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Material Planning under Theory of Constraints

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Abstract

This paper concerns the implementation of theory of constraints (TOC) rules for large-scale firms. Since most of the literature research has applied TOC concepts and rules for very simple process flow, realistic application with the nature of complexity of job shop systems is an interesting issue. Applying TOC concepts and its general rules for material planning in a real and complicated job shop system is investigated here. In this research, a production line of an auto parts manufacturer has been studied based on TOC and developed four new executive rules by using simulation tool. These rules are based on investigation of several simulation models.

Key words: Theory of Constraint (TOC), Production Planning (PP), Scheduling, Bottleneck, Drum Buffer Rope

1. Introduction

Competing situations in today's manufacturing environment force organizations to adopt a new Production Management System (PMS). In the last three decades, different PMS systems have been developed: MRP II, JIT, and TOC. The traditional approach, MRP, is "passive" in that it plans and controls a production system that it assumes rates and times are fixed. These include, but are not limited to, setup times, processing times, move and queue times, breakdown rates, repair times, and scrap rates. Within the constraints of this fixed environment, it tries to maximize the production output. JIT, on the other hand, is 'active'. It reduces inventory levels, making production plans difficult to execute unless improvements are made in the production system. Typical improvements include reducing setup times, move and queue times, breakdown rates, repair times and scrap rates. JIT tries to achieve two equally important goals—maximize production and make improvements [Miltenburg, 1997].

Both MRP II and JIT have their own weaknesses to deal with in different conditions [Fogarty, 1991; Spencer, 1991]. MRP ignores improvement of the production system. To be successfully implemented, JIT needs very rigid and restricted conditions. Goldratt provided a new approach for production planning, done with software called Optimized Production Time Table or OPT.

Developed by Goldratt in the mid-1980s, Theory of Constraints (TOC) evolved from the OPT system. He illustrated the concepts of TOC in form of a novel, *The Goal*. Due to some difficulties to implement TOC concepts, a second book was written by Goldratt and Fox: *The Race* [Spencer et al., 1995].

TOC has now been developed into a powerful and versatile management theory, as a suite of theoretical frames, methodologies, techniques and tools. It is now a

systemic problem-structuring and problem-solving methodology which can be used to develop solutions with both intuitive power and analytical rigor in any environment [Mabin, 2003]

Theory of constraints can be summarized as a solution for continuous improvement including operations strategy tools, performance measurement systems, and thinking process tools [Cox and Spencer 1998, Gupta 2003]. The operations strategy tools include the five focusing steps, VAT analysis, and specific applications such as production management (drum-buffer rope, buffer management, batching, and product mix analysis), distribution management, and project management. TOC performance measurement systems are based on the principles of throughput accounting which are incorporated through the implementation of concepts such as throughput, inventory, operating expense, throughput dollar days, and inventory dollar days [Umble et al., 2006].

The application of TOC was started in production planning and scheduling, which is our focus in this research. From this perspective, the goal of TOC is to maximize output, which it achieves by identifying and exploiting the bottleneck resource. Although the goal, principles and rules of TOC are clear, people use their own ad hoc heuristics to analyze each practical case. Most publications are involved in very simple cases, which are not suitable for actual job shop problems. Operation scheduling in job-shop systems is generally complicated; it is a dynamic system based on bottlenecks. In other words, the role of a bottleneck process can be changed from a bottleneck process to a non-bottleneck process and visa versa while the whole system is working.

In studying a complex case, where bottlenecks are feeding into each other, this paper shows how to apply TOC view for MPS planning and job shop scheduling. Also, an investigation on findings and suggestions in literature research for scheduling issues and material planning has been accomplished to come up with executive rules for a real case.

2. Theory of Constraints

TOC tries to identify constraints in the system, and exploit and elevate them to improve the overall output of the system. The constraints may be internal or external. Internal constraints can be physical (e.g. materials, machines, people, and demand level) or managerial [Fawcett, 1991]. Examples of external constraints are market or governmental rules and policies.

2.1. TOC Principles

Principles for achieving a continuous improvement process are as follows:

- Identify the system's constraint(s).
- Decide how to exploit the system's constraint(s).
- Subordinate every thing else to the above decision.
- Elevate the system's constraint(s).
- If in any of the previous steps a constraint is broken then go back to the first step.

In step 1, the scheduler identifies the bottleneck or internal constraint. The second step requires the scheduler to develop a MPS to maximize the throughput defined as the sales price less the cost of raw materials (RM) [Goldratt, 1990a]. The third step develops a detailed schedule for production that ensures that the constrained

resource can fulfill the MPS schedule established in step 2. The fourth step encourages continual improvement to fully utilize existing capacity and to increase the capacity at the constraint. The fifth step continually reevaluates the entire system to see if there is a new constraint after making the improvements identified in step 4. If the constraint has changed, then the heuristic starts over again with step 1 [Fredendall et al., 1997].

2.2. Production Planning

Production planning procedure has two main steps: Master Production Scheduling (MPS) and detailed Operation Scheduling (OS).

2.2.1. Master Production Scheduling (MPS)

MPS planning is actually a detailed computational procedure based on the two first principles of TOC. It is explained in detail by some authors [Fredendall et al., 1997]. A summary of this procedure is as follows:

Step 1: Identify the system's constraint(s):

The constraint, or bottleneck (BN), is the resource whose market demand exceeds its capacity.

Step 2: Decide how to exploit the system's constraint(s):

- a) Calculate the contribution margin (CM) of each product as the sales price minus the raw material (RM) costs.
- b) Calculate the ratio of the CM to the products' processing time on the bottleneck resource (CM/BN).
- c) In descending order of the products' CM/BN, reserve the BN capacity to build the product until the BN resource's capacity is exhausted.
- d) Plan to produce all the products that do not require processing time on the bottleneck (i.e. the 'free' product) in descending order their CM.

The solution resulting from this procedure may not be optimal. Fredendall and Lea (1997) proposed a revised algorithm that results better than the basic algorithm already mentioned. The revised algorithm recognizes that all products may not use the dominant bottleneck, and it incorporates a tie-breaking rule for products that have the same CM/BN ratios.

The revised algorithm proposed by Fredendall and Lea has also identified bottlenecks using the capacity criterion, which is the difference between a resource's capacity and demand [Fredendall, et al., 1997]. They ignored any other machine bottlenecks generated as the result of scheduling or other situations.

2.2.2 Operation Scheduling (OS)

After planning the MPS, the operation scheduling is accomplished to determine the release time of parts to the system. To synchronize the operations in the system, a technique called Drum-Buffer-Rope (DBR) is applied.

DBR is used in TOC as a control tool. Drum is the bottleneck and the rope is the offset of time between the scheduling of the drum and the release of raw materials. DRB is used to release raw materials from the first work station [Lea et al., 2003]. In other words, a drum is the exploitation of the constraints of the system; since the constraint dictates the overall pace of the system. A rope is a mechanism to force all the parts of the system to work up to the pace dictated only by the drum [Schrageheim et al., 1990 & 1991]. A buffer is the production time, the purpose of a buffer is to protect a schedule; *i.e.*, to ensure that the scheduled parts will be where they are needed at the time they are needed. The protection is expressed in time units. There are three types of buffers:

- ★ **Capacity Constraint Buffer:** this buffer indicates that some parts are needed to arrive earlier at the constraint area. In fact, the total processing times of these parts that need to arrive earlier is equal to the time buffer.
- ★ **Assembly Buffer:** this type of buffer is needed when a bottleneck part is assembled with a non-bottleneck part. In this case, non-bottleneck parts accumulated in the front of assembly station indicates the buffer.
- ★ **Shipping Buffer:** this buffer protects the due dates from disruptions on the way from the constraint buffer to the shipping dock.

The scheduling procedure can now be summarized as follows:

1. Determine which components are routed across the constraint.
2. Schedule any end items that do not contain components routed across the constraint (free goods) evenly in the MPS.
3. Develop a material release schedule by backward scheduling from the constraint.
4. Develop the shipping schedule by forward scheduling from the constraint and create the shipping buffer.

In fact, release time is calculated by subtracting a time buffer from the constraint schedule.

Operation scheduling is very difficult when dealing with complicated situations.

In the following conditions, complexity may occur [Fox et al., 1998]:

- A bottleneck feeds another bottleneck.
- There are a number of setups in the bottlenecks and many items are using them.

- There is a big difference among the production lead time (for the bottleneck machine to the end line) for products.
- The different parts of one product need to use the bottleneck.

2.3. Buffer Management

Buffer management is a control tool to protect the system throughput. The purpose of it is to monitor the inventory in front of the protected resources and to compare the actual performance versus the planned performance [Schrageheim et al., 1991]. The buffer size in TOC is based on time. Instead of the number of parts, the amount of time needed to keep bottleneck busy is considered as the buffer.

When DBR technique is applied for scheduling, the buffer size is set by the initial computation. However, there is two factors which influence the system performance: disruptions and complexities.

Disruptions might stem from a variety of reasons, such as breakdowns, absenteeism, and fluctuations in setup times, process times, unreliable vendors, and scraps.

The second factor, complexities (section 2.2), cause changes on buffer levels. Buffer levels affect operations scheduling and release times. Some authors have suggested that the buffer size might be three times the average lead time to the constraint [Schrageheim et al., 1991]. Others use a rule of thumb, which is to start with a buffer that is five times the sum of the setup and processing times of operations between material release and the constraint [Spencer et al., 1995]. Of course, adjustments need to be made as production occurs because operations scheduling and bottlenecks both influence buffers.

Three important questions to be answered are: what is the suitable buffer for each bottleneck in a job shop system with the frequent setups and variant processes? How could we reduce work in process (WIP) without starving the bottleneck? How can we get maximum throughput while the process variety is high?

We have studied a part-producer job shop system, which has complicated conditions to implement the operations scheduling based on TOC in a real environment. These three questions can be answered through this case study.

3. Case Study

The case studied in this paper is an automobile part manufacturer that has a job shop system. There are three products, A, B and C, which have 2000, 5000, and 2000 units in demand for one month as a period of production, respectively. Figure 1 shows the different routings in which the products are processed. Each block in Figure 1 indicates the operation code, machine code, operation time, and setup time. Although the process flow for each product is like a flow shop, the machine code shows that only one machine is using in a different step of process. As an example, machine code 6 is used in several places in the figure, but this is just one machine in a specific place in a physical layout. The only reason to show the process as a flow shop is to show all steps of the process for each product and the role of each machine in this process.

Since most of the machines are used in different steps of the process, managing the bottleneck machines is not an easy task. Also, some of the bottlenecks, like machine 6 or 13 (which will be discussed later), are operating for two products; each of them is used in different steps of the operation. This characteristic of the production line, which

is not unique in industry, is to show how to apply TOC for a real dilemma – which is one of the motives of this research.

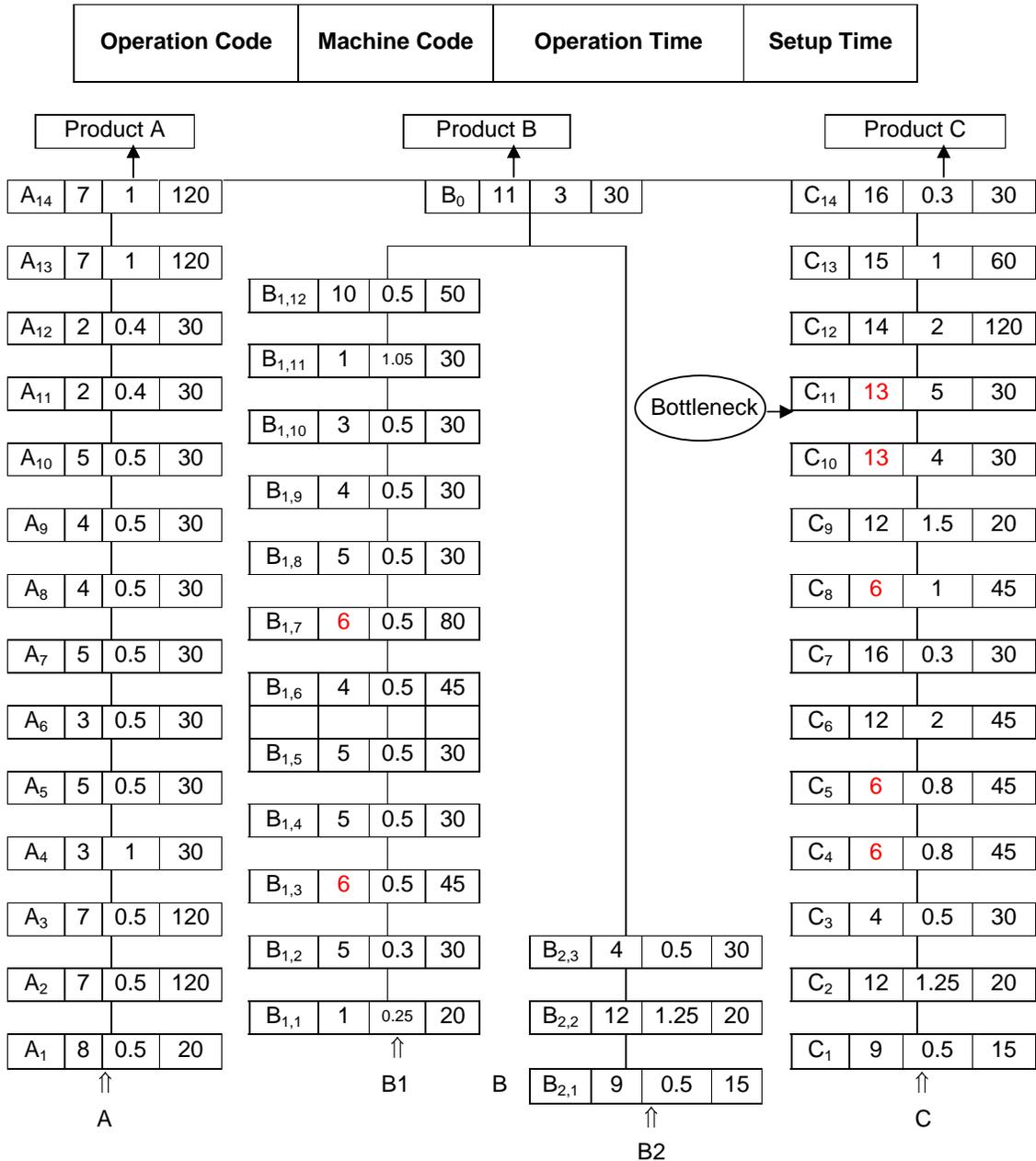


Figure 1. The Process Routing For Each Product

Since most of the machines are used in different steps of the process, managing the bottleneck machines is not an easy task. Also, some of the bottlenecks, like machine 6 or 13 (which will be discussed later), are operating for two products; each of them is used in different steps of the operation. This characteristic of the production line, which is not unique in industry, is to show how to apply TOC for a real dilemma – which is one of the motives of this research.

The framework of material planning for this case study is to follow the general concept and rules of the details of the application. This is prepared in multiple steps. The first step is to find the bottlenecks and make the initial MPS. The next step is to work on scheduling operations, which is to find the release time of raw materials and the buffer size. In the final step, verification of the initial plan and its improvement are examined toward a good and feasible solution by simulation techniques. These steps in detail are as follows:

3.1. MPS Planning

Before MPS development, it is necessary to identify the system's bottlenecks. Table 1 indicates the planning data for MPS planning (i.e. the market demands, the capacity available, the resource's capacity, and difference between them).

The difference between the actual and required capacity shows that four machines (5, 6, 11, and 13) are bottlenecks. Utilizing overtime work and subcontracting, we provide more available capacity available and convert machines 5 and 11 to be non-bottleneck machines. The capacity differences for machines 6 and 13 are also reduced to -720 and -1800, respectively. Comparing these figures, it is observed that machine 13 is the main bottleneck.

Table 1. Data for Processing Times and Capacity Differences

Machine Product	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Demand
A	-	0.9	1.5	1	1.5	-	4	0.5	-	-	-	-	-	-	-	-	2000
B	1.3	-	1	1	2.3	1	-	-	0.5	0.5	3	-	-	-	-	-	5000
C	-	-	-	0.5	-	2.6	-	-	0.5	-	-	4.75	9	2	1	0.6	2000
Capacity Available	8160	1920	8640	9120	1152	4800	9600	1920	7200	3360	1200	1152	1152	4800	2400	1440	
Required Capacity	6500	1800	8000	8000	14500	10200	8000	1000	3500	2500	15000	9500	18000	4000	2000	1200	
Capacity Differences	+1660	+120	+640	+1120	-2980	-5400	+1600	+920	+3700	+1860	-3000	+2020	-6480	+800	+400	+240	

The manager makes an assumption for available capacity.

Table 2. Calculation of the Contribution Margin

Machine Product	6	13	D	CM	$R_i = \frac{CM}{t_i}$
A	—	—	2000	1500	—
B	1	—	5000	2200	—
C	2.6	9	2000	3000	333.33

Using the information regarding the contribution margin as previously defined in Table 2, which comes from the accounting system of the factory, and selecting machine 13 as the main bottleneck, the initial MPS is developed in Table 3.

Table 3. The Initial MPS Based on Machine 13

Priority	Demand	MPS	Machine 13			Machine 6		
			Total Time Available	Used Time	Time Left	Total Time Available	Used Time	Time Left
C	2000	1800	16200	16200	0	9480	4680	4800
B	5000	5000	—	—	—	4800	5000	-200
A	2000	2000	—	—	—	—	—	-200

As Table 3 shows, the MPS stemmed from machine 13 as the base of the MPS, is not feasible. Machine 6 does not have the adequate capacity to produce products A and B. Therefore, it can be concluded that machine 6 is the main bottleneck. Using this information, the final MPS is developed in Table 4.

Table 4. The Final MPS Based On Machine 6

Priority	Demand	MPS	Machine 13			Machine 6		
			Total Time Available	Used Time	Time Left	Total Time Available	Used Time	Time Left
C	5000	5000	9480	5000	4480	16200	—	16200
B	2000	1723	4480	4479.8	0.2	16200	15507	693
A	2000	2000	0.2	—	—	693	—	693

As Table 4 indicates, the product mix is 5000, 1723 and 2000 units of products A, B, and C, respectively.

3.2. Operations Scheduling

The release times are determined based on the system's constraints. Product A is a free product, as it does not use the bottleneck machines. Thus, producing products B and C both have high priority. Product A is produced when there is no WIP for products B or C in front of the machines.

As Figure 1 illustrates, this is a very complicated case. There are bottlenecks (machines 6 and 13) sequentially in the routings in which products B and C are produced. In one part of the routing, there is also a bottleneck that feeds another bottleneck.

3.2.1 Constraint Buffer

Machine 6 is a bottleneck that receives materials earlier than others. It feeds other machines in the routings of producing products B and C. The initial buffer level is

set to be five times the processing and set up times of operations to the bottleneck, which results in the following:

Routing B to the first Bottleneck (machine 6):

$$5 \times [(0.25+0.3)+(20+30)] = 252.75 \text{ min}$$

Routing C to the first bottleneck (machine 6):

$$5 \times [(0.5+1.25+0.5)+(15+20+30)] = 336.25 \text{ min}$$

Therefore, the buffer level is set to 336 min for machine 6. Since the second bottleneck, machine 13, is fed by machine 6, there is no need to assign any buffer to it.

Table 5.Scheduling for Machine 6

Operation Code	Lot size	Starting time(from the start point of production period)
B _{1,3}	5000	0
C ₄	1723 ≈ 1720	41.6
C ₅	1720	64.5
B _{1,7}	5000	87.4
C ₈	1720	110.3

B_{1,3} represents the 3rd operation on product B in sub-routing 1 and C₄ represents the 4th operation on product C in its routing, as shown in Table 5.

As a sample calculation, the start time of the C₄ & C₅ is as follows:

$$5000 \times 0.5/60=41.6 \text{ min} \quad (0.5 \text{ is the process time})$$

$$1720 \times 0.8/60 +41.6 =64.5 \text{ min}$$

The lot size in the scheduling is the same as demand, which is common in TOC-based planning. It leads to the reduction of set-up time in bottlenecks. Of course this can be an initial plan; it may be changed to increase productivity of the whole system.

3.2.2 Assembly Buffer

Product B consists of two parts: B1 and B2. Part B1 goes to machine 6 two times and then it is assembled with part B2. Thus, there is a need to consider a buffer before the assembly operation. The buffer size is as follows:

Five times, the processing and set-up time, from the starting operation to the bottleneck that its output is assembled with B2.

$$5 * [(20+30+46+30+30+45) + (0.25+0.3+0.5+0.5+0.5+0.5+0.5)] = 1015.3 \text{ min}$$

The release time can now be calculated as follows:

Table 6. Releasing Time

Material	Quantity	Arrival Time
B ₁	5000	0
C	1720	36
B ₂	5000	70.5

To calculate the material arrival time, the buffer time is deducted from the starting time. Due to the high priority of product B, entering B1 to the production line is necessary. After passing part B1 through machine 6, another setup is completed and product C is processed by machine 6. Thus, the starting time on product C must be deducted from buffer time, that is:

$$41.6 - \left(\frac{336}{60}\right) \cong 36$$

To calculate the material arrival time for B2, the buffer time is deducted from operation time on B1,7, that is:

$$87.4 - \left(\frac{1015}{60}\right) \cong 70.5$$

Product A is produced when there is an idle machine on the line. To show the effectiveness of our decisions over time, we have applied a simulation tool.

3.3 Simulation

In this section, there are 8 models that show how improvement has been accomplished from the initial plan in the first model to the last model. Running the first model based on the first draft of scheduling is useful in that it shows how the whole system is working, where the bottlenecks are, and how to improve the plan. Taylor II software was used to simulate the problem for different models. Although, processes time, machines failure, etc., may have a statistical distribution, lack of these data forced us to consider the following assumptions:

- There are no defective parts.
- There is no machine failure.
- The process time and set up time are fixed.
- The break time is zero.
- Machine 16 is doing an annealing operation, and then the lot size is fixed to 200 units afterwards.

Model One

The parameter's calculated value was selected as the input data for the first model. The following results were achieved after simulation:

- The output was 986 units for product B.
- The WIP level was high.
- Machine 5 appeared to act as a bottleneck (long queue and making long waiting time for operation ahead, after analyzing the simulation result)

Machine 5, which did not seem to be a bottleneck initially, was acting like a bottleneck. The hidden effect of the queuing system and WIP caused a non- bottleneck

machine to transform into a bottleneck machine. Therefore, some improvements were applied to maximize the output.

Working on effective factors, such as buffer size, lot size, or material release plan, were the key to use the whole capacity of bottleneck machines and to make a synchronize system. In the following sections, changes in these effective factors were applied in each model. Based on the results in each model, the appropriate next step was taken.

Model Two

The complicated situations in this case and the frequent set-ups necessitated a reduction in batch size. The lot sizes for this model were reduced to half their original size prior to running the simulation. The results were as follows:

- The outputs were 948 and 200 units for products B and C, respectively.
- The WIP level was also reduced in comparison to the WIP level in model one.

To reduce WIP and achieve a better result, the next model was run.

Model Three

The release plan in this model was similar to model two; however, not all of the materials were released to the production line. Only half of the MPS was released to reduce the WIP. The results are as follows:

- It gave more opportunity to the non-bottleneck parts having only a few operations remain to be completed for shipping.
- The results of the model were much better compared with two previous models.

Improvement was still needed to increase output and reduce the WIP.

Model Four

In this model the batch sizes were reduced. The batch sizes were reduced to 1000 units for product B and 600 units for product C. The results have been further improved.

Model Five

After reducing the batch size for products B and C to 500 and 600 unit respectively, a new model was developed. The batch size of product A (a free product) was also reduced to 1000 units. Again, the results yielded a better output than other models. In the next model, another experiment was conducted by changing the size of buffers.

Model Six

The batch sizes in this model were reduced to as small as possible. The batch size for products A, B and C were set to 1000, 500 and 400 units, respectively.

Model Seven

Using observations from the previous experiments, the constraint buffer was reduced from 5.5 to 2 hours, and the assembly buffer was reduced from 16.9 to 6 hours. The output for products A, B and C were 861, 3500 and 600 units, respectively.

Model Eight

To improve the productivity of bottlenecks, some expediting procedures were conducted. The goal was to diminish the idle time in any bottleneck machine. The outputs for products A, B and C were 839, 3550 and 800, respectively.

Since working on any other potential factors did not improve the results any further, the latest model shows a very good and feasible solution in comparison with other models. These improvements show how the initial plan has been modified toward a good and feasible solution.

As Figure 2 shows, the different models were compared based on the following criteria:

- **WIP**
- **Benefits**
- **Average lead time**
- **Output time of the first product**
- **Cycle time**

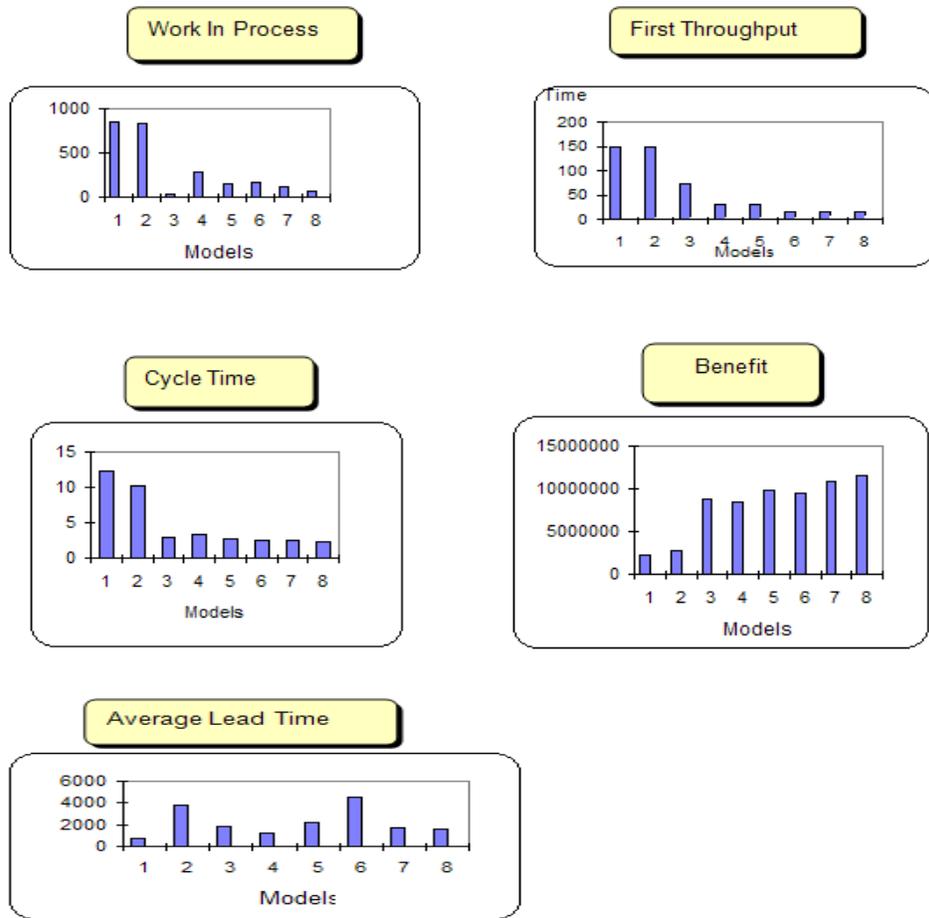


Figure 2. Comparison Between the Results of Different Models

In order to show how the results of TOC scheduling approach are helpful, a material planning for this case was prepared by MRP-DSS software to compare the results. The results from the software show a significant difference among results of TOC – especially for product B. Figure 3 shows this comparison.

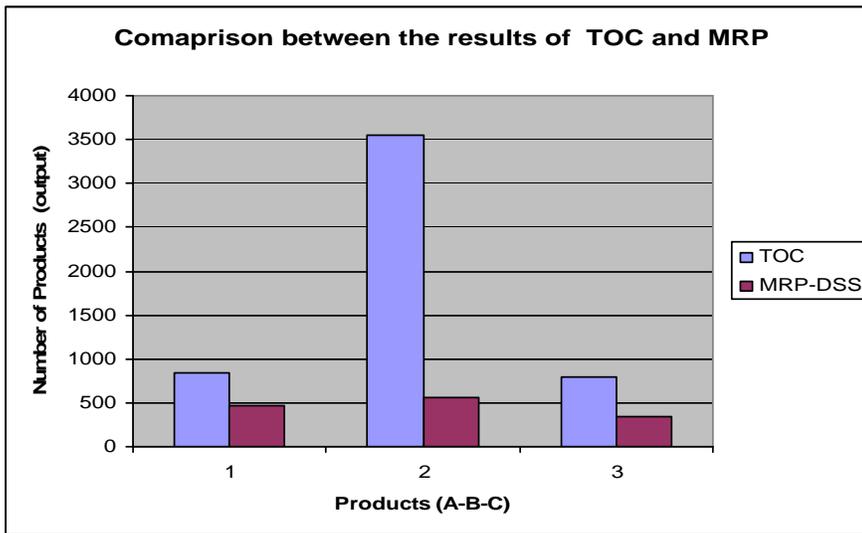


Figure 3. Comparison between the Results of TOC and MRP-DSS

After investigation, analysis and comparison among different models, the following four rules are proposed which can help if one is looking to implement the TOC approach for a job shop system:

Rule 1. In a complex process flow, as defined before, the buffer size factor for a constraint can be less than its value in a simple process flow.

Buffer size factor is a coefficient, which is a number between 3 and 5. This coefficient multiplied by the lead-time to bottleneck position in the process flow yields the constraint buffer size.

The more the part uses the bottleneck or the more time each part uses the bottleneck, the smaller the buffer size factor can be assigned. There is a possibility that in a real job shop system that different parts, arriving at a bottleneck, are accumulated and have built up a huge WIP.

Rule 2. Nearby bottleneck machines should be supervised like main bottlenecks.

Bottlenecks, in real situations, are not only machines with low capacities. Some machines, with enough capacity, can play the role of bottleneck as a result of inefficient scheduling or the complexity of the process. Machine 5 from the case study is an example of this type of bottleneck. This machine has never been idle in any of the models. This kind of bottleneck should be supervised.

Rule 3. While not applicable in all situations, the reduction of number of setups in bottleneck can lead to an increase in benefits. In situations where there process contains complexities and the bottleneck is used by several operations, decreasing the batch sizes (i.e. doing more set-ups) can increase the output. This fact is valid both for bottleneck and non-bottleneck machines.

Rule 4. The production priorities based on CM should not be necessarily followed in the final stage of a period.

For example, in a real production environment, there may be two products X and Y that are competing to use the same bottleneck simultaneously. Following the

priority based on CM in this example, product X would be processed first. However, after this operation, product X is not completed and needs more operations. Whereas, assigning this resource to product Y - a product with low priority - leads to the completion of product Y with this operation, which can then be shipped to the customer. Thus, based on the finishing time of the period, it is preferable to expedite the WIP to be processed and shipped as soon as possible; even though this priority conflicts with original priority based on CM. In other words, while product X has the priority over product Y, the remaining time is not enough to produce a completed product X. The higher priority then switches to product Y, which needs less time to be at the end of production line.

4. Conclusion

Since the rules and research found in literature for scheduling issues, such as buffer size and batch size, are based on simple examples in theory, they may not be helpful in a real job shop system. As explained in this paper, these rules and research findings have been applied to find an initial solution for this case study; and by using simulation techniques, the initial solution was improved. This improvement process helped in developing a good understanding of how to deal with effective factors in scheduling and material planning in a real and common case. The case study showed the effects of the buffer size on system output. Four proposed rules as a result of this investigation were determined for implementation of TOC in a job shop system.

To find the optimal solution, further research needs to be accomplished. However, it can be concluded that the TOC approach is very beneficial for production planning because of its potential improvements. One can also benefit from TOC, not only by implementing its software, but also by using its philosophy.

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