effect of maximizing profit. Carlson and Rosenblatt[2] suggest otherwise, as does Goldratt[3]. An optimal balance for a fixed cycle time may not be optimal in a global sense, especially when factors like cycle time fluctuations and downtime are considered. One also has to consider the cost of capital equipment per unit of capacity for the different processes involved.

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[1] Nahmias, Steven. *Production and Operations Analysis.* Boston, MA: Irwin, 1989, pp. 322-28.

[2] Carlson, R., and M. Rosenblatt. "Designing a Production Line to Maximize Profit." *IEE Transactions* 17, 1985, pp. 117-22.

[3] Goldratt, Eliyahu M. and Robert E. Fox. *The Race*. Croton-on-Hudson, NY: North River Press, 1986, pp. 92-3.

The Unbalanced Line

Realizing that factors like cycle time fluctuations and downtime should be considered since they exist in real factories, Goldratt developed a philosophy based on the notion of bottlenecks. Nahmias[4] provides a list of nine principles which make up the Theory of Constraints philosophy, which I quote:

1. *Balance flow, not capacity.* The idea behind this principle is to focus on maximizing the total flow through the system rather than trying to balance work loads. Effective use of imbalance minimizes the likelihood that time is lost at bottlenecks.

2. *The level of utilization of a nonbottleneck is determined not by its own potential, but by some other constraint in the system.*

3. *Utilization and activation of a resource are not synonymous.* Activating an unneeded resource [unneeded by the bottleneck resource, that is] does not correspond to intelligent utilization of that resource. There is no benefit to running [a resource upstream of the constraint] if [the constraint] cannot absorb its output.

4. *An hour lost at a bottleneck is an hour lost for the total.* If poor scheduling results in a bottleneck machine being left idle, or a breakdown occurs at a bottleneck, the lost time can never be recovered and the production flow will decrease.

5. *An hour saved at a nonbottleneck is a mirage.* Saving time or increasing production at a nonbottleneck location will have no effect on the system production rate.

6. *Bottlenecks govern both throughput and inventory in the system.* One purpose of inventory is to keep bottleneck machines busy. Improper planning of work-in-process (WIP) inventories can adversely affect product flow.

7. *The transfer batch might not, and many times should not, be equal to the process batch.* The transfer batch is the number of units transported from one work center to another, and the process batch is the size of a production or process run. Because setup costs for processing and transporting are different, batch sizes should be different. The idea here is

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[4] Nahmias, *ibid.*, pp. 626-27.

to encourage *lot splitting*, which is especially difficult when scheduling by [Material Requirements Planning]. In some circumstances, lot splitting may increase throughput.

8. *The process batch should be variable, not fixed.* Lot sizing should depend upon the schedule and the operation.

9. *Schedules should be established by looking at all of the constraints simultaneously.*

The basic idea of TOC is to identify the system's constraint(s), and then squeeze every bit of productive capacity out of them through scheduling, set-up time reduction, and process improvements. If the level of system throughput is still unsatisfactory once the constraint has been fully exploited, then the constraint should be broken by the addition of capacity, and the new constraint should be located and managed in the same way as the first. There are certain characteristics which can guide an individual engaged in system management in determining where to permanently locate their system's bottleneck. These characteristics will be explored later in the chapter.

Theoretical Simulations

The best way to evaluate the claims of the two paradigms is through simulation. I used Witness™ by AT&T ISTEL to investigate the effects of cycle time fluctuations on the performance of two simple production systems. The first system is a line of five workstations that are perfectly balanced, and the second system is a somewhat more complicated set-up involving multiple machines in parallel. The base case for each system, with deterministic cycle times shown in each machine's box, is presented in Figure 3. Each run of the simulation consisted of a 10,000 time unit initialization period followed by a run of 100,000 units of time. Detailed data on each run of the simulation can be found in the Appendix.

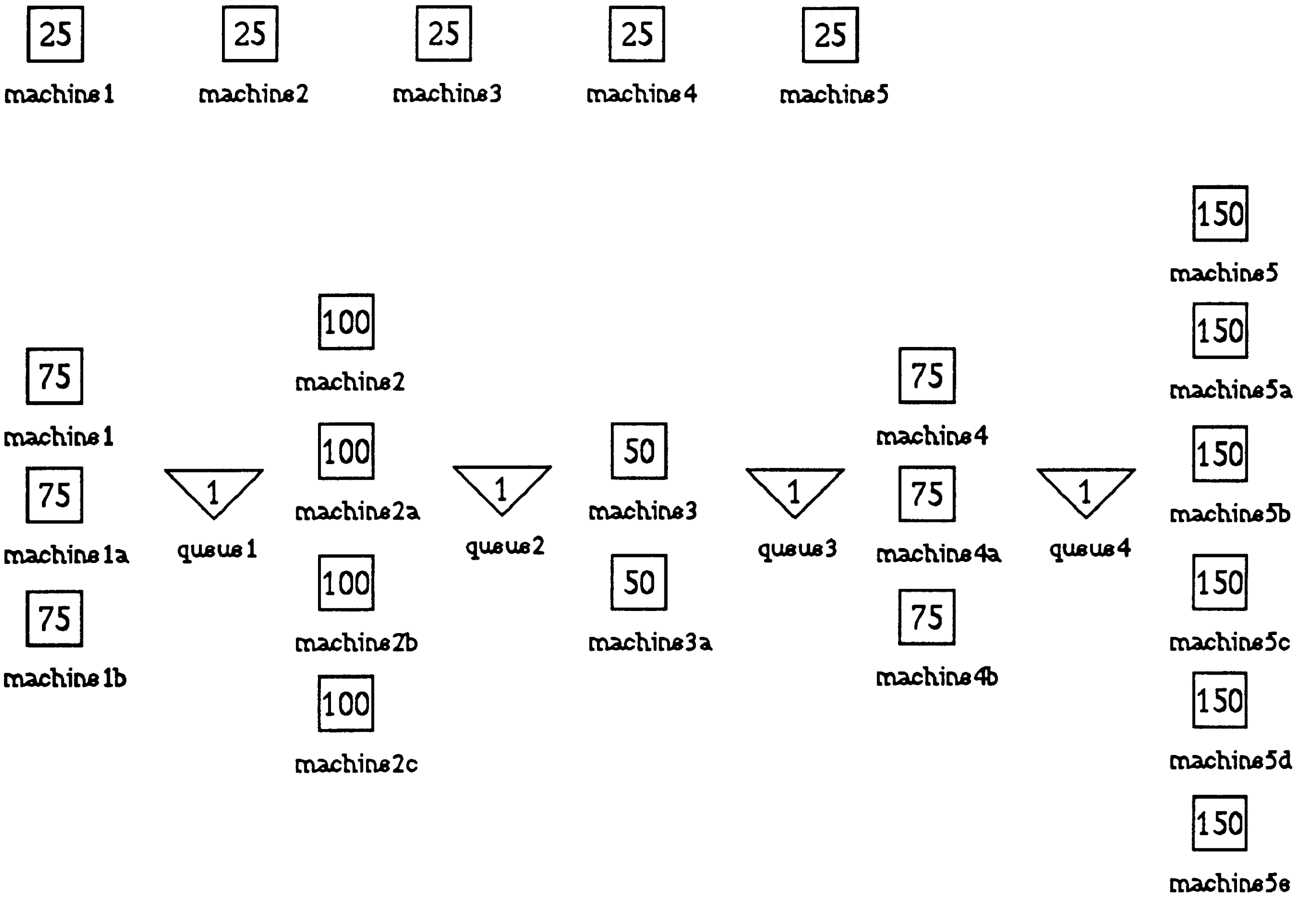

Figure 3: Experimental systems (balanced base cases)

Cycle Time	Buffers	Throughput	Avg. Time	Avg. W.I.P.
25	none	4000	124.84	5.00
20 - 30	none	3,589	132.90	4.78
10 - 40	none	2,972	149.37	4.45
10 - 40	infinite	3,953	1480.5	59.62

Table 2: Effects of cycle time fluctuations on a perfectly balanced, five machine line

The first series of experiments, displayed in Table 2, examined the effects of cycle time fluctuations on a perfectly balanced line. The cycle time was first set at a deterministic length of 25 units. It was then varied between the figures shown using a uniform distribution. Without any buffers, throughput declined from 4,000 pieces in 100,000 units of time to 2,972 units when the cycle time could vary from 10 to 40 units of time in duration. With the addition of "infinite" buffers, throughput rose to 3,953 pieces in

100,000 units of time, generating an average work-in-process inventory of 59.62 pieces. However, is this level of inventory stable? To investigate the stability of the inventory, I ran this case for a longer period of time.

A fundamental principle of the balanced line is that every operation must be kept busy all the time in order to maintain throughput. A look at the machine statistics for this run indicate that the line's "efficiencies" were very high: the "least efficient" operation was busy 98.34% of the time. As the simulation ran for longer periods of time, the line's "efficiencies" continued to grow; however, so did the amount of inventory in the system. At the end of 500,000 units of time, the average work-in-process inventory had grown to 108.82 pieces, and the average time to complete an order had increased from 124.84 units in the deterministic cycle time case to 2,721.3 units at the end of 500,000 units of time in the largest cycle time variation case.

The other question that can be addressed with this experimental scenario is whether the explanation of JIT presented in the opening paragraph of this paper is correct. Namely, does reducing a system's fluctuations decrease the amount of inventory required? To investigate this idea, I pretended that I was an American who went to Japan in the early eighties, came back fixated with the idea that low inventories was the key to success, and immediately implemented a policy of at most 5 pieces of inventory between operations without otherwise changing the operations' characteristics. As is clearly shown in Table 3, as fluctuations increase, throughput falls.

Cycle Time	Buffers	Throughput	Avg. Time	Avg. W.I.P.
25	none	4,000	124.84	5.00
20 - 30	5 pieces	3,980	346.66	13.85
10 - 40	5 pieces	3,320	160.94	5.35

Table 3: Effects of cycle time fluctuations on a pseudo-JIT balanced five machine line

The balanced, deterministic line requires no inventory at all; the line with 10 to 40 second fluctuations requires a lot more inventory than 5 pieces between operations to maintain throughput (as was demonstrated above). The pseudo-JIT lines take less time to complete an order because they have less in-process inventory, with average times of 346.66 time units and 160.94 time units respectively compared with the deterministic case of 124.84 time units.

Having uncovered increases in inventory and decreases in responsiveness in the balanced line if it were allowed sufficient inventory to maintain throughput, I developed a similar production system which would allow me to determine the effects of unbalancing the system. Again, the base case of the system is perfectly balanced (bottom portion of Figure 3), and with deterministic cycle times has identical throughput to the previous system's base case. With the introduction of a plus or minus 50% variation in cycle time of each machine, and maintaining a buffer with a capacity of 1 piece between each set of machines, throughput dropped to 3,600 pieces in 100,000 units. With the adoption of "infinite" buffers between each set of machines, throughput rose to 3,936 pieces in 100,000 units. However, the amount of inventory required to maintain this level of throughput grows with time, as is shown in the graph in Figure 4. Average time to complete an order grew over the same period from 464.58 units for the deterministic case to 2370.1 units at 500,000 units.

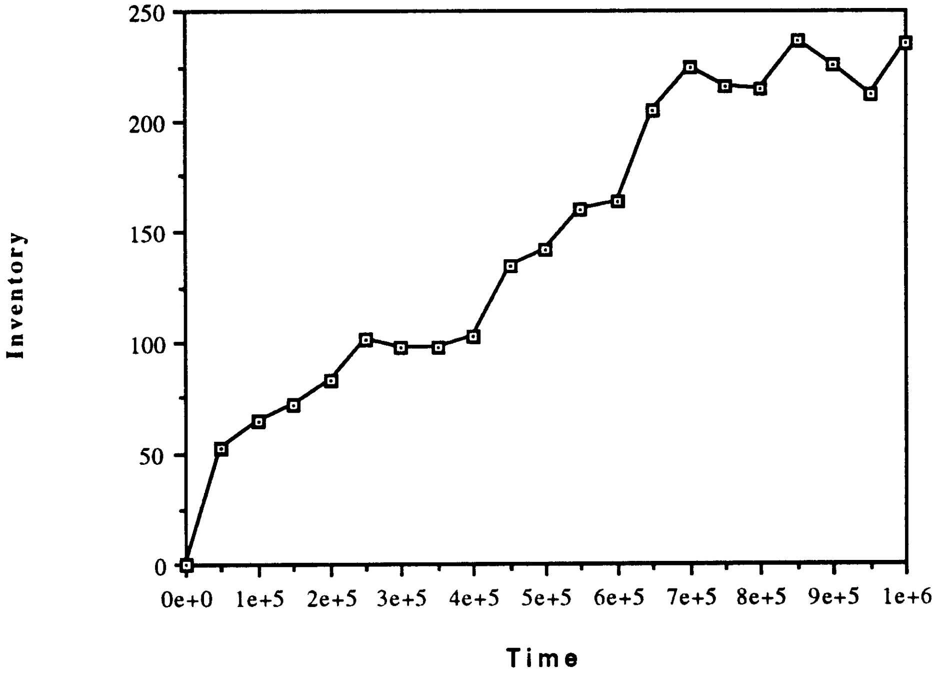

Figure 4: Inventory growth as a function of time for the balanced system

To combat the growth in inventory and corresponding decrease in responsiveness, Goldratt recommends an unbalanced line: such a line allows achievement of JIT's low inventories and high responsiveness without variability reduction of all processes. To examine the validity of Goldratt's view of the world, I tried unbalancing the second system by adding capacity in the form of additional machines. In doing this, I followed the methodology advocated by Technology Systems Corporation (a Goldratt Institute affiliate) which is to have increasing capacity up to the bottleneck operation and increasing capacity downstream of the bottleneck. In this way, the operation directly preceding the bottleneck and the last operation in the production system have the greatest capacities. The resulting system is displayed in Figure 5.

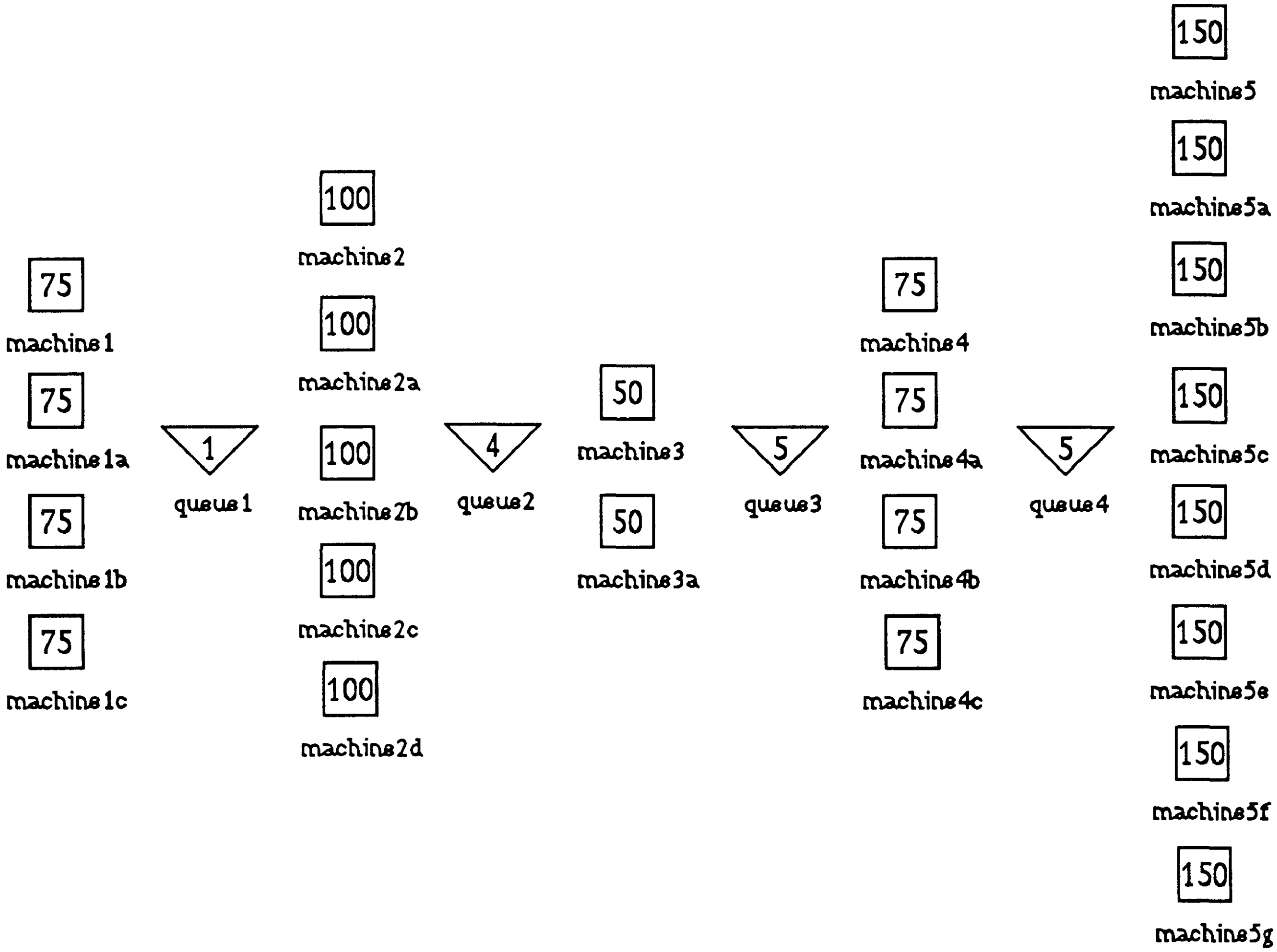

Figure 5: Unbalanced system configuration

This configuration achieved not only throughput similar to the deterministic case (4020 pieces), but did it with an average inventory of 25.01 pieces and an average time to complete an order of 618.22. These figures compare favorably with the deterministic case of average inventory of 18.67 pieces and average time to complete an order of 464.58. Best of all, the inventory does not grow as long as the upstream operations are gated in some fashion based on what the bottleneck operation can produce. In this example, the upstream inventory is capped.

One could complain about only 75% utilization of some machines. The response is not that these machines should not be allowed to sit idle if there is something useful for them to make, but rather that they should not be activated to make more things than the constraint operation can use. If, however, an opportunity exists for these machines to make a product which does not require the constraint process, then they should do so.

One could argue that better results in terms of efficiency and responsiveness could be obtained by capping the inventory in the balanced system case. I tried capping the buffers at 5 pieces between each set of machines. Average inventory was 27.45 pieces and average time to complete an order was 700.89 units. However, throughput was only 3,887 pieces even with 98% efficiencies. This is another excellent example of how one cannot hope to reduce inventory without considering the fluctuations present in the system unless one is indifferent to the resulting throughput.

Key Learnings from the Theoretical Simulations

While we recognize that the unbalanced line has more total processing capacity, these simulations give us a lot to think about. First of all, it should be clear by now that JIT works, but successful implementation requires reduction in the variation of each of the processes so that the system of production can be responsive. Understanding the reason JIT works is important: hopefully no one is going to run out into their plant and order a reduction in work-in-process inventories without dramatically altering the operating characteristics of their equipment.

Then there is the traditional perfectly balanced line concept. We have seen that such a system can produce reasonably high levels of throughput, but at the cost of a slow growth of in-process inventory and a corresponding decline in responsiveness. In some industries, this may not be that big of a problem; however, in many industries, inventory and the corresponding lack of responsiveness result in disaster when competitors live in low-inventory/rapid response environments.

The unbalanced line can enable high levels of throughput in spite of variation and achieve a low-inventory/rapid response environment. The two main factors impacting the choice between JIT, a traditional balanced line, and an unbalanced line that must be considered are: 1) is the inventory reduction and increased responsiveness is worth the additional expenditure required to either unbalance the line or dramatically reduce variation, and 2) is a balanced line is achievable. In the case of 1), a major obstacle to JIT is where the lifetime of the product and/or processes is less than the amount of time required to gain control of the processes (microprocessor fabrication, for example). In the case of 2), the nature of the processing equipment may force an unbalanced line either by having very different costs per unit of capacity or simply by not coming in divisible blocks of capacity enabling balance. Clearly, all three options should receive careful consideration before one is selected, and all of the relevant benefits and costs need to be factored in.

My statement that the growth of inventory for a balanced line will be slow depends on the line being perfectly balanced. However, is it possible to achieve a perfectly balanced line in reality where fluctuations of all kinds abound in the forms of quality, absenteeism, and breakdowns and the cost of a unit of capacity varies widely from one machine to another? I personally doubt if more than a handful of perfectly balanced systems of production exist in the world. And yet our measurement systems encourage every machine to run all the time. But, I have just said that most systems of production are somewhat unbalanced. The result will be that inventory will grow very rapidly in front of the bottleneck operation while the downstream operations are starved. This is the case in Alex Rogo's plant in *The Goal*, and I am confident that most facilities operating on the basis of Labor and Overhead accounting or piece-rate incentive systems whose foremen or operators can pull raw material into the first operation regardless of inventory levels downstream are experiencing this very phenomenon. Unfortunately, a plant run in this manner can potentially tie up too much cash in inventory, potentially resulting in bankruptcy. Thus, traditional manufacturing measurement systems need to be altered to reflect the at least somewhat unbalanced reality of most plants.

Exactly how capacity should be allocated is determined by price and operating costs of the equipment or logical functional assemblages (the most expensive per unit of capacity makes an attractive constraint), the statistical fluctuations present (pieces of equipment that experience a lot of fluctuations or have the processes upstream of them experiencing a lot of fluctuations need excess capacity, and a reliable constraint is key), and the yields of the proposed constraint and the equipment downstream (poor quality parts means wasted constraint time). The end goal is to minimize the amount of constraint time lost in non-productive applications (set-ups, downtime, starvation, blockage, and scrap generation).

Preventive maintenance, while adding to constraint downtime, will actually increase the time available for production if it is successful in preventing a larger amount of breakdown time than was required for the preventive maintenance. Only breaking even in terms of time spent maintaining vs. time saved from breakdowns is helpful in that the ability to control the scheduling of preventive maintenance is vastly preferable to the disruptive randomness of breakdowns.

Other potential benefits of unbalanced lines exist as well. One is in the area of inventory management: in general, unbalanced lines with substantial statistical fluctuations are able to operate without continuously growing inventory found in balanced lines while maintaining a similar level of throughput because of the presence of excess capacity which serves effectively as a buffer. Minimizing inventory is important when short lead times are important, carrying costs are high, no space is available for inventory storage, risk of obsolescence of inventories is high, and/or quality concerns are frequent.

Another potential benefit exists when a plant is being laid out. When designing an unbalanced line, a larger margin for error exists for all operations other than the bottleneck resource without effecting the plant's ability to produce at close to its designed volume. For a balanced line, all of the operations need to be predicted correctly. Therefore, it should be no surprise that in most industries, balanced lines are designed for substantially higher capacities than are really desired in hopes that the real line put in place will have the desired capacity. Of course, if the designer gets the constraint wrong, then the plant will have problems. However, it's easier to focus one's attention and resources on one element rather than trying to get every element perfect.

A third potential benefit exists in increasing plant capacity. It is substantially easier to increase the capacity of an unbalanced line since the constraint and items that adversely affect the constraint are the items upon which improvement efforts are focused. Being able to focus the often limited resources of a plant is much more likely to result in a large improvement than scattering the available resources over numerous improvement efforts. Once the constraint is maximized, the purchase of an additional constraint machine can result in a large increase in capacity. To reach a similar improvement in throughput in a balanced line, every operation's capacity must be improved, and each individual improvement will probably be viewed as disappointing, causing the discontinuation of the improvement efforts.

The bottom line is that from a throughput standpoint, a variety of feasible operating patterns exist. There are many factors that need to be considered when deciding between them, such as the relative costs of capacity and inventory, and the individual plant's manufacturing strategy should be one of them. In a variety of industries, responsiveness to the customer is everything; in others, inventories may not be much of a liability. Clearly, the best way to make the correct decision is to accurately model the proposed facility and consider what its competitive environment will be.

Chapter 3

Applying the Simulation Results to Solving Milan's Challenges

The general paradigm developed in Chapter 2 is that if fluctuations are present and low inventories/high responsiveness are required, the more likely it is that an unbalanced line makes sense. It is important to realize that, in the majority of real-world cases, building a new plant is not an option. Instead, like at Milan, the goal is to improve the operations of an existing facility. In the case of the real plant, the differences between the pieces of equipment are dramatic: the cost of incremental capacity varies from over $90 million for the monoplane paint system to $1 million for a packout cell, and statistical fluctuations vary tremendously in terms of yield, downtime, and operating rate of each piece of equipment. Furthermore, the plant does not have room for another paint system even if the money were available. Therefore, an unbalanced line seems to make a lot of sense since it would assist in squeezing every last bit of productivity out of the most expensive resource (the monoplane). Milan also has an Automatic Storage and Retrieval System which contains all of the plant's inventory and is of finite capacity; therefore, inventory must be maintained at a level less than the capacity of the ASRS.

An examination of both the current and future operating environments will prove that an unbalanced system is an important part of solving the problems the plant experiences and that the monoplane is where the constraint should be located. The other factor that will then have to be considered is how the plant should be scheduled and the inventory managed with the monoplane as the constraint. This will be covered in Chapters 4 and 5.

The Current System

As discussed in Chapter 1 (Figure 1), the bumper process flow is not particularly complex. The major problems the plant experiences take the form of premium transportation: use of trucks and airplanes instead of railroad cars, and heavy use of weekend overtime. The following is a list of what I feel were the strong points and weak points of the plant's operations during May through July of 1993 which affected the plant's ability to satisfy customer demand in a cost-effective manner. As will be further explained at the conclusion of this section, such a list is inherently time-dependent and portions of this listing undoubtedly are no longer true.

Beneficial System Characteristics:

- Packing out parts to the floor at the monoplane. This action decreases the amount of time parts spend occupying in-process racks and decreases the load on the final assembly cells, thereby making more ASRS capacity available and protecting the constraint from being shut down because the ASRS is full.

- Packing out parts at Selective II. This action also decreases the amount of time parts spend occupying in-process racks and decreases the load on the final assembly cells. It is less effective in decreasing time spent in in-process racks than packing out parts to the floor because parts have to travel to Selective II from the monoplane, however.

- Pushing parts across the floor from molding to bonding. This action decreases in-process rack usage and makes molding more responsive to its customer because of space limitations on floor inventory storage and ease of communication between the operations.

- Total Cost Accounting. Most of the causes of undesirable effects can be traced to Labor and Overhead/Local Optimization-style thinking (the need to run all of the equipment all of the time).

- The ASRS. It caps total inventory and by doing so helps identify problem areas (the rocks are exposed since the pond can't fill up beyond a certain point).

Potential Opportunities for Improvement:

Note: by listing an item below I am not indicating that it was financially or even physically possible to correct it.

Molding:

- Molding must become more responsive to bonding/welding requirements than it is currently. The responsiveness must include a willingness to start, stop, or change tools as required. As the first operation, molding must react to all downstream fluctuations in yields and downtime. Lack of responsiveness can fill up the ASRS with parts unneeded by the constraint, adversely affecting the monoplane and the bonders/welders which require empty in-process racks in order to operate.

- Mold change times are far from world class, resulting in less available press capacity and flexibility and larger than desirable batch sizes. If mold change times dropped dramatically, presses could be sold to other plants or could be used to make additional mold and ship parts which do not require painting. If presses could be kept busy doing something else, there also wouldn't be any pressure to make bumpers when they're not wanted.

Bonding/Welding:

- Bonding/welding machines are the plant's constraint (during May - July). Therefore, Overall Equipment Effectiveness ratios (percent of good parts made X percent of theoretical speed equipment is run X percent of machine availability) of 60-65% are not good, especially since many cells are dedicated to one or two products. Since most of the problem is machine availability, steps should be taken to increase it.

- Shutting down of bonders because the ASRS is full is extremely detrimental to plant throughput when they are the plant's constraint. Rigid enforcement of the number of parts allowed in front of Selective I, Packout, and Selective II, even if it means overtime in those areas on the weekends, is critical to ensuring the supply of empty in-process racks that the monoplane and the bonders require.

Monoplane:

- When the monoplane is a non-constraint machine, it should not be running all the time. If it were not for the lower than desirable first-run and the ability to repair and repaint most poor quality parts, the monoplane would be starved in spite of the heroic efforts of scheduling to find something for it to paint. Running it six and one-third days a week under these circumstances generally doesn't make sense. If customer-required bonded stock is not available, and there are no repairs waiting to be painted, the monoplane should be shut down.

- When the monoplane is not the constraint, appropriate preventive maintenance should be performed without hesitation under most operating circumstances. Since color change times would be reduced to be equivalent to a style change if the preventive maintenance were performed, there's no reason not to do it. Maintenance does not cost any throughput most of the time, and if not doing it is adversely affecting yields, it is extremely important that it be done.

- First-run yield is less than 100%. Therefore, parts with constraint time invested in them are potentially wasted. Repairs can fill up the ASRS and force the plant to shut down its constraint, with dire consequences for future throughput.

- Repaired parts can't be painted most colors. Therefore, parts with constraint time invested in them are potentially wasted if the customer doesn't want them in that color. Monoplane also lets repairs build up in the ASRS sometimes, again affecting the constraint. Selective I can be guilty of this as well in its attempts to locally optimize labor usage.

- Batches much larger than customer demand are routinely painted. Parts painted in excess of customer demand are wasted if there is demand with equivalent priority (due date) for the part in a different color and sufficient bonded stock is unavailable (which is almost always the case since bonding is the constraint and the monoplane runs most of the time). Batches in excess of customer demand also require the customer to carry additional inventory. Therefore, emphasis on reducing the number of color changes and running large batches does not make sense in today's (May - July) environment. Unfortunately, yield is especially poor for batches of fewer than 120 parts, and 120 parts can represent a week or more of demand for certain low volume colors.

- Monoplane yield is unpredictable. Therefore, "extra" parts have to be sent to be painted to have any hope of getting the right number out.

- Attempts to satisfy all service parts from repair parts is not always productive. If insufficient demand for service exists, it would be better to take the parts out of the ASRS and scrap them (if necessary) than to allow them to sit in the ASRS, occupying valuable in-process racks, for long periods of time.

Packout:

- The cells are treated as if they are largely dedicated, meaning that if one breaks down, one or more products is not being shipped and the ASRS is at risk of filling up. The area is also unwilling/unable to adapt to large batches of one particular type of product if the monoplane paints it because the customer needs it, forcing product to sit in the ASRS longer.

- Packout supervisors take parts that could be packed out at Selective II simply to keep busy. This can create problems in that, sooner or later, a big batch of packout-only parts will come along and have to wait for the "stolen" parts to be packed out. This state decreases in-process rack availability, thereby threatening the constraint.

- Packout supervisors do not like to deal with small batches of parts and certain types of parts. These parts sit in the ASRS, occupying in-process racks. Since packout can take parts from Selective II, there is even less incentive to get small batches out of the ASRS.

Systemic Issues:

- The assumption when the plant was laid out that there would be no breakdowns, no scrap, no repairs, and extremely flexible equipment is a major obstacle to successfully operating the plant in a world where breakdowns, scrap, repairs, and rigid equipment exist. Since the reality is substantially different, the plant is having difficulties at times. For example, the ASRS was never intended to house repairs; however, it often fills up with repairs.

- Body & Assembly, not the ultimate customer, determines what a quality bumper is. Using the requirements of the person who goes to the dealership and buys the car could dramatically impact the amount of repairs and scrap Milan generates, particularly in the area of paint defects since many of the current defects occur in areas not visible to the consumer. Not using the voice of the customer when the plant's capacity hinges on its paint system could be creating substantial inefficiencies.

- Emphasis on quantities produced rather than the mix of products produced does not meet the needs of the assembly plants. To maximize plant output, there should be only one product to which all pieces of equipment are dedicated, and it should only come in one color (early 1900's Ford). The plant would not be in business for long today. While this situation is extreme, too much emphasis on quantities produced can drive behaviors that resemble this scenario, though. Many of the phenomena detailed above are driven by a lack of emphasis on producing the correct mix. Color and style changes on the monoplane are not the plant's biggest downtime cost like the Quality Office Pareto chart shows they are. They are a necessary cost of doing business, and the monoplane is usually not the constraint operation. Making the right mix requires set-ups and color changes, but the right mix is what the customer wants. Ignoring that fact leads to much of the expediting and premium freight that occurs, as well as excess inventory.

- Labor and Overhead thinking results in local optimization of each resource rather than simply being concerned about the entire plant. With Total Cost accounting, equipment does not need to run all the time to meet financial objectives. Therefore, do not run injection molding presses all the time (at least on things that need to be welded or bonded). Make only what is needed by the constraint; work-in-process inventories beyond constraint requirements use capital and ASRS space unnecessarily.

- Everyone in the plant thinks they are a scheduler. Scheduling, not production, is the only function that has the customer requirements information necessary to make optimal decisions from the entire plant's perspective. Persons not working in the scheduling area should not be engaged in second-guessing. If scheduling is in control and customer needs are not met, at least then it would be easier to identify what procedure or policy needs to be altered.

- Mistagged/misidentified items are a major obstacle to meeting customer requirements. It is impossible to schedule the plant correctly when data about work-in-process and in-transit inventories are wrong, and it is very difficult to correct for last minute discovery of mistakes when the plant is three days by rail away from the customer. Operators should be given the authority and responsibility for making certain that the parts they work on are correctly identified. Far too much management time is spent meeting about the issue of negative work-in-process inventories, and having to keep much of the shop-floor inventory management system turned off because of problems with data integrity deprives schedulers of a useful source of information.

- The premium transportation budget should be eliminated. Every case should be scrutinized for opportunity to improve operations so that the problem won't happen again. Better investigation of the cause would provide the opportunity to justly charge the responsible operation for the premium transportation as an unbudgeted cost. Hopefully, this would provide an incentive for premium transport reduction, thereby freeing up money for process improvements and people to increase throughput and increasing customer satisfaction and the plant's profitability.

- A combination of downtime and poor first-run yield can make molding, bonding/welding, the monoplane, or packout the "real" constraint which should be managed at any given time. Unfortunately, bonding/welding and packout do not have sufficient excess capacity to recover from statistical fluctuations, and molding (particularly tool availability) and monoplane problems can last long enough that the customer is affected. The "moving bottleneck" phenomena also makes it difficult for scheduling to schedule the plant correctly to maximize throughput since the situation is so dynamic. The constantly changing system makes it difficult for individuals unfamiliar with the performance of the entire system at a given time to understand why certain actions are being taken, and can result in indecision even among individuals familiar with the whole situation when a rapid response is of great importance (a rapidly filling ASRS, for example).

- The current solution to the previous problem is running weekends and using premium transportation. Both are expensive, and both may not be enough to recover if one or more pieces of equipment run extremely poorly. Also, the mix of processes run over the weekend can leave the plant in a poor situation for meeting the next week's production needs (not enough bonded stock and/or too much inventory piled up in the ASRS in front of Selective I, Selective II, and/or packout).

Clearly, as is common in most manufacturing facilities, there are a wide variety of causes of undesirable effects. The four biggest issues during the May through July 1993 period were 1) poor bonder Overall Equipment Effectiveness, resulting in the plant not making enough (often) and not making the correct mix (usually), 2) monoplane yield variability, resulting in a very dynamic environment in which to schedule and a lot of less useful parts with constraint time invested in them, 3) an increase in demand combined with the sourcing of all Aerostar products to Milan, and 4) the fact that the monoplane follows the bonding operation. These major problems made other problem areas more serious than would have otherwise been the case. If the reverse of point 4 were true, monoplane yield variability would be much less of a problem as long as it didn't result in bonder starvation (which in most cases it wouldn't since the monoplane has much more throughput capability). The monoplane yield variability is the major factor that will carry-over to the 1995 system.

Unfortunately, the plant's operating environment is extremely dynamic: demand changes radically from month to month, as does equipment performance; therefore, any list of strong and weak points is substantially time-dependent since the location of the bottleneck and the severity of its effects change with time. I have identified four separate steady-state conditions that lasted for 2-4 months each during 1993 alone. During the first quarter of 1993, bonding and welding were the constraint, but since demand was low, the bottleneck's capacity did not adversely affect premium transportation. In the second quarter, demand jumped dramatically, and bonding and welding performance was worse than it had been in the previous quarter, resulting in a rise in premium freight. In the third quarter, the monoplane became the constraint since it had difficulty painting the 1994 model year colors, and demand rose again, resulting in record high premium transportation. And finally, now that demand has fallen with preparation of the assembly plants for the launch of the Mystique and the Contour automobiles, and improvement in the monoplane's performance has occurred, bonding and welding can be viewed as the bottleneck again; however, their effect on the customer is not large since demand is low, and premium freight has dropped to first quarter levels. Beginning with the launch of the Mystique and the Contour bumpers, the monoplane should become the constraint again since new colors will be an issue again and bonding and welding volumes will have dropped somewhat since the Contour Front is a TPO part which does not require bonding. Lots of manual transport of parts is going to have to be done between 1994 and 1995 since all the new ASRS in-process racks will not be in place, however, and that may have all kinds of strange effects. The loss of Selective II's packout ability while it is modified to handle the 1996 products also affects the system by increasing the load on the packout cells.

Rather than try to figure out the effects of the numerous transitional stages between 1994 and 1995, I jumped to the next steady-state of operations which will occur in 1995 with the launch of the new Taurus/Sable. This new operating environment is examined in Chapters 4 and 5.

Chapter 4

The Future System[5]

Any look at the future system must begin with TPO (thermoplastic olefin), the material that will be used to make almost all of the new products in 1996, and perhaps by 1998, all of the bumper products made by Milan. The properties of TPO are much different from the properties of Xenoy, the polycarbonate-based material currently used to make all of the bumpers at the plant. The differences in the materials' properties will have a dramatic effect on the processes used in the plant.

The TPO Production Process

TPO is an intensively mixed compound of polyolefins, elastomers, fillers, additives, and colorants (Figure 6 shows a typical process flow diagram). A typical formulation (there are many varieties of TPOs) includes ethylene propylene rubber, polypropylene, heat and ultraviolet light stabilizers, and fillers such as talc, calcium carbonate, or glass which influence the thermal expansion properties and the modulus. These ingredients are compounded together using high-intensity Banbury mixers. The molten product is then extruded into pellets. Final product lots are typically composed of dry-blended pellets from numerous compounded batches. Material properties are affected not only by the ratios of the raw materials used, but also by the mixing efficiency of the processing equipment, the amount of shear during processing, and the homogeneity of the raw materials.

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[5] The author wishes to thank Mr. Dan Himebaugh and Dr. Rose Ryntz of Ford Motor Co.'s Plastic and Trim Products Division for providing information about their TPO research efforts.

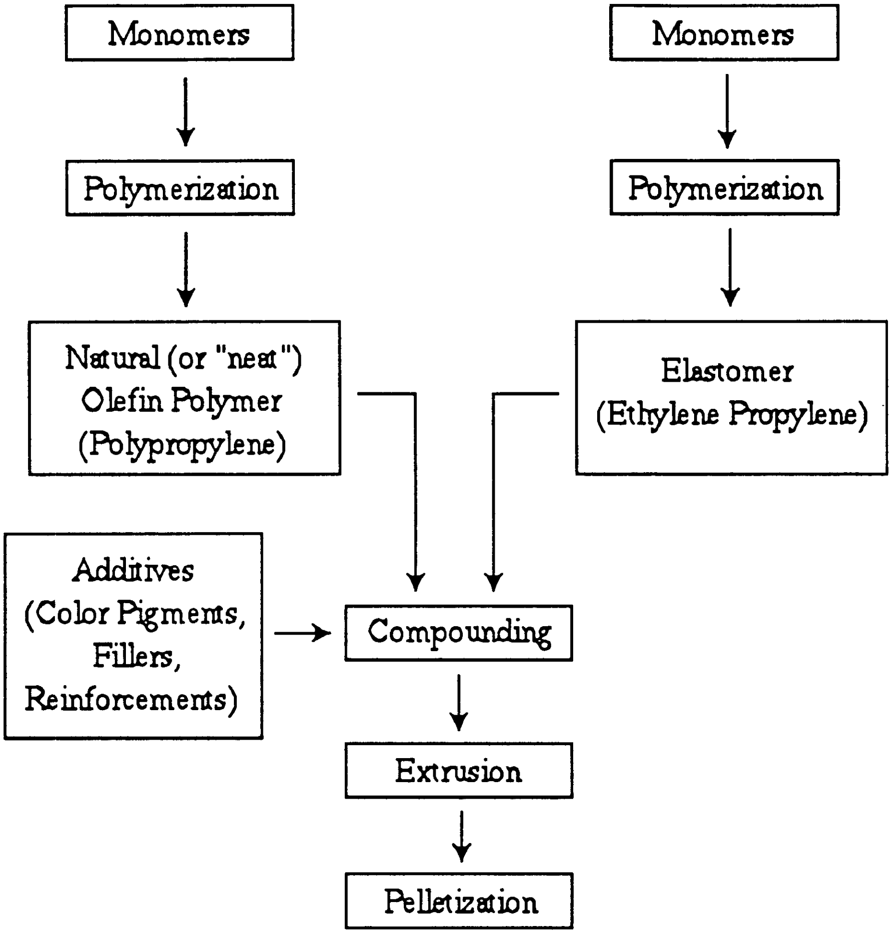

Figure 6: Typical TPO production process[6]

Why Use TPO

Compounded TPO is viewed favorably as a bumper material, from a styling standpoint, because it is soft and flexible. This property allows for a tighter fit between the bumper and the sheet metal of the car body, thereby improving the fit-and-finish of the fascia, hood, fenders, and lamps. Fitting tightly to the sheet metal is important because of the design trend towards flush, integrated front ends where the bumper does not protrude. Integrated front end structures combine the functions of radiator support, headlight assembly, grille opening reinforcement, hood latch mounting, and bumper support in one subassembly. In these designs, the collision energy management structure is built into the vehicle at the assembly plant and is independent of the fascia. Therefore, a soft and flexible

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[6] Based on Figure 1 of Logan, W. N. "Reactor Thermoplastic Olefins - A New Class of High Performance Materials for Bumper Systems." *Society of Automotive Engineers 920526*, 1992, pp. 133-51

material is suitable for use because it is there purely for appearance and aerodynamics. In contrast, the Xenoy bumpers the plant currently produces are intended to be a complete bumper system, and they leave a gap between themselves and the front of the vehicle.

The bumpers produced at the plant today have a Xenoy box-beam bonded or welded inside the fascia which reinforces the fascia and absorbs energy. Xenoy is a much stiffer material than the grade of TPO planned for use at Milan, so it works well in this capacity. The new Taurus/Sable and Contour automobiles will require an energy absorbing structure made of stronger materials than TPO. A variety of reinforcing beam materials can be used, including steel, aluminum, or glass fiber - plastic matrix composites. The new Taurus/Sable will use a Xenoy box beam attached to steel reinforcements.

Several other materials were considered for use as a soft fascia. One which has seen use on several Ford products with integrated front-ends is Reaction Injection Molded Urethane (RIM). The material is soft, has a tough surface, and is easily painted since a urethane-based paint is used which wets the surface nicely. However, a number of drawbacks exist.

The primary disadvantage is that regrind cannot be used in the manufacture of RIM fascias since it is a thermoset. Milan's operations create a substantial amount of rejects which would be extremely expensive to dispose of it they could not be recycled as regrind. Also, Ford's efforts to improve the recyclability of its vehicles makes RIM objectionable. TPO and Xenoy, being thermoplastics, can be successfully reused inside the plant in the bumper injection molding machines if they have not been painted, and painted regrind may find applications in injection molded products other than bumpers. The major issue with painted regrind is that the paint substantially alters material properties, particularly the strength of the molded part, and paint flakes show through unpainted products. To address this issue, a supplier is attempting to develop a process which removes the majority of the paint flakes and restores the material's properties to an acceptable level for use in non-structural applications. Identifying uses for post-consumer Xenoy and TPO bumpers poses a major challenge for automobile manufacturers.

Additional objections to RIM involve cost. First, since the RIM molding process involves a reaction, an additional source of scrap compared with other materials is introduced because reaction variability can result in dimensionally correct but functionally imperfect parts. Quite a lot of scrap is generated because of air entrapment during the reaction molding phase. Second, RIM raw material is somewhat more expensive than TPO.

Other candidates (Texan and a low modulus grade of Xenoy called Lo-mod) were viewed unfavorably because of cost and the fact that they have not been used in the field by the auto industry. Bumpers experience a wide range of operating conditions, and environmental degradation is a big concern and a potentially large source of warranty claims and customer dissatisfaction.

TPO has the advantage of having been used for several years by many companies (Honda, Lexus, and Mazda) without difficulty. It is relatively inexpensive since it is based on polypropylene. Its specific gravity is also lower than the other materials considered (0.9 vs. 1.2 specific gravity). Therefore, less material is required to fill a mold, and the final product weighs less, an important benefit since fuel economy is greatly influenced by vehicle weight. Approximately 10 to 15 pounds of TPO will be used in each fascia, depending on the vehicle type.

TPO's Effects on the Future System

The properties of the material and the design of the parts are driving numerous changes to the current system of production, both positive and negative. The following is a look at how the parts' design and the choice of materials will affect each of the major areas of the plant. Figure 7 shows a typical TPO bumper production process.

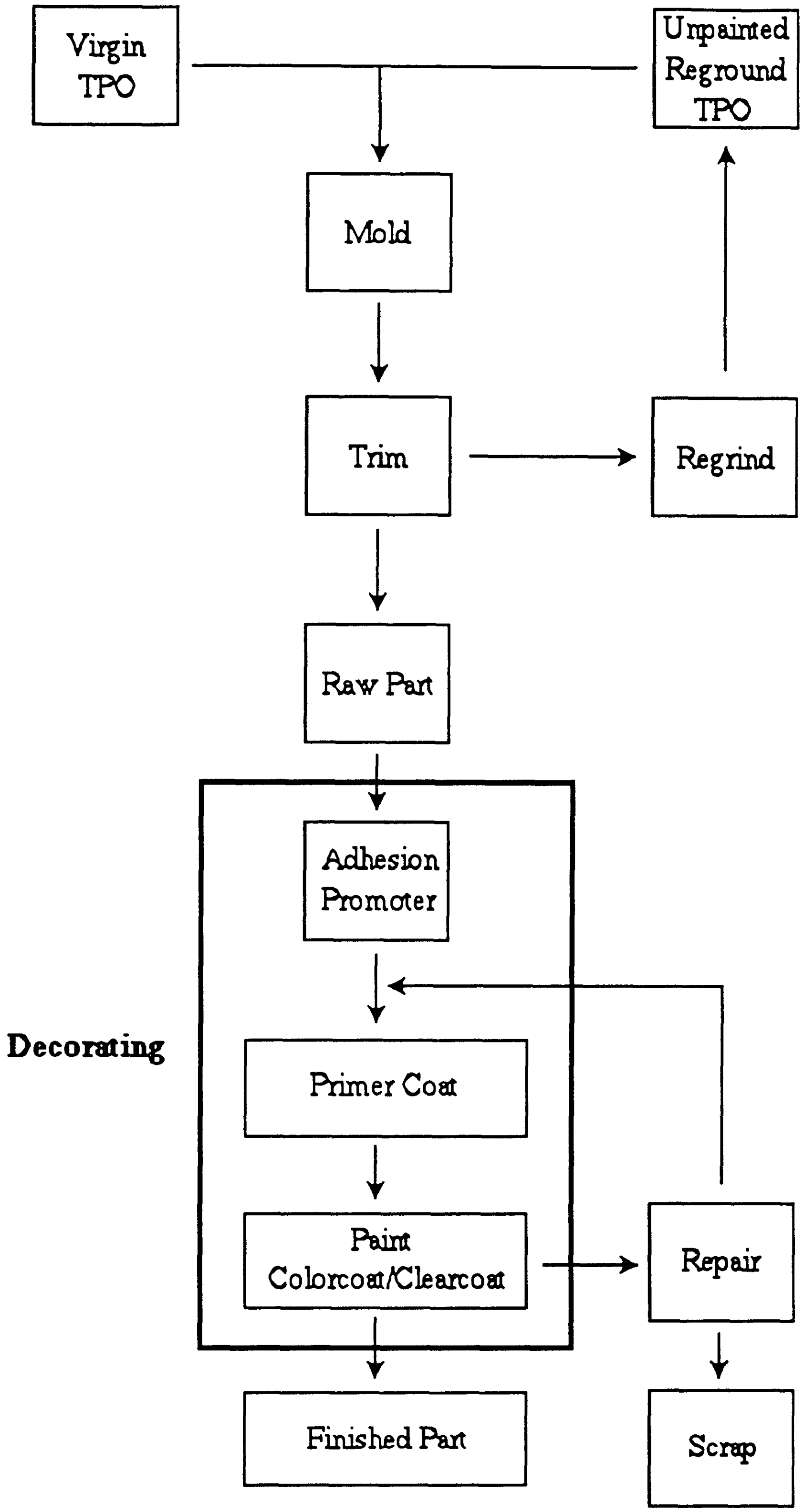

Figure 7: TPO bumper fascia production flowchart[7]

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[7] Based on Figure 2 of Golder, Michael D. "Plastic Materials for Soft Bumper Facia." *Society of Automotive Engineers 910689*, 1991, pp. 107-22.

Injection molding/tool room

Primarily, TPO should have positive effects on the injection molding presses themselves through ease of startup and reduced cycle times, but could pose some problems for the tool room because of the complexity of the tools. Since the material is less viscous than Xenoy, it requires lower temperatures to mold successfully, reducing cycle times from the current 135 seconds for Xenoy to as low as 100 seconds for TPO since the cooling time is shorter. In fact, the current obstacle to faster cycles is the robot unloader, so faster cycle times may be achievable. The decrease in cycle times will increase the capacity of the injection molding area substantially.

Second, presses running TPO should be easier to start up since TPO does not degrade in a heated press as rapidly as Xenoy does. Therefore, preheating the press greatly reduces the amount of time to steady-state since the press is warmed up and a lot of degraded material does not have to be pushed out before good parts can be made. As a result, it should be possible to make good parts in substantially fewer cycles than occurs today with Xenoy. The press can reach the lower required temperature for TPO faster, too.

The tools, on the other hand, may be more difficult to maintain in a usable condition. The TPO parts are quite complex, containing numerous openings for radiator grills, headlamps, etc. The parting lines have also been moved to areas of the part concealed from customer view. However, accomplishing this feat has required molds with collapsing cores, thereby causing the tools to have a much larger number of moving parts than the plant is accustomed to. As a result, it is quite possible that the tools will require more maintenance than the tools currently used to produce Xenoy parts and will break down more frequently.

Bonding/welding

The TPO fascia is attached directly to the sheet metal of the automobile and is not actually attached to the Xenoy box beam reinforcement which manages the energy of a collision. Therefore, the bonding and welding area will experience a dramatic drop in volume since only the Contour Rear, Mystique Front and Rear, and past model service bumpers will require bonding and welding. The TPO Taurus/Sable and Contour Front bumpers will pass directly from injection molding to painting. Therefore, bonding and welding will no longer be a potential bottleneck since plenty of capacity will exist, even after the removal of two bonding cells. If the Contour and Mystique automobiles go to all TPO fascias for the proposed 1998 reskinning, bonding and welding will be entirely removed from the plant except for past model service bumpers.

Monoplane

A major issue with the adoption of TPO is its paintability. Although it has been used by Japanese manufacturers for the last decade, a key processing step to ensure good paint adhesion seems to be the application of trichloroethylene to the surface during the cleaning stage. The use of this chemical will soon be prevented by legislation, so companies wishing to continue with TPO are being forced to develop a new painting process. Ford is currently considering the use of an adhesion promoter to replace the trichloroethylene.

The injection molding process results in two surface layers whose structure differs from that of the bulk. Material near the surface is quenched because of its proximity to the cool mold wall and is amorphous, but material in the bulk stays warmer longer, allowing for the growth of large crystals. An intermediate layer exists where smaller crystals form. Since the rubber and the polypropylene are not very miscible, it is desirable to have large crystals of polypropylene so that the polypropylene will entangle with the rubber. Unfortunately, from a painting standpoint, the two layers distinct from the bulk that form near the surface because of the large temperature gradient near the mold surface have undesirable properties (Figure 8). The surface layer is almost pure polypropylene, which is bad since the urethane-based paint does not wet polypropylene. The second layer is composed of discrete rubber particles embedded in a crystalline polypropylene matrix. Because the polypropylene crystals are small, the rubber and the polypropylene are not securely interlocked with one another . In contrast, the bulk is a fairly homogeneous mix of rubber and polypropylene since the polypropylene crystals have the opportunity to grow for a much longer period of time.

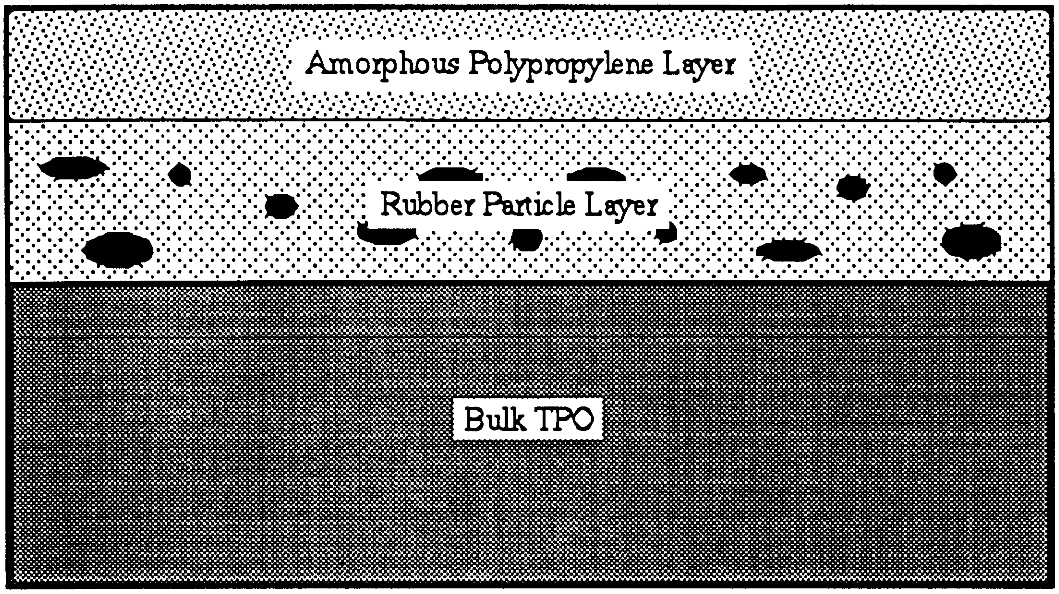

Figure 8: TPO surface morphology

From a thermal shock performance standpoint, the situation is far from ideal in that the paint is expected to adhere to a surface that it doesn't wet, and the rubber in the second layer is expected to keep the polypropylene top layer and the paint layer attached to the bulk in spite of the poor overlap between the rubber and the polypropylene in that layer. However, any attempts to keep the second layer warmer for a longer period of time to promote crystal growth are ill-advised since doing so would allow the top layer of polypropylene to become thicker, denser, and crystalline rather than amorphous, preventing penetration of the adhesion promoter solvent. Fortunately, as long as the polypropylene surface area is amorphous and thin, adhesion promoters exist which make the surface suitable for paint adhesion.

The adhesion promoter consists of polymers and a solvent. The solvent is very important in determining the effectiveness of the adhesion promoter. The solvent has to penetrate the polypropylene surface (hence the desire for a thin and amorphous layer) and enter the rubber particles found in the second layer. As the rubber particles absorb solvent, they begin to swell and break through the polypropylene layer. At this point, the polymers in the adhesion promoter can entangle with the rubber phase of the TPO, providing attachment points for the paint. The rubber particles then have two duties: holding onto the polypropylene surface layer and holding onto the paint via the adhesion promoter polymers.

In their swollen state, however, the rubber particles are substantially weaker. Therefore, it is desirable to remove the solvent from the rubber. Baking the part at 250 °F before painting has been found to result in sufficient removal of the solvent so that the rubber performs acceptably. The higher temperature also seems to assist the adhesion promoter polymer in its efforts to mechanically interlock with the rubber . Finally, the bake temperature seems to remove the effects of injection molding variability on the parts' dimensional characteristics.

But, although a successful painting process seems to be available, it has some unfortunate effects. First of all, Milan's current bake oven does not reach 250 °F, so an extensive modification costing approximately seven million dollars is required. Second, repairing monoplane rejects becomes much more tricky since sanding through to the substrate or scratching the part make it unusable because a "haloing" effect occurs upon repainting. Once fresh adhesion promoter has been locally applied and the part is repainted, the substrate swells at the interface between the old paint and the sand-through. The raised "halo" reflects light differently than the surrounding material, making the part look discolored and therefore unusable. If the monoplane does not paint better than it does currently, the scrap rate from the plant will be higher if a robust repair process is not found.

Fortunately, a new repair process has been identified which is very promising. The process is called cold gas polishing, and it is much less aggressive than the power sanders currently used; in fact, it can convert parts with minor defects such as foreign substances trapped in the paint directly into end-items. Such a process would effectively increase monoplane first-run since the parts would not have to be repainted and thereby increase the entire plant's capacity, and the chances of polishing all the way through the existing coat of paint to the substrate are greatly reduced.

Packout

TPO itself will not pose great difficulty in the packout cells, but the new Taurus/Sable design will because substantially more bumper assembly content exists. Headlamps, grills, mylar rubstrips, and license plate brackets are some of the many things that will be attached at Milan rather than at the assembly plants. Unfortunately, each product has a large number of unique parts and different amounts of assembly content, so the products will not be able to be run interchangeably on all cells. Most cells will run two or three products requiring different amounts of assembly. As a result, a labor imbalance exists if the cell is staffed for the highest assembly content part but is packing out one of the other ones. Changeover times between products are also potentially significant, ranging from 5 to 30 minutes since the parts for what the cell was running will have to be removed and the parts for the new bumper will have to be brought in from a storage area.

Material Handling

Handling TPO is almost as difficult as painting it. Because it is a lower modulus material than the Xenoy part, particularly because it does not have a box-beam attached to it while it is at Milan, it is difficult to handle due to its flexibility. To make matters worse, the new Taurus/Sable bumpers are larger than the current Xenoy bumpers and have very long ends. In addition to the difficulties associated with handling a bulky, low modulus part, TPO is easily marred. Fortunately, if it is damaged before painting, it can be reground and reused easily. However, as mentioned earlier, if the surface is damaged after painting in such a way that it cannot be repaired because the substrate is exposed, the part will have to be processed off site to make it acceptable to the non-bumper injection molding machines which make non-structural parts. Either case is expensive, so it would be preferable to avoid damaging the parts. Ergonomics issues also exist with the handling of such a large and flexible part.

To assist in the handling of the part, both to assist employees and because Milan uses many robots in material handling applications, a number of steps have been taken. First of all, wire frames have been designed to support each part from molding through the rest of the system. The frames provide people and robots with a much more stable part that is easier to grab onto and control, hopefully avoiding damage to the surface. Second, the people will be provided with manipulators (a powered mechanical arm supported from the ceiling which can hook onto the wire frames) for the largest parts so that one person can handle the part easily, reducing the chance of damage.

The need for wire frames creates a number of issues, however. First of all, they are expensive, and they will have to be tracked, particularly since they are unique to the molded part that goes on them. Second, they will get paint on them each time they pass through the monoplane, so they will need to be cleaned regularly. Third, the frame's dimensional consistency is essential since the part will be getting quite warm while it is on them in the bake oven. If the frame is bent out of shape and applies pressure to the part, the part may distort. Therefore, inspection of the frames will be required. A potential benefit is that paint transfer efficiency may be improved by the ability to adopt an electrostatic process because the frames are conductors.

The need for wire frames has resulted in the creation of a framing area where the frames can be added to or removed from the system. Management of injection molding and packout activities will be important if the requirements for the number of in-process racks requiring the changing of frames are not to exceed the framing area's capacity to reframe racks. The framing area will have to correct any imbalance between the number of wire frames of each type that the packout area is generating and the number of wire frames of each type that the injection molding area is requiring by changing the types of frames on the in-process racks as they pass from packout to injection molding.

Locating the Constraint

With the detailed descriptions of the current and future system in hand, we can now use the criteria for constraint location developed in Chapter 2 to determine where the constraint should be placed. The monoplane is clearly the most expensive piece of equipment, so it is a clear winner in the first and second categories (we want to purchase the least amount of the resource, and we want to protect it by having excess capacities in the cheaper resources to buffer the constraint against statistical fluctuations). The equipment downstream of the monoplane also has a good first-run yield. Thus, the monoplane is the logical choice in spite of its unpredictable yields, particularly because there is no way the plant can secure any additional amounts of this resource. Also, the monoplane is the only piece of equipment with a minimum batch size limitation that makes sense since it impacts yield favorably (larger batches tend to have fewer defects). Unfortunately, because the monoplane yield is still highly variable even with the minimum batch size condition because of airborne particles, part temperature, ambient temperature, humidity, and paint color, the development of a successful scheduling approach for the entire plant is quite difficult. This problem, and possible solutions, will be explored in Chapter 5.

Chapter 5

Production Management in 1995

From the preceding chapter, it is obvious that much will change when the new products are launched. It should now be clear that an unbalanced line, with the monoplane as the constraint, represents the most profitable configuration of the production system by providing the most throughput per dollar of investment. Exactly how unbalanced the plant can be is determined by the amount of space available and the amount of the investment that can be made, almost all of which were determined before I arrived at the plant. Thus, it is now time to consider the problem of how to schedule and manage inventory in 1995 based on the planned configuration which, fortunately, is somewhat unbalanced.

Initially, after the success of applying Goldratt's Theory of Constraints ideas to allocating capacity, I planned to take the next step and adopt his Drum-Buffer-Rope scheduling and inventory management strategy presented in *The Race*.[8] The basic idea is to use the constraint's schedule to drive all the other operations of the line, thereby limiting the inventory in the plant to only that which the constraint will use in the near future and that which the constraint has already processed. It is possible to establish a close to deterministic lead-time as well using his system of time buffers between the first operation and the constraint, and between the constraint operation and the actual shipment of the finished product. Unfortunately, the characteristics of Milan's future system are not amenable to this approach.

Although Drum-Buffer-Rope effectively protects the product's due date against all types of downtime and yield fluctuations upstream of the constraint, it does not allow for large fluctuations in yield in either the constraint or processes downstream of the constraint if upstream processes cannot respond quickly to compensate for the loss. Remember that in the future, the monoplane will be the constraint, and it has extremely varied, unpredictable yields. Thus, a constraint schedule cannot be written that will remain unchanged for a long period of time. Milan's injection molding machines are not very responsive since they are run in large batches with a minimum of tool changing that takes 4 to 6 hours or more, and the plant's management is skeptical about changing the area's operating practices. So, this approach was ruled out. However, if greater control is ever gained over the monoplane or the practices of the injection molding area are radically overhauled to enable the area to

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[8] Goldratt and Fox, *ibid.*, pp. 96-138.

respond quickly to changes in monoplane schedules, then a Drum-Buffer-Rope system could be very effective at Milan.

At this point, I consulted with Ron Horton at the Saline Plastics Plant where they have been using Theory of Constraints to totally revamp the plant. He suggested the use of a pull-system, which would have many of the advantages of Drum-Buffer-Rope and be feasible, with the only cost being inventory and responsiveness. Since inventory is and will be capped, the amount of inventory required to run the system is critical.

General Operating Criteria for Each Area in 1996

Monoplane

With the transfer of Sable Front and Taurus/Sable Station Wagon Rear bumpers to the Utica Trim Plant and a decrease in the volume of products requiring bonding and welding, the monoplane will be the plant's constraint. Therefore, it will be important to run it as efficiently as possible. The first requirement is to ensure a minimum number of ASRS empty racks are always available because if there are not enough empty racks, the monoplane will be blocked. Second, the monoplane will need to prevent the buildup up repaired bumpers in the system. To do this efficiently, it will be important to have a number of qualified repair colors, preferably high volume ones, or the ability to track the original color of the repaired parts so that they can be painted the same color. Finally, the monoplane will need to be scheduled properly.

The scheduling concept I have arrived at is much like the one used today: a minimum batch size of 120 pieces and long runs of each color. Both of these actions should reduce the amount of time lost in color changes and improve first-run. The difference will be that the batches of each individual style will not be much larger than 120 pieces in most cases (this is a cost since yield tends to go up with increasing batch size), and additional inventory will be required compared with what would be necessary if the plant painted exactly to demand. In order to achieve large batches, low volume end-items will have to be painted less frequently than every day. The monoplane cannot hope to paint every color of every style every day with a minimum batch size of 120 pieces. Therefore, I have arrived at the criteria, based on 93B Financial Planning Volumes (forecasts of expected sales volumes for new Taurus/Sable and Mystique/Contour), displayed in Table 4:

# of times/week painted	Criteria based on demand	# end-items meeting criteria
5	≥ 486 pieces/week	29
4	< 486 pieces/week	16
3	< 389 pieces/week	9
2	< 291 pieces/week	10
1	< 194 pieces/week•	42
		106 end-items

•9 batches of 60 pieces/week where (weekly demand/0.81) < 60.

Note: the production mix consists of 20 unique colors and 8 unique molded parts. Taurus Rear Sedan Export bumpers should be painted in sequence with Taurus Rear Sedan bumpers since they are identical molded parts.

Table 4: Monoplane scheduling criteria

The goal is to spread the total number to be painted equally over all 5 days. It is also preferable to spread the number painted of each style equally over the 5 days rather than painting a full week's worth of one style in all colors on one day since packout, injection molding, and bonding/welding cannot handle that much of one kind of part. The batch size ordered on the monoplane is determined by taking the demand for the 1, 2, 3, 4, or 5 day period and dividing by expected first-run (current expectation is 0.81).

Hopefully, this amount of excess will be sufficient to allow each needed end-item to be only ordered once per day. If yield is worse than 0.81 on a particular batch, though, it will have to be reordered later in the day. By balancing the amount required over the 5 days, the monoplane should not have any difficulty meeting each day's schedule. However, if volumes rise much above the Financial Planning Volumes, a sixth day would probably be required; parts with weekly demand greater than 583 would be painted on a six day basis.

Selective I

Selective I is the repair area. It will need to process monoplane rejects as quickly as possible since allowing bumpers requiring repair to fill up the ASRS will result in lost throughput. Therefore, the area will need to run 24 hours per day. Also, there is little point in spending a lot of time figuring out whether the part is any good or not. If it is not obviously good, it should be scrapped, and another part should be pulled in for processing.

It is a poor use of constraint time to have it repainting parts that should have been scrapped since repainting them will not make them acceptable. The scrap rate for this area will be fairly high anyway, so making the pile of repairs in front of the area wait while one part is thoroughly investigated does not make a lot of sense.

Packout

Packout will be critical to ensuring a smooth flow of parts out of (and into) the system since parts cannot come into the system unless parts are going out if the ASRS is to maintain a minimum number of empty in-process racks. Although the monoplane will be taking the inflexibility of the cells into account by painting each style on a regular basis, the cells that run multiple products will still need to changeover frequently, presumably every time they complete a monoplane batch of an individual style. This will need to be done in spite of the labor imbalance that exists referred to in Chapter 4 if the cells are not to be starved for substantial periods of time and then buried in inventory. The cells simply are not capable of large swings in throughput. Having the correct amount and type of purchased parts will also be critical in keeping the cells running smoothly. Since packout is not the bottleneck, however, it will be impossible to keep all of the cells busy all of the time.

Selective II

This area's goal is similar to that of packout: expedite the exit of products from the ASRS. To accomplish this, relative interchangeability of Xenoy service parts, Contour Rear packout, and Sable Rear selective decorating is essential. Since the load for the area only justifies its operation for two shifts, staggered shifts offset by 4 hours rather than 8 hours of downtime all at once would be preferable in assuring a smooth flow of product and availability of product to prevent starvation during operating periods. In this area, a labor imbalance exists, but will have to be tolerated.

Injection Molding

Injection molding is the only area involved in new Taurus/Sable production with significant flexibility. In particular, excess capacity exists, and molds can be changed. Utilization of the flexibility in the interest of the global optimum regardless of what it does to the area's local efficiency will be essential.

To avoid placing unreasonable demands upon the framing area to absorb frames from packout while producing frames for injection molding, injection molding will need to follow packout's operating patterns with no more than a two hour lag. Ideally, the rate of injection molding usage of frames of a particular type should be identical to the rate of generation of frames of that particular type by packout. Here again, it is clear why smaller batches of lots of styles are preferable to large batches of one or two styles: injection molding has limited resources to build each type of product, but in aggregate can outrun the packout area. Keeping close to packout will require a willingness to start, stop, and change tools on a regular basis. Decreasing tool change time would be very helpful also, particularly if the plant wishes to take advantage of the excess capacity present by acquiring additional mold and ship business.

Bonding/Welding

Since bonding and welding will have a tremendous amount of excess capacity, their goal is to use this capacity to keep the amount of inventory ahead of them in the ASRS as close to zero as possible. To accomplish this, they will need to changeover in synch with injection molding's production and be staffed on a 24 hour basis. To assist this area in maintaining low ASRS inventory, the Contour Rear (the highest volume bonded part) will be kept on the floor rather than in the ASRS.

Capacity Constrained Resources:

As with most systems, a few exceptions to the above rules exist in the 1996 production system. These exceptions I am classifying as Capacity Constrained Resources (CCR). CCR is Goldratt's term for operations which are not the plant's overall constraint but could adversely affect the plant's production of certain products if attention is not paid to the demands placed upon them and their operating patterns. Fluctuations in the operations of CCRs (yield, downtime, blockage/starvation) or the demand for those resources can result in the dreaded "moving bottleneck" phenomenon. Moving bottlenecks typically result in expediting on a massive scale. One would generally not lay out a plant with CCRs, unless the amount of investment required to avoid them made it impossible to do so, because they are the root of moving bottlenecks. They are quite common in plants converting from a somewhat balanced system to an unbalanced one, however.

Unfortunately, from an ease of management standpoint, several Capacity Constrained Resources potentially exist in the Milan plant of the future; only once production has started can they be identified with certainty since important factors like demand, cycle time, and downtime are all forecasts at this point. As a result, I can only make an educated guess as to which operations will be CCRs. Based on the 93B volume forecasts used to develop the monoplane scheduling procedure and current assumptions regarding cycle times and downtime, the following equipment will be capacity constrained (Table 5):

Machine	Product(s) and type of operation performed
103	Mystique Front molding
114	Contour Rear molding
115	Contour Rear molding
116	Mystique Rear molding
111	Sable Rear Sedan molding
501	Contour Rear bonding
146	Contour Front, Mystique Front & Rear Packout

Table 5: Potentially capacity constrained resources in 1996

These operations are either very close to being fully loaded or are overloaded under current assumptions, and therefore should be scheduled to attain at least the planned utilization (assuming cycle times do not change), and should be the primary focus of cycle time reduction/utilization improvement efforts. Notably, 4 of the 5 presses which are capacity constrained run Xenoy.

The key to addressing this issue is to keep cell 146 busy packing out customer-needed product since presses 103 and 116 will need to be putting parts into the ASRS continually, regardless of whether or not the parts are coming out the other end. To maintain empty in-process racks, packout cell 146 will need to keep up; fortunately, the Xenoy parts do not require wire frames, so even a radical imbalance will not harm the framing area. Likewise, Selective II will need to keep parts flowing out so that presses 114 and 115 can be kept running. Another reason to avoid shutting those presses down is that bonder 501 is dependent on presses 114 and 115 for work.

Since the capacity constrained presses will be violating the ASRS mass balance rule of one in only when one comes out from time to time, the job of ensuring ASRS empty racks will fall to the packout cells and injection molding presses making Taurus Front, Taurus Rear Sedan, and Contour Front bumpers. These operations, with the exception of packout cell 146, all have excess capacity. Therefore, these presses can march in lockstep with their respective packout operations, and the third or fourth press making each of these products should be the first to be shut down if empty in-process racks fall to unacceptably low levels.

The capacity constrained operations listed in Table 14 will require attention to ensure that the monoplane and the assembly plants are not starved of needed products. Periodic review of their operations and the demands placed upon them will be essential to identifying the need for special scheduling attention. To assist with accurate forecasting, these operations should be maintained in statistical control, preferably with minimal spread about the mean for the relevant factors like yield, breakdowns, and cycle time so that available capacity can be realistically compared with demand. A major cultural change will be the acceptance of the reality that operations that are potential bottlenecks today may require a different operating pattern next week than they did today because of changes in demand for that resource. Put simply, equipment that is fully loaded should be run differently and have more attention paid to it than equipment with demand requiring only 50% utilization.

One difficulty in managing the CCR problem is that Ford's evaluation of investments in capacity does not properly address the CCR concept. Milan is under pressure to get rid of injection molding presses because it appears to have excess capacity when the production capacity for all bumper products is compared with available press capacity. Yet, such an examination pretends that any product can run on any press (far from true) and that changeover from one product to another costs no time. Thus, Milan can have five potentially overloaded presses and one overloaded packout cell and be under pressure to dispense with a packout cell and several presses. One cannot add together unlike quantities, ignoring real physical constraints on what can be run where, compare that quantity with another addition of unlike quantities, and expect to get a useful number. Unfortunately, this is exactly what is occurring as the Plastic and Trim Products Division evaluates its investment in equipment at Milan.

Complete Production System Concepts

The fundamental objective for the management of an unbalanced line is to ensure that the constraint is never blocked because of downstream occurrences or starved of needed parts, since in either case plant throughput is affected. In the case of Milan, the key conditions that must be met to assure the complete utilization of the constraint are that the ASRS can never be without empty in-process racks, and it must always have the correct mix of products in front of the monoplane to run any customer-demanded order. The current system of scheduling and operation is incapable of meeting either condition with any reliability. Bonding and welding will not be the plant's overall constraint in the future, though, so there is some hope of satisfying the second condition. The goal of my production management concepts is to ensure that both conditions hold at least most of the time in spite of the statistical fluctuations that are bound to occur, while also attending to the needs of the capacity constrained resources.

The following two concepts are complete systems of production based on the general operating criteria for each area that I have developed.

The Pull Concept (version 1)

To make both conditions hold, I initially proposed to fix the quantity of each part type that can be in the system at any one time through limiting the number of wire-frames of each type and by using a limited number of *kanban* cards for each of the three Xenoy part types which will not require wire frames. This action would ensure that the ASRS is 1) never filled up with a skewed mix of parts which would make some parts less available to the monoplane than would be desirable, 2) never forced to shut down presses making needed parts because it is full, and 3) never forced to shut down the monoplane because it is full (the number of frames + the number of *kanban* cards will be less than the total capacity of the in-process racks, thereby always leaving enough empty in-process racks to run the system).

The system would be managed in the following manner:

1) The monoplane scheduler schedules in a manner similar to today as far as grouping colors together. However, he or she tries to run smaller batches of each style so that the paint system throughput can be spread over all the final assembly cells since they do not

have much ability to recover from starvation. It will be important to keep in mind that an excessive number of color and style changes will adversely impact the plant's ability to satisfy customer demand since each set-up causes throughput to be lost.

2) Packout and Selective II assemble and pack out the painted products as quickly as possible, freeing up ASRS in-process racks and wire frames. The advantages of keeping most of the system's inventory in front of the monoplane are two-fold: the monoplane has great flexibility in how it goes about satisfying customer demand and can therefore run efficiently, and since the inventory will be either molded or bonded stock, its density should be extremely close to one hundred percent since only full in-process racks will be shipped from molding, and bonding has a greater than ninety-nine percent yield. Therefore, the inventory is protecting the constraint while occupying the ASRS in the most efficient manner.

3) The empty wire frames then represent "holes" in the inventory held in the ASRS which must be filled so that the monoplane will not be starved. If a press is already running the product that would use the newly generated empty wire frames, then the frames travel directly from the final assembly cell to the press. If the press is down or is full, then the frames travel to the framing area. If the lanes for the particular frame type are full, then the frames are removed and replaced with ones whose lanes are not full. As soon as a space opens up in the appropriate lane, the frames that were removed are put back on an in-process rack and placed in the appropriate lane. If a packout cell is not producing empty wire frames of the particular type required by a press, then the press draws frames from the framing area. If the framing area is also empty, then the press shuts down until sufficient frames have accumulated in the framing area. **By balancing frame generation by final assembly with frame usage by injection molding, the amount of reframing required is minimized.** Reframing will have to occur because not doing it will adversely affect the monoplane. However, it should be done in a way which incurs the minimum operating expense and investment as long as monoplane throughput is not threatened.

4) The quantity and type of frames available in the framing area dictates the injection molding schedule because they equal real customer demand (historical by a few hours). In this way, a potentially wildly inaccurate forecast of future monoplane usage, which would be required to use Drum-Buffer-Rope in this environment, is avoided. The inventory kept in front of the monoplane protects it from any differences between what the customer wants

now and what the customer wanted earlier (which molding is currently responding to). Thus, packout and injection molding are tightly coupled, with injection molding being subordinated to packout. Injection molding's goal is to prevent the monoplane from being starved in the most cost-effective manner.

5) The mix of frames allowed in the system can only be adjusted at the framing area. Frames can also be taken out to be repaired and replaced with good ones on a one-for-one basis in the framing area as well.

6) *Kanban* cards for parts that do not require wire frames are treated just like the wire frames except that they accumulate at the press that will satisfy the demand rather than in the framing area. The main difference is that *kanban* cards can be exchanged with one another on a one-for-one basis, but six wire frames of the same type have to be exchanged with 8 *kanban* cards of the same type for the exchange to be equivalent when it becomes necessary to adjust the allowable product mix.

7) The mix of wire frames/*kanban* cards needs to be adjusted when the demand mix changes, not for colors, but for the unique molded part. This happens infrequently; therefore, I imagine that the mix of products allowed in the ASRS would only need to be considered on a weekly, monthly, or maybe even quarterly basis. Near-misses or actual monoplane starvation would be an excellent indicator that either the mix is wrong or one or more pieces of equipment are not behaving as expected and require attention to eliminate a special cause of variability.

8) The important measurable would be the shortest time by part type that a frame with a new molded part on it sat in front of the monoplane before being used. Parts that sit a long time can have frames/*kanban* cards removed, thereby reducing inventory without adversely affecting the paint system. Parts that sit a very short time are parts that could cause starvation; therefore, more inventory of that type (in the form of frames/*kanban* cards) is needed. The goal is to have all part types sit roughly the same amount of time in front of the monoplane, and to minimize that time. In that way, Manufacturing Cycle Time (the time from raw material usage to end-item shipment) would be minimized.

The Pull Concept (version 2): Computer-assisted Mass Balancing

Plant management generally viewed the pull system concept favorably, but disliked the idea of having the quantities of wire frames control production. Admittedly, some flexibility was lost since frames would have to physically enter and be removed from the system in large quantities all at once if the desired mix changed, and timely acquisition of information would be much more difficult. Therefore, I developed a new system which utilizes information systems technology instead of the low-tech solution of allowing only a fixed number of frames and *kanban* cards. However, this new system accomplishes the same goal of achieving a mass balance such that

$$\text{in - out = accumulation} \leq \text{Automated Material Handling System capacity} \qquad \text{(Equation 1)}$$

by scheduling new molded parts only when existing parts of the same type have left the Automated Material Handling System as either end-item product shipped to the customer, parts placed on the floor awaiting action of some type, or scrap. The measureables and the basic goals outlined in the preceding section are all unchanged. The mechanism by which the goals are achieved is the only thing that changes.

The system's key component is a computer with access to the following information in real-time: how many parts of each type are leaving packout or Selective II as good product, how many of each type are being scrapped at each operation in the plant, how many frames of each type are in the framing area, and the status of each press (down, setting up, available) including the tool it is using or is being set-up to use. The computer ensures that the system's accumulation doesn't exceed AMHS capacity by placing orders with the appropriate injection molding press only when parts have left the system, either as end-items, floor storage, or scrap.

A unique case is that of the Contour Rear, which is push-carted from injection molding to bonding. In this case, orders get placed by the computer with the bonding cell. Molding press production is controlled by the floor space allocated to storage between molding and the bonding cell; some type of reorder point scheduling methodology for the press might work to manage the floor inventory level while running the press(es) making the parts in the most efficient manner.

A variety of decision rules can be used to decide how to allocate parts to presses based on the urgency of the need for new molded parts. For example, if there is plenty of inventory of a particular part in the ASRS in front of the monoplane, then the computer would load one press with all the demand so that the press could run for a long time. On the other hand, if there is not enough inventory in the ASRS in front of the monoplane, then the computer would spread demand over as many presses as possible so that new inventory would be generated quickly. A variety of ASRS targets could be developed to indicate the relative urgency of need so that presses could be committed appropriately. I think a lower and an upper threshold would be appropriate. Crisis action would be initiated at the lower threshold and discontinued at the upper threshold.

The following is a more detailed examination of how the system would run:

1) The monoplane scheduling would be the same as the first case: small batches of styles, large batches of colors. Packout and Selective II work on a first in, first out basis, recognizing that styles will have to be run in batches, with an exception for parts urgently required by the customer.

2) Once parts are removed from the system in one of the three forms, the computer is notified as to what style was removed. At that point, the computer determines which presses could make replacement parts, and assigns the demand to the press(es) based on the urgency of the need, which is assessed by examining the material in front of the monoplane and comparing it with the target(s) which have been developed. The demand is assigned in full rack quantities (1-6 pieces = 1 rack of Taurus/Sable, 1-8 pieces = 1 rack of Mystique/Contour, etc.). Any overshipment at the end of an order because of the full rack quantity rule will be subtracted against the next one. Also, if parts enter the system from the floor, then a corresponding number of parts will be subtracted from press orders either immediately, if the demand for the press is greater than or equal to the number entering, or from future demand. The computer will also keep track of the inventory in the framing area and direct reframing as it is needed.

3) The scheduling person in charge of the injection molding area receives a real-time indication of the demand the computer has allocated to each of the presses. Based on this and a monoplane schedule (which serves as a fairly good forecast of what the demand for injection molding will be in about 5 hours), he or she determines what tools should be set-up and which presses should be activated. Once a press is activated, it runs until the

demand allocated to it is 0. It would be preferable to link the rack deliveries to the allocated demand so that the operators know that they should stop production when there are no more racks in the press' queue. At that point, the press should be shut down and the operator moved if it is apparent from the monoplane schedule that there will be no further demand for that part in the near future in sufficient quantities to justify waiting. At this point, the press and its tool would be available for maintenance or set-up. Otherwise, the press could be kept heated, awaiting permission to start, with its operator in place. As long as the monoplane is not starved, it does not matter from a throughput standpoint how the presses go about satisfying demand; however, how the presses are run does impact the operating expense required to satisfy the demand. The scheduling person would have full authority to experiment and figure out the cheapest ways to run the area as long as plant throughput would not be compromised, and a production person would have responsibility for keeping the computer updated as to the status of all the presses through some type of graphical interface (presumably Windows-based) so that demand is not allocated to unavailable presses or presses with a different tool in place than the one that is required.

4) The injection molding scheduler would have the ability to interact with the computer in a variety of ways through a graphical interface. He or she would be aware of each press' status and be able to adjust the quantities ordered from each press via a keyboard so that adjustments to the plant's molded part mix can be made to take into account assembly plant demand changes, the need to build ahead so that a tool or press can be shut down for maintenance, or process improvements that result in less inventory being required. As long as the net changes to the orders are 0 or negative, the system will have achieved a new steady-state which can be maintained as long as is necessary. The scheduler will also be responsible for adjusting the target quantities of each part to be kept in front of the monoplane when changes are required, keeping an eye on empty system racks, and watching ASRS inventory levels in front of the monoplane. Since there are time lags between when things go in and when they come out, the number of empty in-process racks will fluctuate some, and could hit 0 if the amount entering exceeds the amount exiting for an extended period of time. Also, it is possible that parts could get trapped in the system because of poor monoplane yields or final assembly cell downtime. If either of these eventualities occur, the scheduler will need to take the appropriate action: shutting down equipment, getting repairs loaded to the floor, etc.

The major advantages of this system over the previous one is that it is much more flexible since the entering mix can be changed with a keyboard rather than by pulling frames out of the system and replacing them with another kind all at once, the time lag between the removal of a part from the system and the scheduling of its replacement is reduced (molding can know what it needs to do before the wire frame gets there), and a computer screen will provide a much easier and timely way of getting information and controlling the system than trying to guess what is going on based on the count of wire frames in the framing area.

Aggressive ASRS Management

Both of the preceding concepts operate under the assumption that most of the ASRS should be used to keep parts in front of the monoplane. I am implicitly assuming that a substantial portion of the ASRS will be required to store monoplane repairs during launch periods regardless of how Selective I is run. However, once a steady-state is achieved, I believe that a substantial portion of the ASRS will not be required to have parts in it for the monoplane to be adequately supplied.

At this point, the "rules" of the system could be altered to achieve a reduction in end-item inventory at the assembly plants. The monoplane would continue to paint as recommended earlier, but packout would produce strictly to customer daily demand. This would result in the assembly plant getting exactly what they intend to use each day rather than receiving overshipments. The key to the success of this idea is that the ASRS would have sufficient space to keep painted stock of some end-items for up to a week at a time without adversely affecting the monoplane. I believe that once steady-state is achieved, such an operation would be feasible.

Chapter 6

Conclusion

I had planned to evaluate one or both of the production management ideas detailed in Chapter 5 using a simulation of the future Milan facility prepared by Rapistan Demag. However, simply assembling all of the relevant data and having it coded in the model took longer than the duration of the internship. Preliminary data received during my last week indicated an unforeseen problem with AGV capacity between the packout cells, the framing area, and injection molding due to the removal of presses and subsequent movement of products to deal with product constraints in terms of required press tonnage. Therefore, I have been unable to further develop my ideas and validate them as I had planned. However, I gained a much better understanding of the importance of capacity and flexibility, and I was successful in encouraging plant management to increase the flexibility of Selective II.

To Balance or Unbalance?

Based on the simulations and cognitive effort, I have arrived at the conclusion that there is no general rule as to whether a balanced or unbalanced line should be used. A cost/benefit analysis must be performed to determine the appropriate trade-offs between capital costs, time, inventory, and ease of management. The lifecycle of the product and process, the market's responsiveness expectations, and competitive environment play a role as well. Simulation of various plant layouts and market scenarios can greatly assist the strategic planner in determining the appropriate production paradigm for a given product.

Applying the Capacity Allocation Paradigm at the Corporate Level

As far as the particular case analyzed in this thesis, there should be no doubt that squeezing every last bit of productivity out of Milan's paint shop is a good idea that everyone at every level of Ford management would endorse. Let's now consider the company as a whole, since Milan is far from being the only plant with a paint system. It's not even the only plant with a paint system in the Plastic and Trim Products Division. The paint system is probably the most expensive element present in Milan's sister plants as well. And how about Body & Assembly? The paint systems used there are more complicated, more expensive, and more environmentally sensitive since greater volumes of paint are sprayed. In fact, they are the most expensive resource used in production.

Would it not make sense to make each paint system the plant's constraint where one is present, and to make the Body & Assembly paint systems the production system's constraint? All plants producing parts which don't require a paint system should then have sufficient capacity allocated to them so that their most expensive resource exceeds the system's constraint (each Body & Assembly plant's paint shop) by just enough to overcome its own statistical fluctuations and those of any constraints upstream. In this way, the system's constraint would always be kept busy, investment everywhere upstream would be minimized since just enough of the most expensive resources would be purchased, and inventories between plants would be minimized as well. A system like this could be a key step in developing the ability to build the majority of Ford's products to order, resulting in the release of billions of dollars in cash from in-process and finished-goods inventories. This cash could be used to develop new products or cover the additional capital expenditures required to create the unbalanced system in the first place.

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Appendix: Witness™ Results

```
MODEL2   Report                    Time:110000.00
===============                    ==============

PART STATISTICS                                     REPORTED BY ON-SHIFT TIME
          Number  Number  Number   Number    Number              Av.     Av.
 Name     Entered Shipped Scrapped Assembled Rejected  W.I.P   W.I.P   Time
---------------------------------------------------------------------------
 part        4005    4000       0         0        0       5    5.00 124.84

MACHINE STATISTICS                                  REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.   %Idle   %Cycle          %Stopped            %Waiting
-----------------------------------------------------------------------------
 machine1        4000    0.00   Busy :100.00   Blocked :   0.00   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine2        4000    0.00   Busy :100.00   Blocked :   0.00   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine3        4000    0.00   Busy :100.00   Blocked :   0.00   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine4        4000    0.00   Busy :100.00   Blocked :   0.00   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine5        4000    0.00   Busy :100.00   Blocked :   0.00   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
```

```
MODEL2   Report                    Time:110000.00
===============                    ==============

PART STATISTICS                                     REPORTED BY ON-SHIFT TIME
          Number  Number  Number   Number    Number              Av.     Av.
 Name     Entered Shipped Scrapped Assembled Rejected  W.I.P   W.I.P   Time
---------------------------------------------------------------------------
 part        3594    3589       0         0        0       5    4.78 132.90

MACHINE STATISTICS                                  REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.   %Idle   %Cycle          %Stopped            %Waiting
-----------------------------------------------------------------------------
 machine1        3589    0.00   Busy : 89.77   Blocked :  10.23   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine2        3589    2.02   Busy : 89.98   Blocked :   8.00   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine3        3589    3.92   Busy : 89.88   Blocked :   6.21   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine4        3589    6.12   Busy : 89.57   Blocked :   4.30   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
 machine5        3589   10.29   Busy : 89.71   Blocked :   0.00   Setup  :   0.00
                                               Setup   :   0.00   Cycle  :   0.00
                                               Down    :   0.00   Repair :   0.00
```

```
MODEL2   Report               Time:110000.00
===============               ==============

PART STATISTICS                                    REPORTED BY ON-SHIFT TIME
           Number  Number  Number    Number    Number              Av.      Av.
 Name      Entered Shipped Scrapped Assembled Rejected  W.I.P   W.I.P    Time
 ---------------------------------------------------------------------------
 part         2977    2972        0         0        0      5    4.45  149.37

MACHINE STATISTICS                                 REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.   %Idle  %Cycle         %Stopped          %Waiting
 ---------------------------------------------------------------------------
 machine1        2974    0.00  Busy : 74.24   Blocked : 25.76   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine2        2973    4.92  Busy : 75.00   Blocked : 20.08   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine3        2974    9.84  Busy : 74.59   Blocked : 15.57   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine4        2973   15.26  Busy : 74.07   Blocked : 10.67   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine5        2972   25.31  Busy : 74.69   Blocked :  0.00   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
```

```
MODEL2   Report               Time:110000.00
===============               ==============

PART STATISTICS                                    REPORTED BY ON-SHIFT TIME
           Number  Number  Number    Number    Number              Av.      Av.
 Name      Entered Shipped Scrapped Assembled Rejected  W.I.P   W.I.P    Time
 ---------------------------------------------------------------------------
 part         4027    3953        0         0        0     74   59.62  1480.5

BUFFER STATISTICS                                  REPORTED BY ON-SHIFT TIME
                 Total   Total                            Average  Av. after Delay
 Name               in     out Now in    Max    Min    Size   Time    No.   Time
 -------------------------------------------------------------------------------
 queue1           3996    3940     56     66      0   35.31 883.55
 queue2           3951    3945      6     18      0    7.92 200.37
 queue3           3949    3946      3     22      0    5.32 134.72
 queue4           3957    3953      4     20      0    6.12 154.57

MACHINE STATISTICS                                 REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.   %Idle  %Cycle         %Stopped          %Waiting
 ---------------------------------------------------------------------------
 machine1        3987    0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine2        3940    0.18  Busy : 99.82   Blocked :  0.00   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine3        3945    0.73  Busy : 99.27   Blocked :  0.00   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine4        3946    1.66  Busy : 98.34   Blocked :  0.00   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
 machine5        3953    1.31  Busy : 98.69   Blocked :  0.00   Setup  :  0.00
                                              Setup   :  0.00   Cycle  :  0.00
                                              Down    :  0.00   Repair :  0.00
```

```
MODEL2  Report                Time:210000.00
==============                ==============

PART STATISTICS                                    REPORTED BY ON-SHIFT TIME
          Number  Number  Number   Number    Number             Av.    Av.
Name      Entered Shipped Scrapped Assembled Rejected  W.I.P  W.I.P   Time
--------------------------------------------------------------------------
part         8042    7912        0         0        0    130  84.18 2093.5

BUFFER STATISTICS                                  REPORTED BY ON-SHIFT TIME
               Total  Total                         Average   Av. after Delay
Name              in    out Now in    Max    Min   Size   Time   No.   Time
-----------------------------------------------------------------------------
queue1          8011   7963     48     76      0  43.63 1089.2
queue2          7974   7944     30     49      0  17.88 448.46
queue3          7948   7914     34     42      0   7.84 197.31
queue4          7925   7912     13     37      0   9.86 248.75

MACHINE STATISTICS                                 REPORTED BY ON-SHIFT TIME
           Number
Name       of Ops.  %Idle  %Cycle          %Stopped           %Waiting
---------------------------------------------------------------------------
machine1      8002   0.00  Busy :100.00  Blocked :  0.00   Setup  :  0.00
                                          Setup   :  0.00   Cycle  :  0.00
                                          Down    :  0.00   Repair :  0.00
machine2      7963   0.09  Busy : 99.91  Blocked :  0.00   Setup  :  0.00
                                          Setup   :  0.00   Cycle  :  0.00
                                          Down    :  0.00   Repair :  0.00
machine3      7944   0.36  Busy : 99.64  Blocked :  0.00   Setup  :  0.00
                                          Setup   :  0.00   Cycle  :  0.00
                                          Down    :  0.00   Repair :  0.00
machine4      7914   1.19  Busy : 98.81  Blocked :  0.00   Setup  :  0.00
                                          Setup   :  0.00   Cycle  :  0.00
                                          Down    :  0.00   Repair :  0.00
machine5      7912   0.99  Busy : 99.01  Blocked :  0.00   Setup  :  0.00
                                          Setup   :  0.00   Cycle  :  0.00
                                          Down    :  0.00   Repair :  0.00
```

```
MODEL2  Report                  Time:510000.00
==============                  ==============

PART STATISTICS                                             REPORTED BY ON-SHIFT TIME
          Number  Number  Number   Number    Number               Av.     Av.
 Name     Entered Shipped Scrapped Assembled Rejected  W.I.P  W.I.P   Time
 ---------------------------------------------------------------------------
 part       19994   19863        0         0        0    131 108.82 2721.3

BUFFER STATISTICS                                           REPORTED BY ON-SHIFT TIME
               Total   Total                                   Average  Av. after Delay
 Name             in     out Now in     Max     Min   Size    Time    No.  Time
 -----------------------------------------------------------------------------
 queue1        19963   19956      7      76       0  34.33  859.85
 queue2        19967   19936     31      49       0  19.07  477.56
 queue3        19940   19912     28      59       0  18.68  468.34
 queue4        19923   19863     60      79       0  31.75  796.89

MACHINE STATISTICS                                          REPORTED BY ON-SHIFT TIME
             Number
 Name        of Ops.  %Idle  %Cycle          %Stopped            %Waiting
 ----------------------------------------------------------------------------
 machine1      19954   0.00  Busy :100.00  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine2      19956   0.15  Busy : 99.85  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine3      19936   0.31  Busy : 99.69  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine4      19912   0.49  Busy : 99.51  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine5      19863   0.40  Busy : 99.60  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
```

```
jit      Report                 Time:110000.00
===============                ==============

PART STATISTICS                                        REPORTED BY ON-SHIFT TIME
         Number  Number  Number   Number    Number               Av.     Av.
 Name    Entered Shipped Scrapped Assembled Rejected   W.I.P   W.I.P    Time
 ---------------------------------------------------------------------------
 part       3994    3980       0          0        0      14   13.85  346.66

BUFFER STATISTICS                                      REPORTED BY ON-SHIFT TIME
                Total   Total                             Average  Av. after Delay
 Name             in      out  Now in    Max    Min   Size   Time    No.   Time
 ---------------------------------------------------------------------------------
 queue1         3981     3978       3      5      0   2.99  75.13
 queue2         3981     3978       3      5      0   2.18  54.74
 queue3         3980     3978       2      5      0   1.71  43.07
 queue4         3981     3980       1      5      0   1.97  49.59

MACHINE STATISTICS                                     REPORTED BY ON-SHIFT TIME
               Number
 Name          of Ops.  %Idle  %Cycle          %Stopped             %Waiting
 ------------------------------------------------------------------------------
 machine1         3978   0.00  Busy : 99.52  Blocked :   0.48  Setup  :   0.00
                                             Setup   :   0.00  Cycle  :   0.00
                                             Down    :   0.00  Repair :   0.00
 machine2         3978   0.13  Busy : 99.86  Blocked :   0.01  Setup  :   0.00
                                             Setup   :   0.00  Cycle  :   0.00
                                             Down    :   0.00  Repair :   0.00
 machine3         3978   0.21  Busy : 99.68  Blocked :   0.11  Setup  :   0.00
                                             Setup   :   0.00  Cycle  :   0.00
                                             Down    :   0.00  Repair :   0.00
 machine4         3978   0.46  Busy : 99.37  Blocked :   0.17  Setup  :   0.00
                                             Setup   :   0.00  Cycle  :   0.00
                                             Down    :   0.00  Repair :   0.00
 machine5         3980   0.52  Busy : 99.48  Blocked :   0.00  Setup  :   0.00
                                             Setup   :   0.00  Cycle  :   0.00
                                             Down    :   0.00  Repair :   0.00
```

```
jit      Report                    Time:110000.00
===============                    ==============

PART STATISTICS                                   REPORTED BY ON-SHIFT TIME
          Number  Number  Number   Number    Number            Av.     Av.
 Name     Entered Shipped Scrapped Assembled Rejected  W.I.P  W.I.P   Time
 -------------------------------------------------------------------------
 part        3324    3320        0         0        0      4   5.35 160.94

BUFFER STATISTICS                                 REPORTED BY ON-SHIFT TIME
               Total  Total                          Average  Av. after Delay
 Name             in    out Now in    Max    Min   Size   Time   No.  Time
 ----------------------------------------------------------------------------
 queue1            0      0      0      0      0   0.00   0.00
 queue2         3320   3320      0      5      0   0.33  10.06
 queue3         3320   3320      0      5      0   0.33   9.84
 queue4         3321   3321      0      4      0   0.36  10.85

MACHINE STATISTICS                                REPORTED BY ON-SHIFT TIME
             Number
 Name        of Ops.  %Idle  %Cycle          %Stopped          %Waiting
 ---------------------------------------------------------------------------
 machine1       3320   0.00  Busy : 83.02  Blocked : 16.98  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine2       3320  16.30  Busy : 83.70  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine3       3320  16.68  Busy : 83.32  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine4       3321  17.32  Busy : 82.68  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
 machine5       3320  16.80  Busy : 83.20  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
```

```
newmod2  Report                Time:110000.00
===============                ==============

PART STATISTICS                                      REPORTED BY ON-SHIFT TIME
          Number  Number  Number    Number    Number              Av.     Av.
 Name     Entered Shipped Scrapped Assembled Rejected  W.I.P  W.I.P   Time
-----------------------------------------------------------------------------
 part        4018    4000        0         0        0     18  18.67 464.58

BUFFER STATISTICS                                    REPORTED BY ON-SHIFT TIME
               Total   Total                           Average  Av. after Delay
 Name             in     out Now in    Max   Min   Size   Time    No.  Time
-------------------------------------------------------------------------------
 queue1         4000    4000      0      1     0   0.67  16.67
 queue2         4000    4000      0      1     0   0.00   0.00
 queue3         4000    4000      0      1     0   0.00   0.00
 queue4         4000    4000      0      1     0   0.00   0.00

MACHINE STATISTICS                                   REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.  %Idle  %Cycle         %Stopped          %Waiting
-----------------------------------------------------------------------------
 machine1        1333   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 machine2        1000   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 machine3        2000   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 machine4        1333   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 machine5         667   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach1a          1333   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach1b          1333   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach2a          1000   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach2b          1000   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach2c          1000   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach3a          2000   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach4a          1333   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
                                             Down    :  0.00   Repair :  0.00
 mach4b          1334   0.00  Busy :100.00   Blocked :  0.00   Setup  :  0.00
                                             Setup   :  0.00   Cycle  :  0.00
```

```
                                                 Down    :  0.00  Repair :  0.00
mach5a           667    0.00   Busy :100.00     Blocked :  0.00  Setup  :  0.00
                                                 Setup   :  0.00  Cycle  :  0.00
                                                 Down    :  0.00  Repair :  0.00
mach5b           667    0.00   Busy :100.00     Blocked :  0.00  Setup  :  0.00
                                                 Setup   :  0.00  Cycle  :  0.00
                                                 Down    :  0.00  Repair :  0.00
mach5c           666    0.00   Busy :100.00     Blocked :  0.00  Setup  :  0.00
                                                 Setup   :  0.00  Cycle  :  0.00
                                                 Down    :  0.00  Repair :  0.00
mach5d           666    0.00   Busy :100.00     Blocked :  0.00  Setup  :  0.00
                                                 Setup   :  0.00  Cycle  :  0.00
                                                 Down    :  0.00  Repair :  0.00
mach5e           667    0.00   Busy :100.00     Blocked :  0.00  Setup  :  0.00
                                                 Setup   :  0.00  Cycle  :  0.00
                                                 Down    :  0.00  Repair :  0.00
```

```
newmod2  Report                Time:110000.00
===============                ==============

PART STATISTICS                                         REPORTED BY ON-SHIFT TIME
           Number  Number  Number    Number    Number                Av.     Av.
 Name      Entered Shipped Scrapped Assembled Rejected  W.I.P  W.I.P   Time
-----------------------------------------------------------------------------
 part         3617    3600        0          0        0      17  19.06 527.09

BUFFER STATISTICS                                       REPORTED BY ON-SHIFT TIME
                 Total  Total                              Average  Av. after Delay
 Name              in     out Now in    Max    Min    Size   Time    No.  Time
------------------------------------------------------------------------------
 queue1          3599   3598      1      1      0   0.63  17.63
 queue2          3598   3598      0      1      0   0.64  17.72
 queue3          3597   3596      1      1      0   0.42  11.67
 queue4          3597   3597      0      1      0   0.32   8.81

MACHINE STATISTICS                                      REPORTED BY ON-SHIFT TIME
                  Number
 Name             of Ops.  %Idle  %Cycle          %Stopped           %Waiting
-----------------------------------------------------------------------------
 machine1          1216    0.00  Busy : 90.60  Blocked :   9.40  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 machine2           901    2.32  Busy : 89.73  Blocked :   7.95  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 machine3          1802    4.92  Busy : 89.77  Blocked :   5.31  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 machine4          1188    7.42  Busy : 89.03  Blocked :   3.55  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 machine5           611    9.54  Busy : 90.46  Blocked :   0.00  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach1a            1190    0.00  Busy : 91.07  Blocked :   8.93  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach1b            1192    0.00  Busy : 90.40  Blocked :   9.60  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach2a             897    2.23  Busy : 90.06  Blocked :   7.71  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach2b             909    2.18  Busy : 90.18  Blocked :   7.64  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach2c             891    1.86  Busy : 89.78  Blocked :   8.36  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach3a            1795    4.92  Busy : 89.18  Blocked :   5.90  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach4a            1201    6.87  Busy : 89.45  Blocked :   3.68  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
                                               Down    :   0.00  Repair :   0.00
 mach4b            1207    7.15  Busy : 89.05  Blocked :   3.80  Setup  :   0.00
                                               Setup   :   0.00  Cycle  :   0.00
```

```
                                                   Down     :  0.00  Repair :  0.00
mach5a            598   8.99  Busy : 91.01  Blocked  :  0.00  Setup  :  0.00
                                                   Setup    :  0.00  Cycle  :  0.00
                                                   Down     :  0.00  Repair :  0.00
mach5b            596   9.37  Busy : 90.63  Blocked  :  0.00  Setup  :  0.00
                                                   Setup    :  0.00  Cycle  :  0.00
                                                   Down     :  0.00  Repair :  0.00
mach5c            599   8.58  Busy : 91.42  Blocked  :  0.00  Setup  :  0.00
                                                   Setup    :  0.00  Cycle  :  0.00
                                                   Down     :  0.00  Repair :  0.00
mach5d            595   8.70  Busy : 91.30  Blocked  :  0.00  Setup  :  0.00
                                                   Setup    :  0.00  Cycle  :  0.00
                                                   Down     :  0.00  Repair :  0.00
mach5e            601   9.29  Busy : 90.71  Blocked  :  0.00  Setup  :  0.00
                                                   Setup    :  0.00  Cycle  :  0.00
                                                   Down     :  0.00  Repair :  0.00
```

```
newmod2  Report                Time:110000.00
===============                ==============

PART STATISTICS                                           REPORTED BY ON-SHIFT TIME
           Number  Number  Number   Number    Number                  Av.     Av.
 Name      Entered Shipped Scrapped Assembled Rejected  W.I.P  W.I.P   Time
 ------------------------------------------------------------------------------
 part        4003    3936        0          0        0     67  59.37 1483.2

BUFFER STATISTICS                                         REPORTED BY ON-SHIFT TIME
                  Total   Total                              Average  Av. after Delay
 Name               in      out  Now in    Max    Min     Size    Time   No.   Time
 ---------------------------------------------------------------------------------
 queue1            3981    3976       5     30      0     9.93  249.34
 queue2            3979    3971       8     26      0    10.61  266.57
 queue3            3971    3967       4     15      0     3.29   82.91
 queue4            3968    3936      32     39      0    17.68  445.66

MACHINE STATISTICS                                        REPORTED BY ON-SHIFT TIME
                 Number
 Name            of Ops.  %Idle  %Cycle         %Stopped              %Waiting
 ------------------------------------------------------------------------------
 machine1          1339    0.00  Busy :100.00   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 machine2           997    0.54  Busy : 99.46   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 machine3          1980    1.24  Busy : 98.76   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 machine4          1313    1.48  Busy : 98.52   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 machine5           669    0.52  Busy : 99.48   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach1a            1312    0.00  Busy :100.00   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach1b            1320    0.00  Busy :100.00   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach2a             986    0.81  Busy : 99.19   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach2b            1005    0.62  Busy : 99.38   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach2c             988    0.76  Busy : 99.24   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach3a            1991    1.03  Busy : 98.97   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach4a            1320    1.69  Busy : 98.31   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
                                                Down    :   0.00   Repair  :   0.00
 mach4b            1332    1.77  Busy : 98.23   Blocked :   0.00   Setup   :   0.00
                                                Setup   :   0.00   Cycle   :   0.00
```

```
                                              Down    :  0.00  Repair :  0.00
mach5a           653   0.70  Busy : 99.30    Blocked :  0.00  Setup  :  0.00
                                              Setup   :  0.00  Cycle  :  0.00
                                              Down    :  0.00  Repair :  0.00
mach5b           653   0.60  Busy : 99.40    Blocked :  0.00  Setup  :  0.00
                                              Setup   :  0.00  Cycle  :  0.00
                                              Down    :  0.00  Repair :  0.00
mach5c           650   0.64  Busy : 99.36    Blocked :  0.00  Setup  :  0.00
                                              Setup   :  0.00  Cycle  :  0.00
                                              Down    :  0.00  Repair :  0.00
mach5d           648   0.55  Busy : 99.45    Blocked :  0.00  Setup  :  0.00
                                              Setup   :  0.00  Cycle  :  0.00
                                              Down    :  0.00  Repair :  0.00
mach5e           663   0.57  Busy : 99.43    Blocked :  0.00  Setup  :  0.00
                                              Setup   :  0.00  Cycle  :  0.00
                                              Down    :  0.00  Repair :  0.00
```

```
newmod2  Report                    Time:210000.00
===============                    ==============

PART STATISTICS                                        REPORTED BY ON-SHIFT TIME
          Number  Number  Number    Number    Number               Av.     Av.
 Name     Entered Shipped Scrapped  Assembled Rejected  W.I.P   W.I.P    Time
-----------------------------------------------------------------------------
 part        7998    7914        0          0        0     84   67.89  1697.8

BUFFER STATISTICS                                      REPORTED BY ON-SHIFT TIME
                Total   Total                              Average   Av. after Delay
 Name              in     out Now in     Max     Min    Size    Time    No.   Time
----------------------------------------------------------------------------------
 queue1          7976    7940     36      42       0   11.58  290.36
 queue2          7943    7931     12      35       0   11.38  286.55
 queue3          7931    7922      9      29       0    5.93  149.57
 queue4          7923    7914      9      41       0   21.10  532.54

MACHINE STATISTICS                                     REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.   %Idle   %Cycle          %Stopped             %Waiting
-----------------------------------------------------------------------------
 machine1        2676    0.00   Busy :100.00    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine2        1980    0.43   Busy : 99.57    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine3        3952    0.80   Busy : 99.20    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine4        2654    1.15   Busy : 98.85    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine5        1325    0.26   Busy : 99.74    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach1a          2641    0.00   Busy :100.00    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach1b          2649    0.00   Busy :100.00    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach2a          1975    0.60   Busy : 99.40    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach2b          1997    0.52   Busy : 99.48    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach2c          1988    0.61   Busy : 99.39    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach3a          3979    0.74   Busy : 99.26    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach4a          2614    1.31   Busy : 98.69    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach4b          2652    1.36   Busy : 98.64    Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
```

```
                                           Down     :  0.00  Repair :  0.00
mach5a          1318   0.35  Busy : 99.65  Blocked  :  0.00  Setup  :  0.00
                                           Setup    :  0.00  Cycle  :  0.00
                                           Down     :  0.00  Repair :  0.00
mach5b          1319   0.30  Busy : 99.70  Blocked  :  0.00  Setup  :  0.00
                                           Setup    :  0.00  Cycle  :  0.00
                                           Down     :  0.00  Repair :  0.00
mach5c          1317   0.32  Busy : 99.68  Blocked  :  0.00  Setup  :  0.00
                                           Setup    :  0.00  Cycle  :  0.00
                                           Down     :  0.00  Repair :  0.00
mach5d          1317   0.27  Busy : 99.73  Blocked  :  0.00  Setup  :  0.00
                                           Setup    :  0.00  Cycle  :  0.00
                                           Down     :  0.00  Repair :  0.00
mach5e          1318   0.29  Busy : 99.72  Blocked  :  0.00  Setup  :  0.00
                                           Setup    :  0.00  Cycle  :  0.00
                                           Down     :  0.00  Repair :  0.00
```

```
newmod2  Report                 Time:510000.00
===============                 ==============

PART STATISTICS                                    REPORTED BY ON-SHIFT TIME
          Number  Number  Number    Number     Number                Av.     Av.
 Name     Entered Shipped Scrapped Assembled  Rejected   W.I.P   W.I.P    Time
 ------------------------------------------------------------------------------
 part       19978   19828        0         0         0    150   94.70  2370.1

BUFFER STATISTICS                                  REPORTED BY ON-SHIFT TIME
               Total   Total                          Average  Av. after Delay
 Name             in     out  Now in     Max   Min   Size    Time     No.  Time
 ----------------------------------------------------------------------------------
 queue1        19956   19881      75     112     0  43.52  1090.4
 queue2        19884   19847      37      55     0  10.55  265.28
 queue3        19847   19840       7      45     0   8.45  212.99
 queue4        19841   19828      13      44     0  14.27  359.57

MACHINE STATISTICS                                 REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.   %Idle  %Cycle         %Stopped          %Waiting
 ------------------------------------------------------------------------------
 machine1        6663    0.00  Busy :100.00   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 machine2        4950    0.17  Busy : 99.83   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 machine3        9900    0.83  Busy : 99.17   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 machine4        6616    0.92  Busy : 99.08   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 machine5        3303    0.72  Busy : 99.28   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach1a          6619    0.00  Busy :100.00   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach1b          6664    0.00  Busy :100.00   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach2a          4965    0.24  Busy : 99.76   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach2b          4976    0.21  Busy : 99.79   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach2c          4990    0.24  Busy : 99.76   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach3a          9947    0.81  Busy : 99.19   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach4a          6596    0.97  Busy : 99.03   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
                                              Down    :   0.00  Repair :   0.00
 mach4b          6626    1.04  Busy : 98.96   Blocked :   0.00  Setup  :   0.00
                                              Setup   :   0.00  Cycle  :   0.00
```

```
                                            Down    :  0.00  Repair :  0.00
mach5a          3324   0.70  Busy : 99.30  Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5b          3316   0.62  Busy : 99.38  Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5c          3282   0.66  Busy : 99.34  Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5d          3309   0.64  Busy : 99.36  Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5e          3294   0.62  Busy : 99.38  Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
```

```
newmod2  Report                   Time:1000000.00
===============                   ===============

TIMESERIES STATISTICS                          REPORTED BY ON-SHIFT TIME
                                Minimum         Maximum          Observations
 Timeseries  Pl   Mean     SD  Value  @Time   Value  @Time   n   Time   Value
 ---------------------------------------------------------------------------
 inv          1 152.05 63.016 52.000  50000 237.00 850000
                                                              1   50000 52.000
                                                              2  100000 65.000
                                                              3  150000 72.000
                                                              4  200000 83.000
                                                              5  250000 101.00
                                                              6  300000 98.000
                                                              7  350000 98.000
                                                              8  400000 103.00
                                                              9  450000 134.00
                                                             10  500000 142.00
                                                             11  550000 160.00
                                                             12  600000 163.00
                                                             13  650000 205.00
                                                             14  700000 224.00
                                                             15  750000 216.00
                                                             16  800000 215.00
                                                             17  850000 237.00
                                                             18  900000 226.00
                                                             19  950000 212.00
                                                             20  1.0e+6 235.00
```

```
newunbal Report                 Time:110000.00
===============                 ==============

PART STATISTICS                                          REPORTED BY ON-SHIFT TIME
           Number   Number   Number    Number    Number                 Av.     Av.
 Name      Entered  Shipped  Scrapped  Assembled Rejected  W.I.P   W.I.P   Time
-------------------------------------------------------------------------------------
 part        4045     4020       0          0          0      25   25.01  618.22

BUFFER STATISTICS                                        REPORTED BY ON-SHIFT TIME
                  Total    Total                                 Average   Av. after Delay
 Name               in       out  Now in    Max    Min    Size    Time    No.   Time
----------------------------------------------------------------------------------------
 queue1           4020     4020      0       1      0     0.93   23.04
 queue2           4024     4021      3       4      0     3.86   96.03
 queue3           4021     4020      1       3      0     0.07    1.80
 queue4           4019     4019      0       3      0     0.07    1.63

MACHINE STATISTICS                                       REPORTED BY ON-SHIFT TIME
               Number
 Name          of Ops.   %Idle   %Cycle           %Stopped            %Waiting
------------------------------------------------------------------------------------
 machine1         1008    0.00   Busy : 75.32   Blocked :  24.68   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 machine2          810    0.16   Busy : 80.34   Blocked :  19.50   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 machine3         2007    0.00   Busy :100.00   Blocked :   0.00   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 machine4         1003   24.80   Busy : 75.20   Blocked :   0.00   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 machine5          508   24.51   Busy : 75.49   Blocked :   0.00   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach1a            997    0.00   Busy : 76.03   Blocked :  23.97   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach1b           1007    0.00   Busy : 75.78   Blocked :  24.22   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach2a            801    0.18   Busy : 80.47   Blocked :  19.35   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach2b            813    0.24   Busy : 80.65   Blocked :  19.11   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach2c            796    0.22   Busy : 80.31   Blocked :  19.47   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach3a           2014    0.00   Busy :100.00   Blocked :   0.00   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach4a           1006   25.08   Busy : 74.92   Blocked :   0.00   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
                                                Down    :   0.00   Repair :   0.00
 mach4b           1014   25.42   Busy : 74.58   Blocked :   0.00   Setup  :   0.00
                                                Setup   :   0.00   Cycle  :   0.00
```

```
                                            Down    :  0.00  Repair :  0.00
mach5a          503  23.73  Busy : 76.27    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5b          505  23.27  Busy : 76.73    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5c          501  23.67  Busy : 76.33    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5d          499  23.80  Busy : 76.20    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5e          503  24.16  Busy : 75.84    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach1c         1006   0.00  Busy : 75.96    Blocked : 24.04  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach2d          799   0.21  Busy : 80.25    Blocked : 19.54  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach4c          996  24.91  Busy : 75.09    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5f          498  23.79  Busy : 76.21    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
mach5g          503  23.99  Busy : 76.01    Blocked :  0.00  Setup  :  0.00
                                            Setup   :  0.00  Cycle  :  0.00
                                            Down    :  0.00  Repair :  0.00
```

```
newmod2  Report                 Time:110000.00
===============                 ==============

PART STATISTICS                                          REPORTED BY ON-SHIFT TIME
           Number   Number   Number    Number     Number                Av.      Av.
 Name      Entered  Shipped  Scrapped  Assembled  Rejected  W.I.P  W.I.P    Time
 -------------------------------------------------------------------------------------
 part         3917     3887        0          0         0      30   27.45  700.89

BUFFER STATISTICS                                        REPORTED BY ON-SHIFT TIME
                 Total   Total                                 Average   Av. after Delay
 Name              in      out  Now in    Max    Min    Size    Time     No.   Time
 ------------------------------------------------------------------------------------
 queue1          3895    3893      2       5      0     2.75   70.54
 queue2          3895    3892      3       5      0     2.72   69.71
 queue3          3892    3887      5       5      0     2.06   52.97
 queue4          3889    3887      2       5      0     2.18   56.03

MACHINE STATISTICS                                       REPORTED BY ON-SHIFT TIME
             Number
 Name        of Ops.   %Idle   %Cycle           %Stopped              %Waiting
 ---------------------------------------------------------------------------------
 machine1       1311    0.00   Busy : 97.77     Blocked :   2.23    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine2        973    1.00   Busy : 97.00     Blocked :   2.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine3       1937    1.86   Busy : 96.64     Blocked :   1.50    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine4       1289    1.90   Busy : 96.66     Blocked :   1.44    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 machine5        660    2.02   Busy : 97.98     Blocked :   0.00    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach1a         1287    0.00   Busy : 98.22     Blocked :   1.78    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach1b         1295    0.00   Busy : 98.10     Blocked :   1.90    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach2a          970    0.77   Busy : 97.50     Blocked :   1.73    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach2b          980    0.98   Busy : 97.11     Blocked :   1.90    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach2c          970    0.64   Busy : 97.46     Blocked :   1.90    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach3a         1956    1.53   Busy : 97.14     Blocked :   1.34    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach4a         1292    2.20   Busy : 96.28     Blocked :   1.52    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
                                                Down    :   0.00    Repair :   0.00
 mach4b         1305    2.36   Busy : 96.22     Blocked :   1.42    Setup  :   0.00
                                                Setup   :   0.00    Cycle  :   0.00
```

```
                                           Down    :  0.00  Repair :  0.00
mach5a          647   1.84  Busy : 98.16  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
mach5b          645   1.86  Busy : 98.14  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
mach5c          643   2.10  Busy : 97.90  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
mach5d          639   1.94  Busy : 98.06  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
mach5e          653   1.94  Busy : 98.06  Blocked :  0.00  Setup  :  0.00
                                           Setup   :  0.00  Cycle  :  0.00
                                           Down    :  0.00  Repair :  0.00
```

```
newunbal Report               Time:1000000.00
===============               ===============

TIMESERIES STATISTICS                        REPORTED BY ON-SHIFT TIME
                               Minimum        Maximum        Observations
 Timeseries  Pl   Mean     SD  Value  @Time  Value  @Time  n   Time  Value
-------------------------------------------------------------------------
 inv          1 6948.7 3821.8 638.00  50000  13259 1.0e+6
                                                           1  50000 638.00
                                                           2 100000 1289.0
                                                           3 150000 1979.0
                                                           4 200000 2666.0
                                                           5 250000 3315.0
                                                           6 300000 3992.0
                                                           7 350000 4667.0
                                                           8 400000 5309.0
                                                           9 450000 5931.0
                                                          10 500000 6611.0
                                                          11 550000 7249.0
                                                          12 600000 7908.0
                                                          13 650000 8589.0
                                                          14 700000 9276.0
                                                          15 750000 9947.0
                                                          16 800000  10582
                                                          17 850000  11247
                                                          18 900000  11933
                                                          19 950000  12587
                                                          20 1.0e+6  13259
```

```
newunbal Report                    Time:1000000.00
===============                    ===============

PART STATISTICS                                          REPORTED BY ON-SHIFT TIME
          Number  Number  Number    Number     Number                Av.     Av.
 Name     Entered Shipped Scrapped  Assembled  Rejected    W.I.P    W.I.P    Time
 ------------------------------------------------------------------------------
 part       52924   39661       0          0          0    13263   6687.6  125098

BUFFER STATISTICS                                        REPORTED BY ON-SHIFT TIME
                 Total   Total                                 Average    Av. after Delay
 Name               in     out  Now in    Max    Min    Size      Time       No.  Time
 -------------------------------------------------------------------------------------
 queue1          52813   49453    3360   3360     36  1708.7     32030
 queue2          49543   39660    9883   9885     88  4958.7     99089
 queue3          39660   39660       0      4      0    0.07      1.83
 queue4          39661   39661       0      4      0    0.05      1.26

MACHINE STATISTICS                                       REPORTED BY ON-SHIFT TIME
              Number
 Name         of Ops.   %Idle  %Cycle          %Stopped             %Waiting
 ---------------------------------------------------------------------------------
 machine1       13167    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 machine2        9874    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 machine3       19800    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 machine4        9930   24.89  Busy : 75.11    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 machine5        4966   25.05  Busy : 74.95    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach1a         13190    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach1b         13219    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach2a          9901    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach2b          9882    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach2c          9914    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach3a         19860    0.00  Busy :100.00    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach4a          9945   24.64  Busy : 75.36    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
                                               Down    :  0.00     Repair :  0.00
 mach4b          9910   25.06  Busy : 74.94    Blocked :  0.00     Setup  :  0.00
                                               Setup   :  0.00     Cycle  :  0.00
```

```
                                          Down    :  0.00  Repair :  0.00
mach5a        4957  24.99  Busy : 75.01   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach5b        4969  24.85  Busy : 75.15   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach5c        4942  24.59  Busy : 75.41   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach5d        4961  24.75  Busy : 75.25   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach5e        4986  24.57  Busy : 75.43   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach1c       13201   0.00  Busy :100.00   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach2d        9882   0.00  Busy :100.00   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach4c        9876  25.05  Busy : 74.95   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach5f        4920  24.89  Busy : 75.11   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
mach5g        4960  24.93  Busy : 75.07   Blocked :  0.00  Setup  :  0.00
                                          Setup   :  0.00  Cycle  :  0.00
                                          Down    :  0.00  Repair :  0.00
```