A System Dynamics View of the Theory of Constraints

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ABSTRACT

System Dynamics can be used to facilitate the understanding and develop alternatives for a system. In the same way, The Theory of Constraints (TOC) is based on Eli Goldratt's work on "how to think"[1], System Dynamics (System Dynamics) is based on a way of thinking about systems from a global perspective. The primary application of TOC embodies a systems thinking approach to manufacturing systems. By knowing how to think from a systems perspective, we can better understand the system under study. Through better understanding, the performance of these systems can be improved. The concepts of ongoing improvement embodied in the TOC are enhanced using System Dynamics. By providing a way to model and simulate the system under study through System Dynamics and applying the rules of TOC to the model, alternative solutions to improve system operation can be developed. System Dynamics software further enhances this process by adding the ability quickly evaluate various alternatives versus testing these alternatives on live production runs that may take weeks, or months.

INTRODUCTION

The central concept of TOC is the acknowledgement of cause and effect. The core idea of TOC is that “Every real system must have at least one constraint.”[2] Just as the thinking processes of TOC provides a series of steps that combine cause-effect and our experience and intuition to gain knowledge[3], System Dynamics provides a methodology for studying and managing complex feedback systems, such as one finds in business and other social systems.[4] System Dynamics and TOC provide the tools to understand system constraints and thus make it possible to improve system performance.

One extraordinary benefit of these thinking processes is that they provide the ability to recognize the paradigm shifts that occur when times change but our assumptions and rules don't. We cannot constantly monitor every assumption to be sure we are in line with constantly evolving reality, so the ability to spot the shifts can be a real advantage. Those who continue their patterns of operation, regardless of the changing reality, will suffer when the effects of their actions are not those that they expect[5]. Eli Goldratt's novel The Goal[6] completely exposed the magnitude to which this problem can exist.

TOC uses a system perspective to analyze and understand the entire system, not just parts of the system. This makes it possible to identify elements of the system that constrain, or limit, the

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output of the system. By identifying such constraints, it is possible to find ways to alleviate these constraints to improve overall system performance. As such, it uses a system thinking approach to facilitate the understanding of how a particular system works. System Dynamics provides the additional steps of constructing and testing a computer simulation model, and testing alternative policies in the model to test various hypotheses for eliminating system constraints. As Jay Forester states, "Without a foundation of systems principles, simulation, and an experimental approach, systems thinking runs the risk of being superficial, ineffective, and prone to arriving at counterproductive conclusions." (Jay Forester, Germeshausen Professor Emeritus and Senior Lecturer at the Sloan School of Management, Massachusetts Institute of Technology). System Dynamics addresses this concern through computer simulation of the system at hand.

System Dynamics methodology follows the scientific method in the identification and resolution of system problems to improve performance. This methodology includes the following steps:

1. Identify the problem
2. Develop a dynamic hypothesis explaining the cause of the problem
3. Build a computer simulation model of the system at the root of the problem
4. Test the model to be certain it reproduces the behavior observed in the real world
5. Devise and test alternative policies that alleviate the unwanted behavior
6. Implement the solution [7]

Thus, System Dynamics provides a rigorous approach to solving system problems that can be applied to systems that have limited output due to constraints that have been built into the existing system. Furthermore, newly proposed systems, and propose changes to these systems can be modeled to identify potential constraints before expensive mistakes are made. The Theory of Constraints methodology provides specific guidelines for modeling system behavior and analyzing systems to identify and alleviate system constraints. The combination of applying Theory of Constraints methodology and building a computer model of the system using System Dynamics software provides a superior tool for analyzing systems and improving their performance. There are several different System Dynamics software packages available. The one chosen for this project is Stella by High Performance Systems, Inc. 46 Centerra Parkway, Suite 200, Lebanon, NH 03766-1487

CONSTRAINT MANAGEMENT

To manage constraints (rather than be managed by them), Goldratt proposes a five-step Process of On-Going Improvement of existing systems. The steps in this process are:

1. Identify: In order to manage a constraint, it is first necessary to identify it.
2. Exploit: Focus on how to get more production within the existing capacity limitations.

3. Subordinate: Prevent the materials needed next from waiting in a queue at a non-constraint resource.
4. Elevate: If, after fully exploiting this process, it still cannot produce enough products to meet market demand, find other ways to increase capacity.
5. Go back to Step 1. [8]

This methodology can be compared to the steps of the scientific method that System Dynamics follows. However, System Dynamics aided by special software, provides a means to quickly test the affects on the system when these changes are made in order to verify their effectiveness. Evaluating these changes in real time on a system in operation is much more time consuming and costly. System Dynamics provides the means to evaluate prospective changes before they are installed. Thus, System Dynamics provides a much more efficient, and cost effective way of managing constraints by assisting in identification of constraints and developing ways to manage these constraints through simulation of the system.

SYSTEM OPERATION IMPROVEMENT

So, how does TOC improve system operation? Improvement efforts are focused where they will have the greatest immediate impact on the performance of the system. TOC provides a reliable process that insures implementation. Stella modeling enables identification of system constraints and exploration of alternative means of managing these constraints. The first step is to identify the system constraints that prevent the system from achieving its goal. Next, identify the most constrained resource, called the Critically Constrained Resource (CCR).

Traditional cost accounting methods demand that each resource is fully loaded to achieve maximum utilization. However, this causes serious problems due to the build-up of in-process inventory and wasted machine time. TOC takes a different view of this situation as illustrated by a simple manufacturing line (figure 1). Or, in order to smooth out production, managers may opt to balance the line to the critically constrained resource (figure 2).

Raw material flows from left to right through five processes and become finished goods. Note that process C is the limiting process in that it can only produce 5 parts per day. [9]

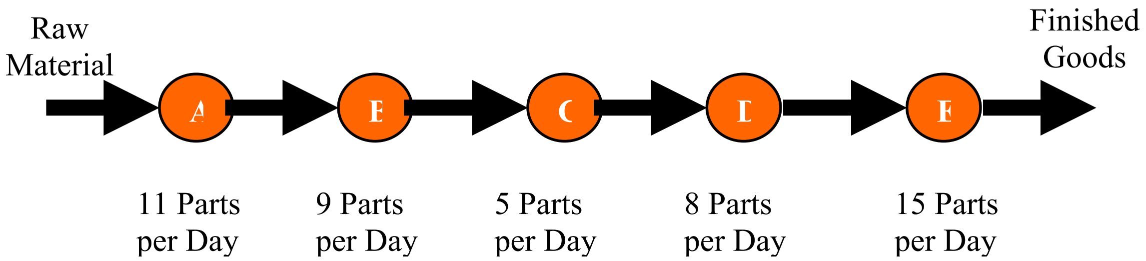


Figure 1, A Simple Manufacturing Line

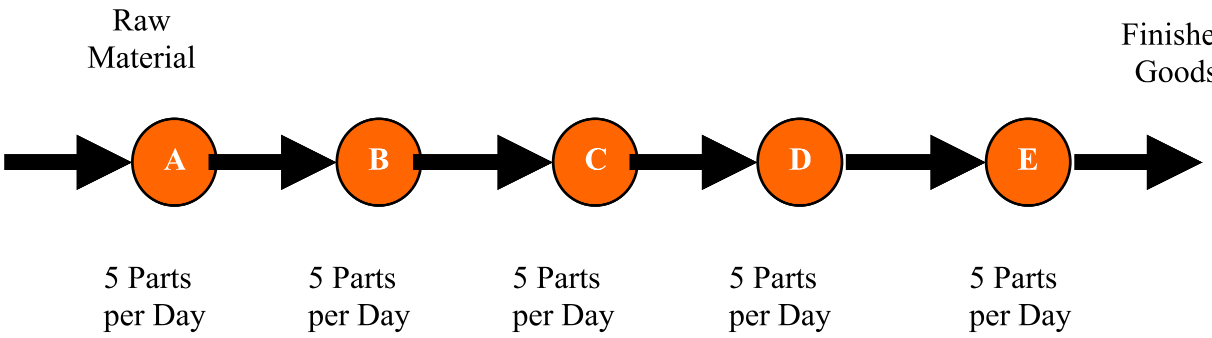


Figure 2, A "Balanced" Manufacturing Line

Many managers attempt to avoid waste and make everyone efficient by balancing the line. This balanced line won't work. It can rarely achieve five parts per day. However, in reality, every process has some variation. Consider a 50% chance per machine of producing five items per day or more. The probability two independent machines produce five or more the same day is 0.5*0.5=0.25 or 25% (figure 3). Most processes have more than five steps. And with as few as five steps, there is only a 3% chance of producing five or more per day.[10]

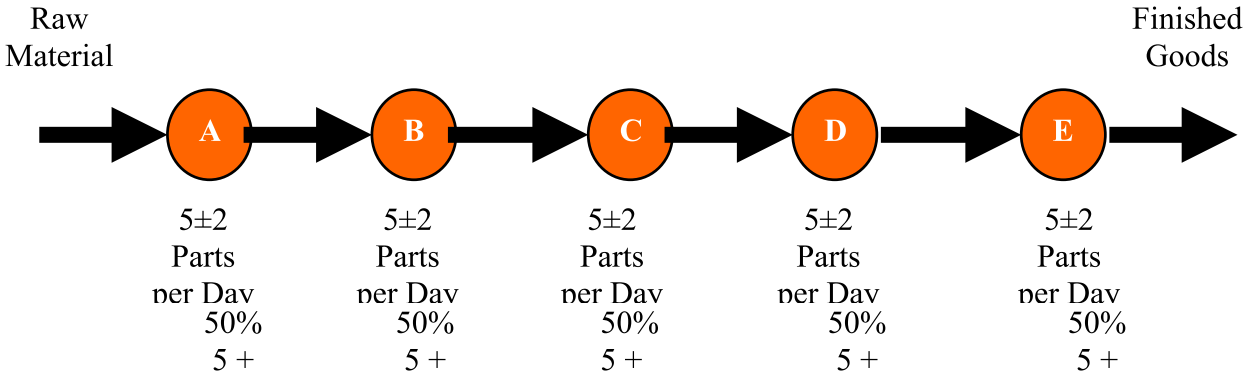


Figure 3, Problems With a Balanced Manufacturing Line

A proven approach to managing production through the constraint is known as "Drum-Buffer-Rope" and "Buffer Management."[11] TOC encourages every process to work as fast as possible, when there is work. The constraint is like a drum that beats the cadence of the plant. A time buffer of material placed between the Raw Material (RM) and the constraint protects it from starvation. A rope throttles the RM to maintain Work In Process (WIP) at minimum levels (Figure 4). Work completes at predictable flow times.

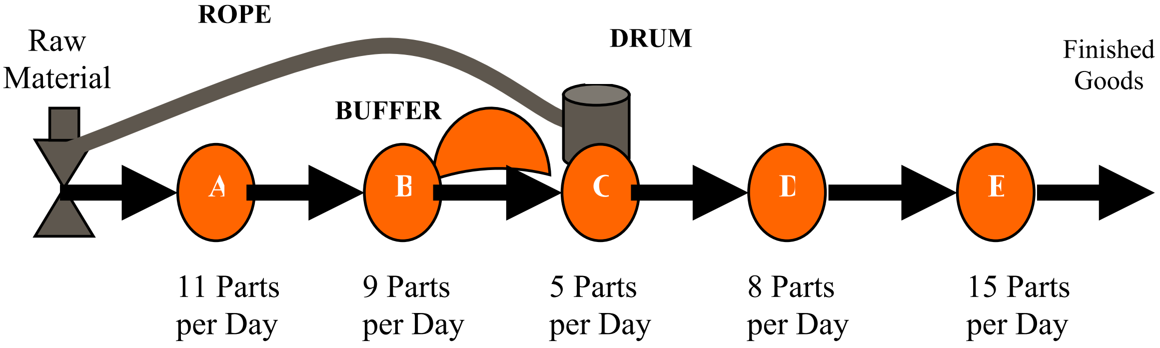


Figure 4, TOC Process Control

In a production environment, the plant's constraint (bottleneck) must be the driving factor in how it is managed. In production, the productivity of the constraint is the productivity of the entire plant.

- **Drum** - The constraint(s), linked to market demand, is the drumbeat for the entire plant.
- **Buffer** - Time/inventory that ensures that the constraint(s) is protected from disturbances occurring in the system.
- **Rope** - Material release is "tied" to the rate of the constraint(s).

The drum, buffer, and rope provide feedback to the production manager for building a production schedule that is highly immune to disruption, avoids creating excess inventory, and uses small batches to minimize overall lead time. However, even with "Drum-Buffer-Rope," occasionally disruptions occur which require special attention. "Buffer Management" is used to mitigate and often prevent those disruptions.[12]

Implementations of "Drum-Buffer-Rope" and "Buffer Management" typically result in "lean," low-inventory production operations capable of consistently 95% (or better) on-time delivery, lead-time reduction of 35-50%, and inventory reduction of 50%, as well as significantly reduced need for expediting and rescheduling.[13]

STELLA MODEL OF BUFFER MANAGEMENT

The important distinction between TOC and System Dynamics is that, although TOC involves systems thinking it does not provide a way to simulate the system under study to test whether the recommendations developed under TOC will be effective. This is where System Dynamics can aid in making the TOC concepts more effective, particularly when a SD software package such as Stella is used to aid with the analysis.

The building blocks of Stella models are "stocks" and "flows."[14] Stocks act as "accumulators" of system objects, and flows act as the transport mechanism between stocks. Converters are System Dynamics elements that pass information to flows or from stocks to flows. They can also pass information from one stock to another. A simple example of a stock and a flow is that of a bank balance as shown in figure 5.

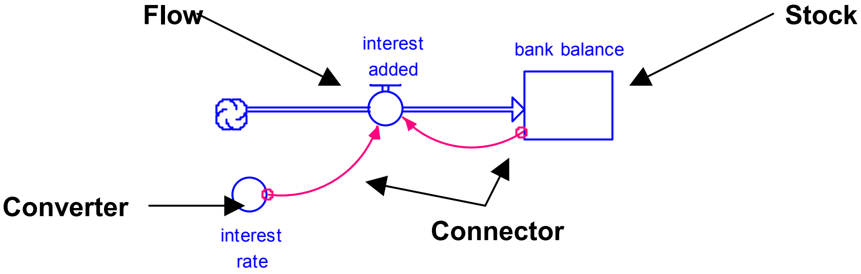


Figure 5, A Simple Stock – Flow Stella Model of a Bank Balance

In this example, the bank balance is increased by the flow from "interest added." The bank balance multiplied by the interest rate controls the amount of "interest added". Therefore, the greater the interest rate, the more interest is added to the bank balance. A graph depicting this simulation is shown in figure 6.

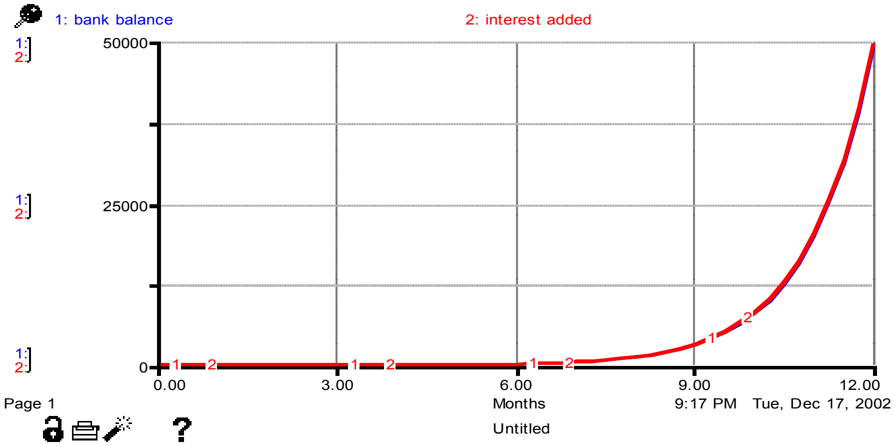


Figure 6, Graph of Interest Added to Bank Balance

In the Stella model of a simple production system, the process stocks are a special type of stock called a conveyor. Conveyors are a special version of the stock variable that simulates material moving through the system in a tightly controlled pattern.[15] Work-in-process (WIP) inventories are ordinary stocks between each operation. Connectors (red arrows) provide feedback to the WIP that tell each flow between the WIP stock and the next conveyor operation not to send any more material to the next operation than it can handle. Logic is provided to each flow to limit the amount of material from going to the conveyor to be processed to no more than is required. This stops any flow from the WIP stock if the process is full. Figure 7 is a Stella model of the simple production system that consists of a series of conveyors connected by flows with WIP stocks between operations.

A Stella model of the simple production system would appear like the model in figure 7. The time to process parts through each conveyor is based on an 8 hr day. Therefore, since A can process 11 parts per day, the process time is 8 hrs / 11 parts, or .72 hrs for one part to be processed. This sets the transit time for conveyor A at .72 hrs, or about 44 minutes. The Stella software rounds fractions, so, the time units for this model are best handled in minutes. Likewise, B can process 9 parts per day, or a transit time of 53 minutes, C is 96 minutes, D is 60 minutes, and E is 32 minutes.

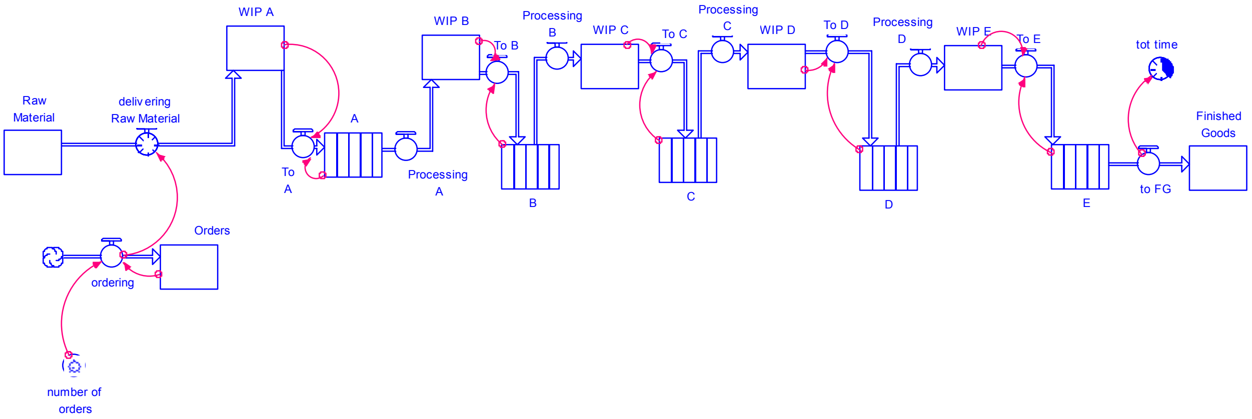


Figure 7, A Stella Model of a Simple Production System

Running this simulation yields some interesting information about the model. Figure 8 shows a graphical output of the time it takes to produce 5 units. Figure 9 shows that it takes 1,275 minutes, or, 21.25 hours to achieve the Finished Goods total equal to the number of orders if the number of orders are set to 5.

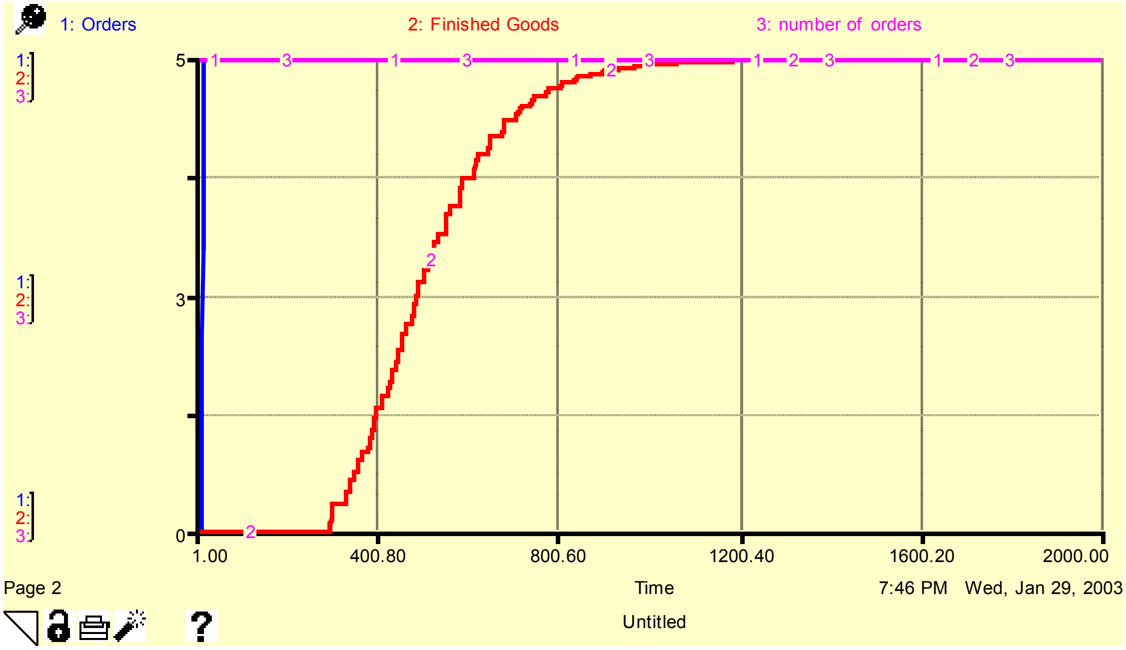
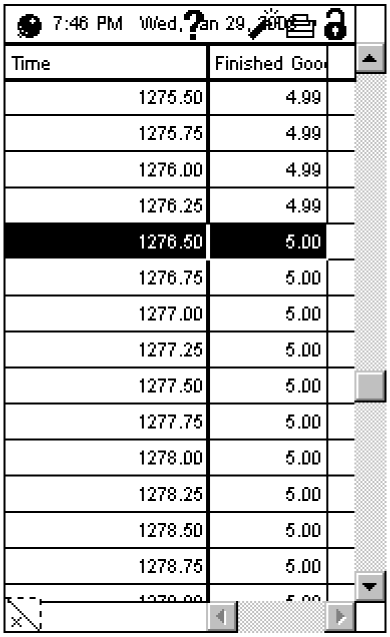


Figure 8, Time to Achieve Finished Goods of 5 equal to 1,275 Minutes, or 21.25 hrs



Time	Finished Goo
1275.50	4.99
1275.75	4.99
1276.00	4.99
1276.25	4.99
1276.50	5.00
1276.75	5.00
1277.00	5.00
1277.25	5.00
1277.50	5.00
1277.75	5.00
1278.00	5.00
1278.25	5.00
1278.50	5.00
1278.75	5.00

Figure 9 is a graph of the time it takes to produce 5 units of finished goods.

Figure 9, Graph of Time to Produce 5 units of Finished Goods, Time = 1,275 min

The drum-buffer-rope (DBR) concept of TOC states that feedback is provided from the critically constrained resource (CCR) to the Raw Material delivery source. A time buffer of material placed between the Raw Material (RM) and the constraint protects it from starvation. A rope throttles the RM to maintain Work In Process (WIP) at minimum levels of the CCR (Figure 4). Work completes at predictable flow times. This concept is represented in the Stella model shown in figure 10. Note a feedback connector represents the “Rope” from C, the CCR, to WIP A. This has the effect of limiting the flow from the processes prior to C to the same level of C. Next, a buffer is added to Process B so that C is protected from starvation, yet, A and B are not producing more than C. A feedback loop to ordering tells the system how many more units are needed to keep C from starving. It would seem that this logic would cause the model to take longer to produce the 5 units of output. However, in reality, the process is faster. Now, instead of 1,275.5 minutes to produce 5 units of output, it only takes 910.25 minutes (Figure 11).

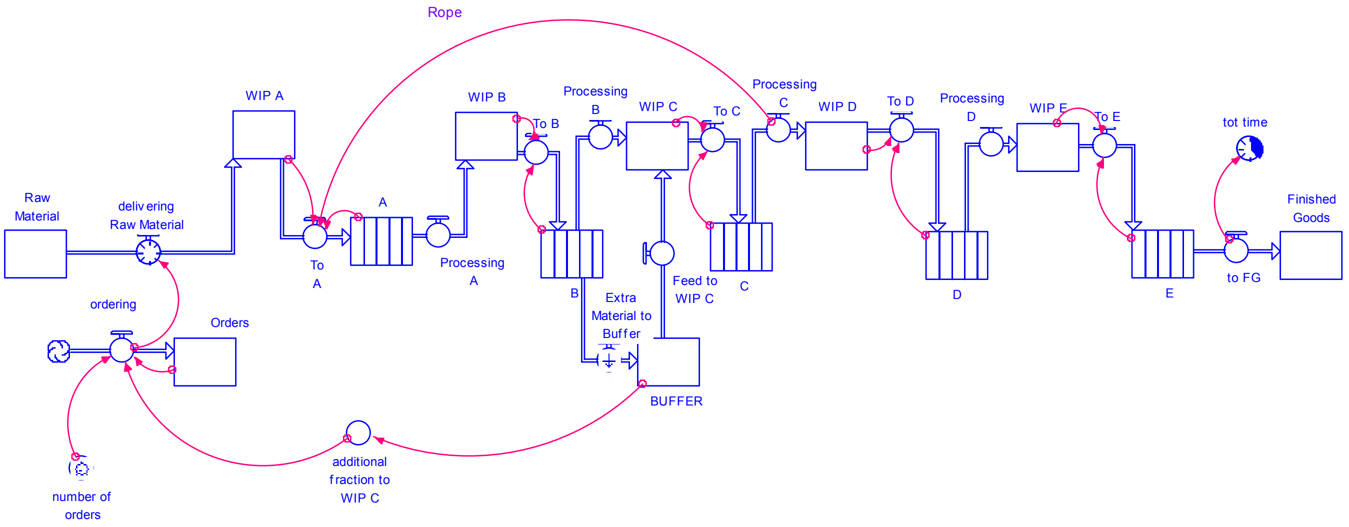
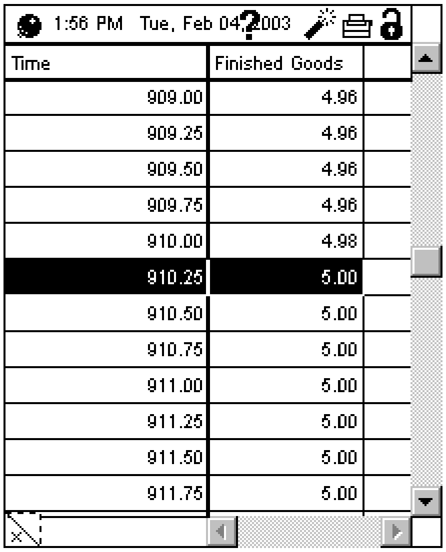


Figure 10, Stella Model With Feedback Loops and Buffer



Time	Finished Goods
909.00	4.96
909.25	4.96
909.50	4.96
909.75	4.96
910.00	4.98
910.25	5.00
910.50	5.00
910.75	5.00
911.00	5.00
911.25	5.00
911.50	5.00
911.75	5.00

Figure 11, Partial Output from Stella Model Without Buffer

Figure 11 shows the tabular output from the model. This shows Finished Goods of 5 units being completed at 910.25 minutes. A graph of this output is shown in Figure 12. Note the steeper slope on the curve and earlier completion of finished goods. Also, note that the number of orders is increased by 1 that accounts for the additional inventory needed to keep process C from starving.

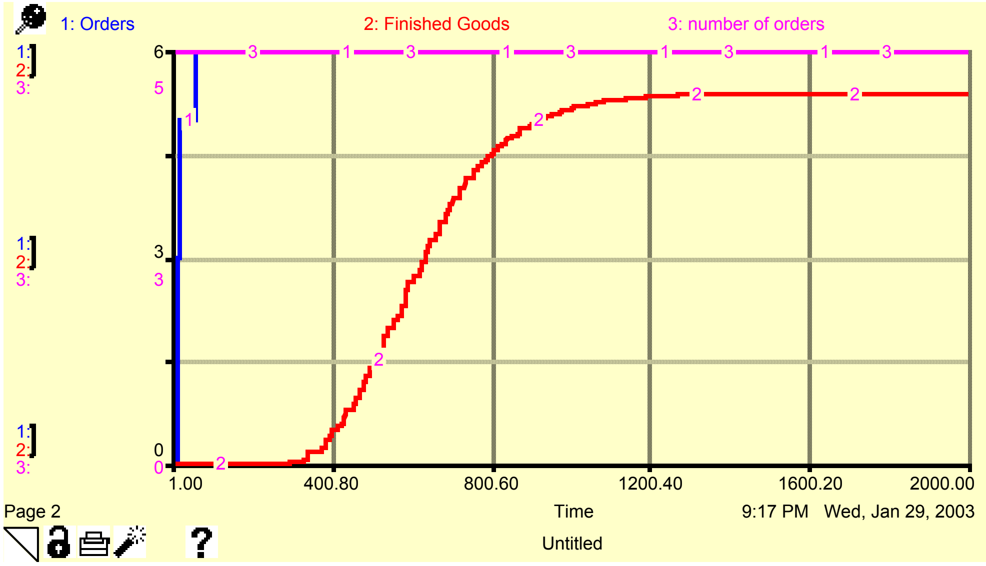


Figure 12, Graph of Time to Produce 5 units of Finished Goods with TOC in place

Further confirmation of the buffer effect on the system can be seen in figure 13 and 14. These graphs compare the output of each process without and with TOC applied. Note the differences in each process. The processes with TOC applied have a more controlled, gradual slope. The spikes of production at the beginning of each of the process are leveled out over the process. This shows that the processes are more in control. This information, coupled with the graph in figure 12 and the numerical output in figure 11 confirm that the DBR method does control system throughput resulting in a much more even flow through the system. This in turn improves throughput by allowing every process to work as fast as possible, when there is work, maintaining WIP at minimum levels, and protecting the constrained resource from starvation. Furthermore, it confirms that the Stella model is working properly and effectively models the DBR concept.

Figure 14 shows the various WIP levels and compares them without TOC and with TOC applied. Note the significantly higher WIP level in WIP A with TOC Applied than without TOC applied. Recall that process A could produce 11 parts per day. Thus, without TOC applied, its WIP would be about 50% that of process C that has a throughput of 5 parts per day due to the higher production level. This shows that the Stella model is working as expected by increasing the amount of material released to process A which in turn improves throughput by allowing every process to work as fast as possible. Also, other WIP levels are maintained at minimum levels. Note that WIP B, C, and D are somewhat lower when TOC is applied. WIP E appears to be about equal. However, in each case except for perhaps A, the slope of inventory building is less dramatic and the initial spikes are gone. This indicates the process is more in control.

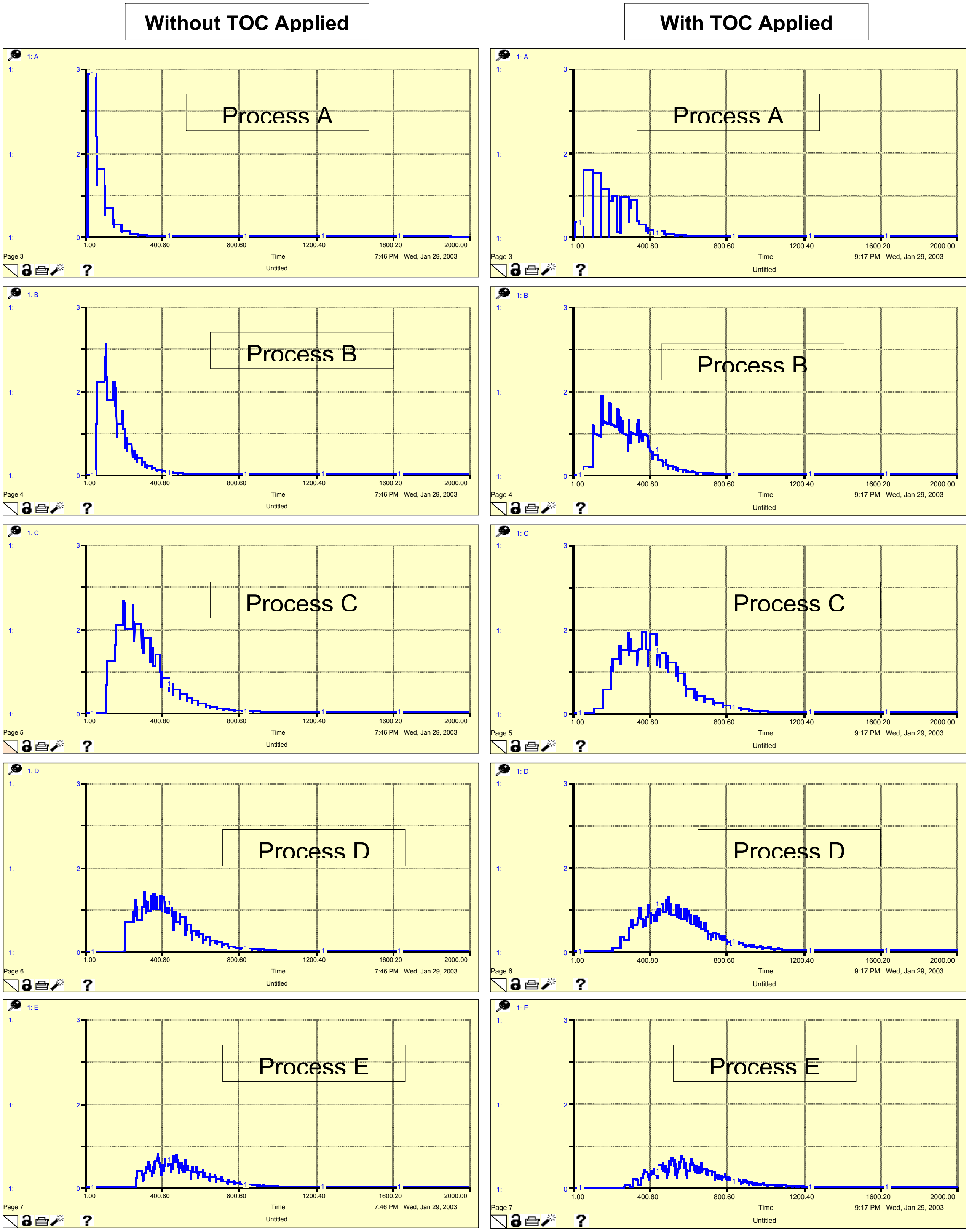


Figure 13, Output Graph Material Flow Patterns

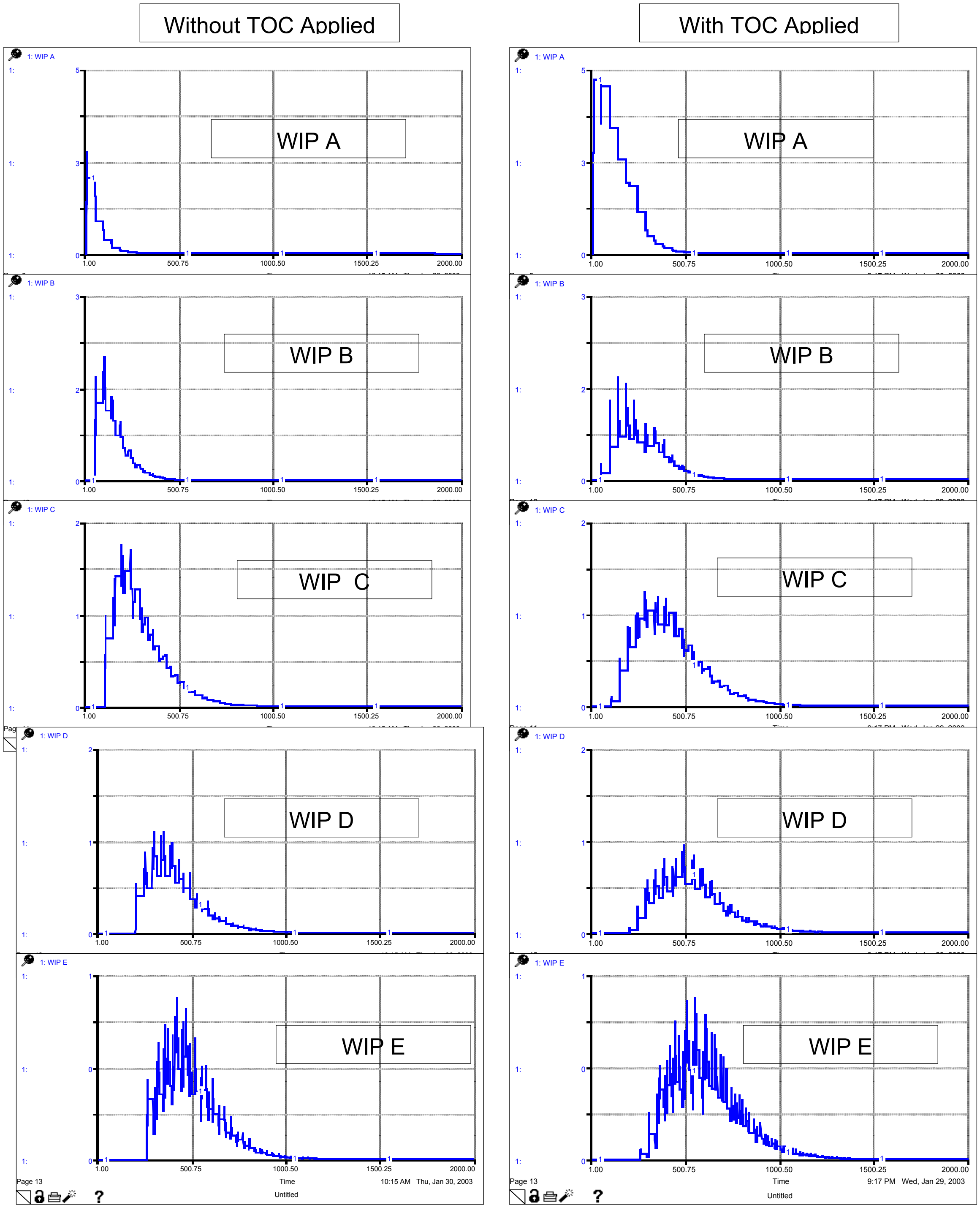


Figure 14, Effect TOC has on work-in-process inventories

Note the initial increase in WIP A in comparison of the two models. This is due to the extra WIP necessary to keep C from starving. Also, the initial order quantity in figure 12 is for 6, whereas, the finished goods quantity ends up at 5. This is showing where the extra WIP in A is coming from. However, WIP at B is somewhat lower and at C WIP is significantly lower in the TOC model than without TOC applied. Finally, WIP D and E are at about the same levels, but there is indication the process is more in control since the initial slopes are more gradual.

It is the conclusion of this study that TOC does improve throughput of a production system. These improvements come from overall reductions in work-in-process inventories and smother flow through the system.

CASE STUDY EXAMPLE: CASE COIL COMPANY

Next, a more complicated case study is presented to further illustrate the concept of Theory of Constraints and how System Dynamics can improve the process. This case study is that of a hypothetical company called Case Coil developed by John Tripp of TOC Scotland.[16] It is used to illustrate the various aspects of the Theory of Constraints. The traditional approach to analyzing this case study is to analyze the given data using the TOC process. However, the application System Dynamics can provide some valuable insights into the system constraints by providing feedback on testing of various alternatives that would otherwise take weeks, or months to accomplish using a real system.

The hypothetical Case Coil Company manufactures commodity copper coils by rolling copper billets into wide rolls, and slitting them into different widths to form coils. The copper coils are available in five thicknesses, five widths, and four hardness levels. There are seven processing steps for all products. All raw material is supplied by the smelter in billets weighing one and one half metric tons. Annealing softens the billets for the rolling process. A degrease operation is next. This is a two-stage process that uses an acid clean followed by a neutralizing rinse. Heat treat is the next process. This requires clean material or the process may result in problems. Next is metallurgical testing where both the gauge and hardness are tested. Typically, there is a 15% failure rate at this process. The next operation is slitting which cuts the original roll into various widths and trims the outside edges. Slitting has a 10% failure rate. Each coil is then packed, wrapped with vapor-retardant material and tagged for identification purposes. Finally, shipping allocates packaged coils to specific orders, palletizes, and ships the orders to waiting customers. Shipping also inventories the remaining coils.[17] Figure 15 is a breakdown of the throughput for each of these operations.

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CASE COIL THROUGHPUT

STEP NUMBER	DESCRIPTION/ACTIVITY	PROCESS TIME/Hr	SETUP TIME	LOAD TIME	parts/hr	QUEUE TIME / hrs	# OF MACH	Total hrs/Part w/Queue Time	# SHIFTS	Available mach hrs/wk.	Potential Parts/wk	COMMENT
10	DRAW FROM RAW MATL STORES	-	-	-								
20	ANNEAL TO SPECIFICATIONS	0.200			5.00	11.00	2	11.20	2	160	14.29	
30	ROLL	0.303			3.31	15.00	1	15.30	2	80	5.23	CCR
40	DEGREASE	0.640			1.56	15.00	3	15.64	2	240	15.35	
50	HEAT TREAT TO GAUGE SPECS	0.745	0.18	0.17	1.34	6.00	1	6.75	3	120	17.79	
60	METALLURGICAL TEST	1.447			0.69	2.00	6	3.45	2	480	139.26	
70	SLIT TO REQUIRED WIDTH	0.837			1.20	2.00	4	2.84	2	320	112.81	
80	PACKAGE AND STORE	0.078			12.77	2.00	5.5	2.08	2	440	211.71	

Figure 15, Case Coil Throughput Table

From this table, it can be seen that the rolling operation is the critically constrained resource (CCR) because its potential parts per week is only 5.23 compared to 14.29 for Anneal, 15.35 for Degrease, 17.79 for Heat Treat, 139.26 for Metallurgical Test, 112.81 for Slit to Required Width, and 211.71 parts per week for Package and Store. Using System Dynamics and the lessons learned in the Simple Production System a SD model was constructed to depict the throughput of Case Coil. Special conveyor stocks, called arrays, are used for multiple machine operations. The process time to produce one unit is used as the transverse time in each conveyor. Additional controls are added to this SD model to control failure rates, queue times, and possibly other parameters that can be manipulated to improve system performance.

In this example, controls have been added to control queue time and failure rates. Converters are added so queue time can be added and controlled between each operation. A queue time reduction converter is added to control the percent of queue time allowed to affect the system. For simplicity, only a simple percentage applied to all queue time converters is allowed. All of these features allow testing of various parameters to see what impacts and improvements can be made on the system. Time is measured in minutes in this model due to the large disparity between process times and queue time. In order to input the correct process times, minutes are required.

The layout of this model is shown in figure 16. Running the model establishes a base throughput time of 19,928 min., or 320.5 hrs to produce 20 units. Output from the model is shown graphically in figure 17. Tabular output is shown in figure 18.

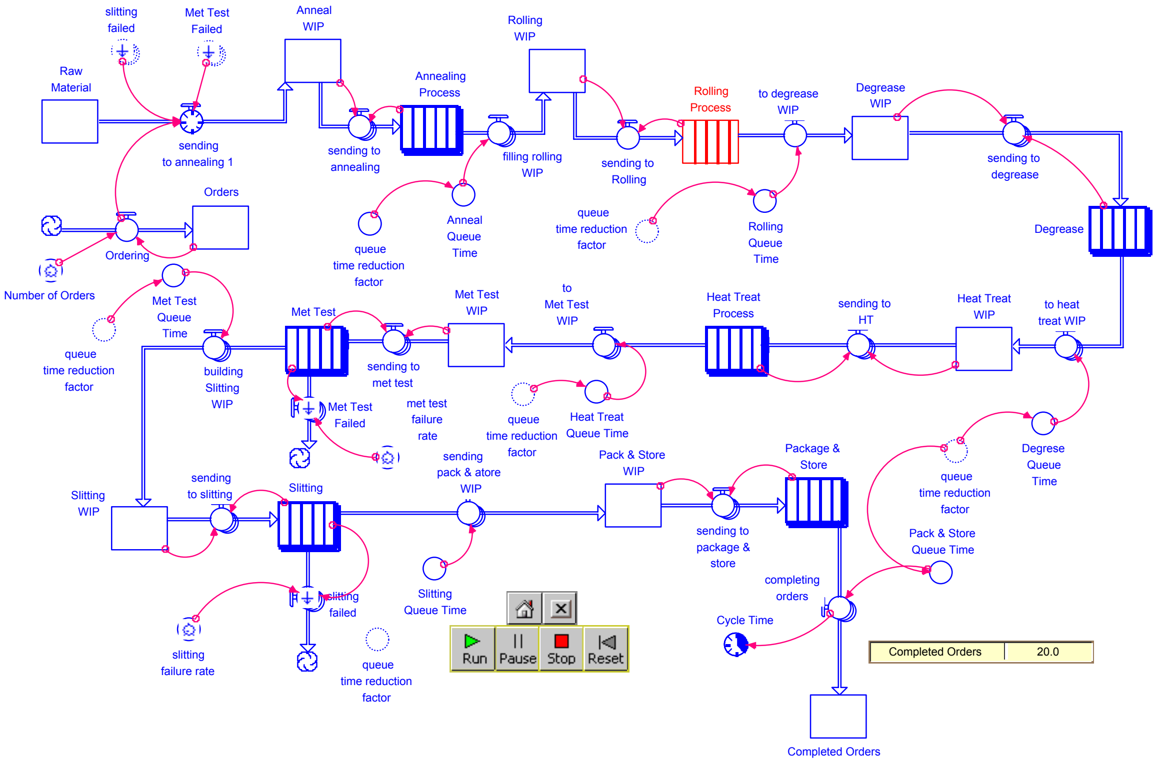


Figure 16, Stella model of Case Coil Company.

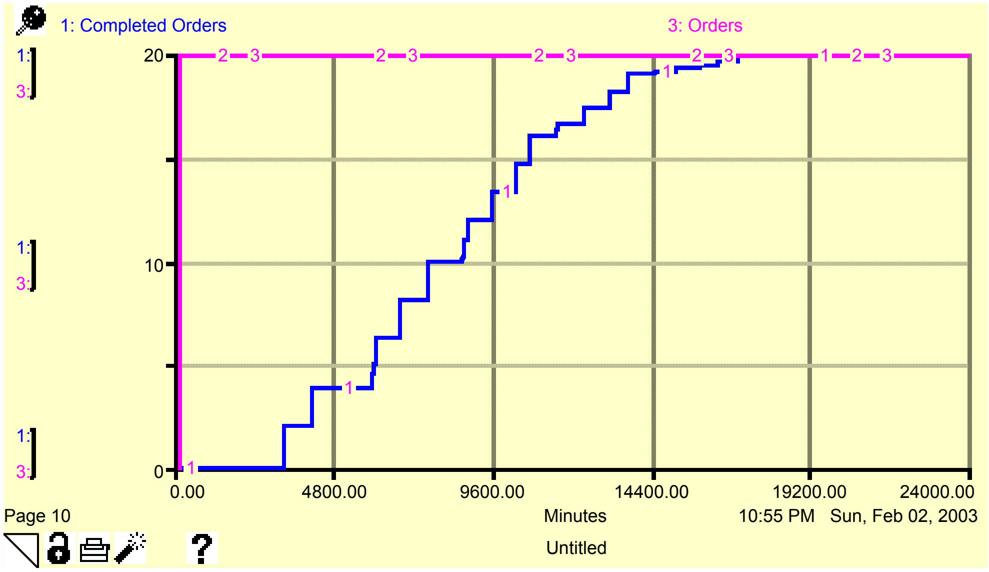
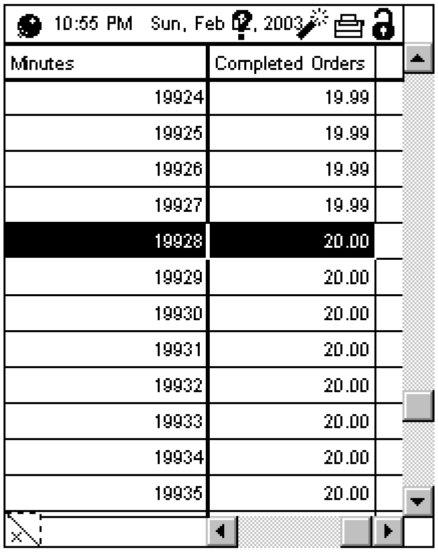


Figure 17, Model Output of Case Coil Company Baseline Case



Minutes	Completed Orders
19924	19.99
19925	19.99
19926	19.99
19927	19.99
19928	20.00
19929	20.00
19930	20.00
19931	20.00
19932	20.00
19933	20.00
19934	20.00
19935	20.00

Figure 18, Case Coil Base Case Partial Output – 19,928 min., or 332.1 hrs. for 20 units

Recalling the 5 TOC rules we start with the base case (figure 16), then, go to rule number 2 and focus on how to get more production within the existing capacity limitations. First a drum, buffer, rope is added to the system just as in the simpler example of a five step production system. This time the buffer is added between the Annealing operations and Rolling operation since Rolling is the critically constrained resource. The feedback to ordering and from rolling and sending to annealing to simulate the Rope in the DBR scenario is also added. Figure 19 shows the Stella model of this production system.

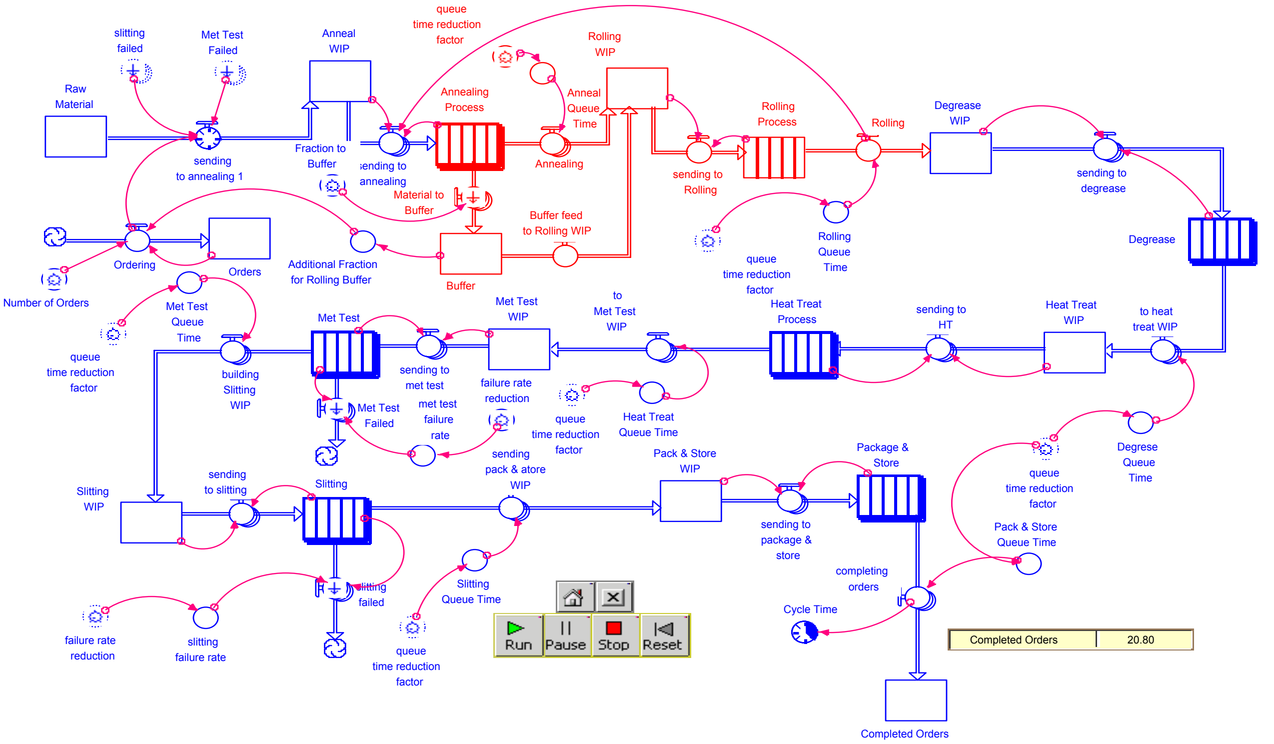


Figure 19, Case Coil – Stella Model with DBR Added

Running this revised model yields a throughput time of 17,699 min., or 295.0 hrs. This is an improvement of about 11% by simply adding the buffer and feedback loops. The amount of material sent to the buffer is set at 10%. This can also be varied to see what impact it has on the system. Output from this model is shown in figures 20 and 21. Note that the orders exceed the Number of Orders and Completed orders by 6 units. This is due to the feedback loop requesting additional material for the buffer.

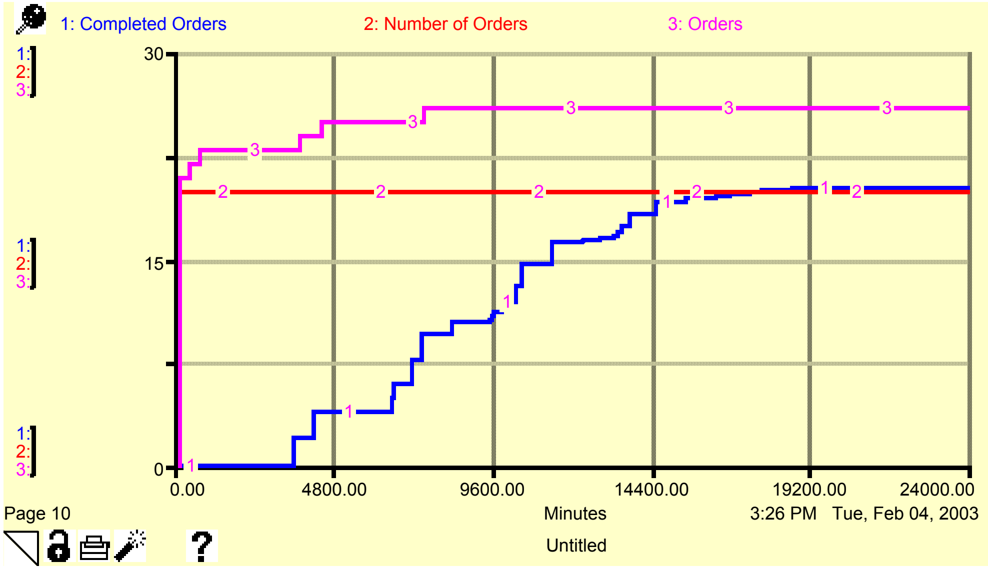
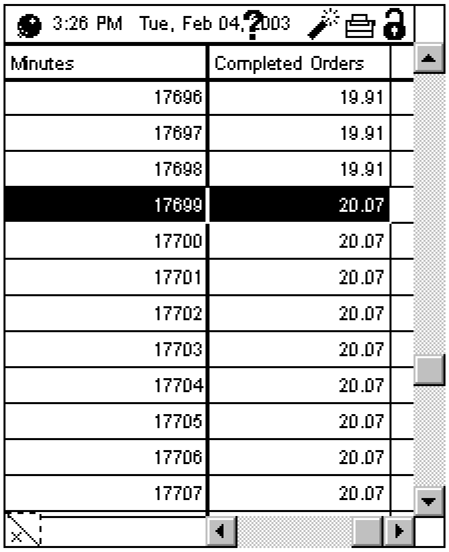


Figure 20, Case Coil DBR Graphical Output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Minutes	Completed Orders
17696	19.91
17697	19.91
17698	19.91
17699	20.07
17700	20.07
17701	20.07
17702	20.07
17703	20.07
17704	20.07
17705	20.07
17706	20.07
17707	20.07

Figure 21, Case Coil DBR Partial Tabular Output – 17,699 min., or 295.0 hrs. for 20 units

Next, the failure rates for metallurgical test and slitting were reduced by 50%. This yields a process time of 11,444 min., or 190.7 hours. This is an incremental improvement of 35% in cycle time to produce 20 units. Graphical and partial tabular output from this run of the model is shown in figures 22 and 23.

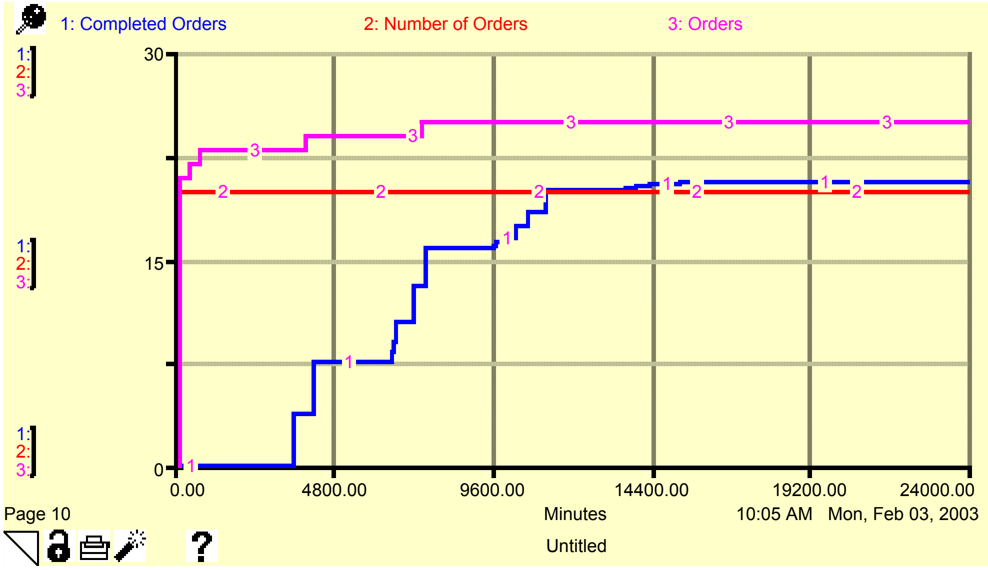
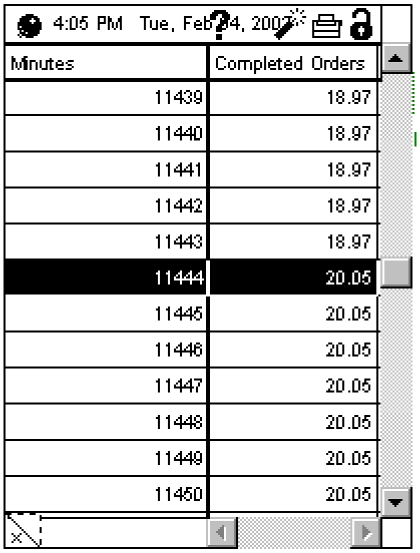


Figure 22, Reduce Failure Rate by 50% - 190.7 hours to produce 20 units



Minutes	Completed Orders
11439	18.97
11440	18.97
11441	18.97
11442	18.97
11443	18.97
11444	20.05
11445	20.05
11446	20.05
11447	20.05
11448	20.05
11449	20.05
11450	20.05

Figure 23, Tabular output, Reduce Failure Rate by 50% - 11,444 min., or 190.7 hours for 20 units

The next example looks at reducing the overall queue time in half. Note the failure rates were left at their original level of 15% at metallurgical test and 10% at slitting. This run yields an overall production time of 8,678 minutes, or 144.6 hours as shown in figure 24. This is a 35% reduction in cycle time.

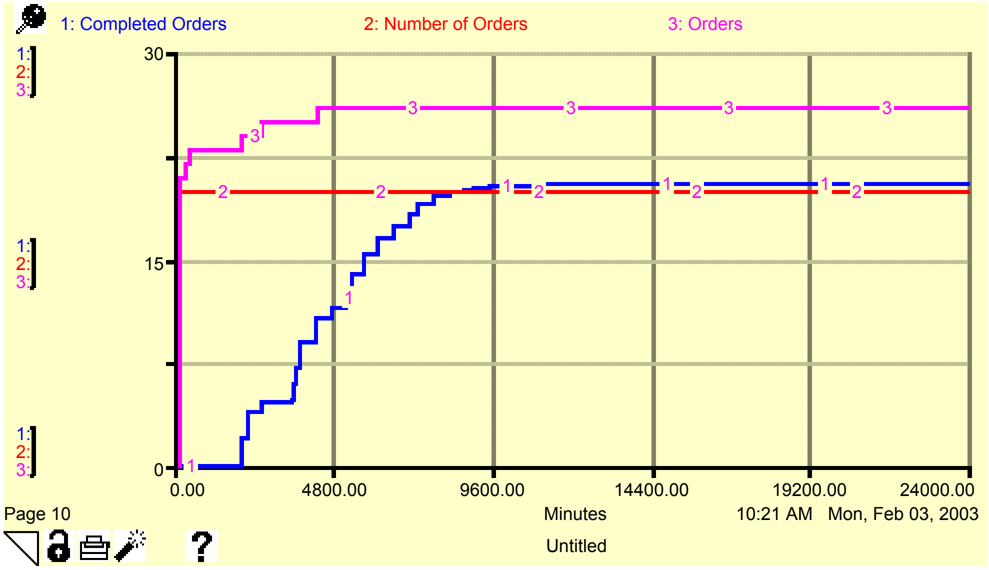
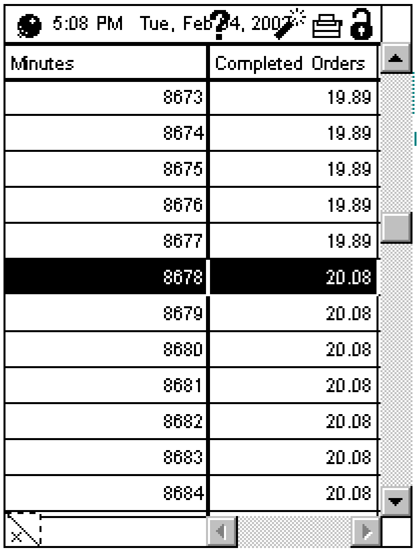


Figure 24, Reduce Queue Time by 50% - 8678 min., or, 144.6 hours to produce 20 units



Minutes	Completed Orders
8673	19.89
8674	19.89
8675	19.89
8676	19.89
8677	19.89
8678	20.08
8679	20.08
8680	20.08
8681	20.08
8682	20.08
8683	20.08
8684	20.08

Figure 25, Tabular Output Reduce Queue Time by 50% - 8678 min., or, 144.6 hours to produce 20 units

Next, reducing both failure rates and queue time by 50% resulted in 100.7 hrs to produce 20 units as shown in figures 26 and 27. This is an overall reduction of 43.5% in cycle time with the DBR in effect and an incremental improvement of 49%.

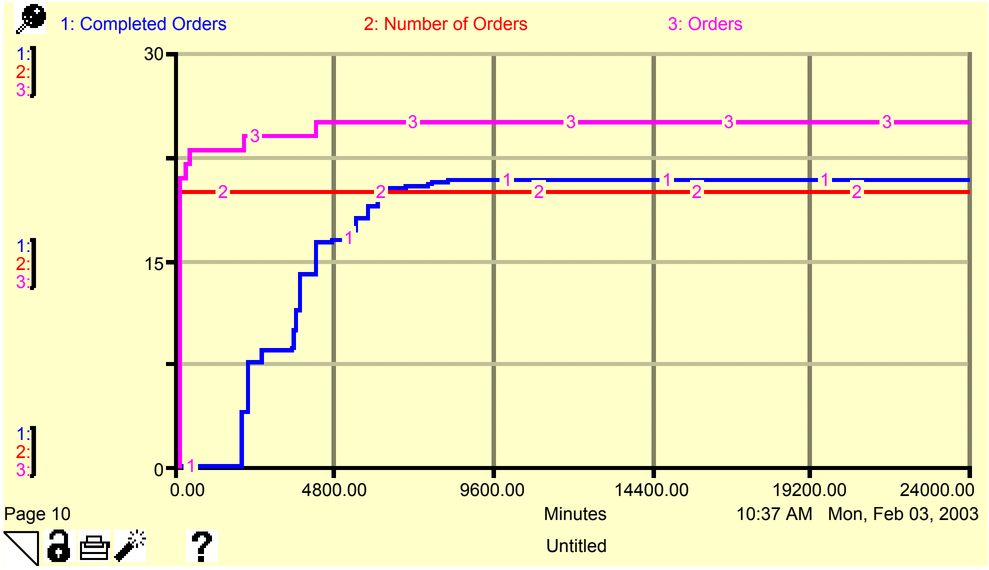
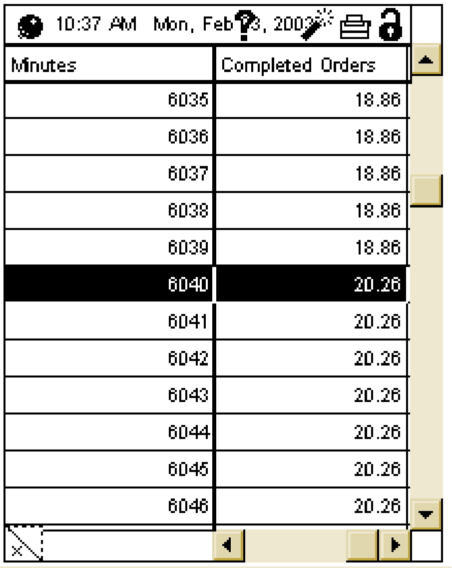


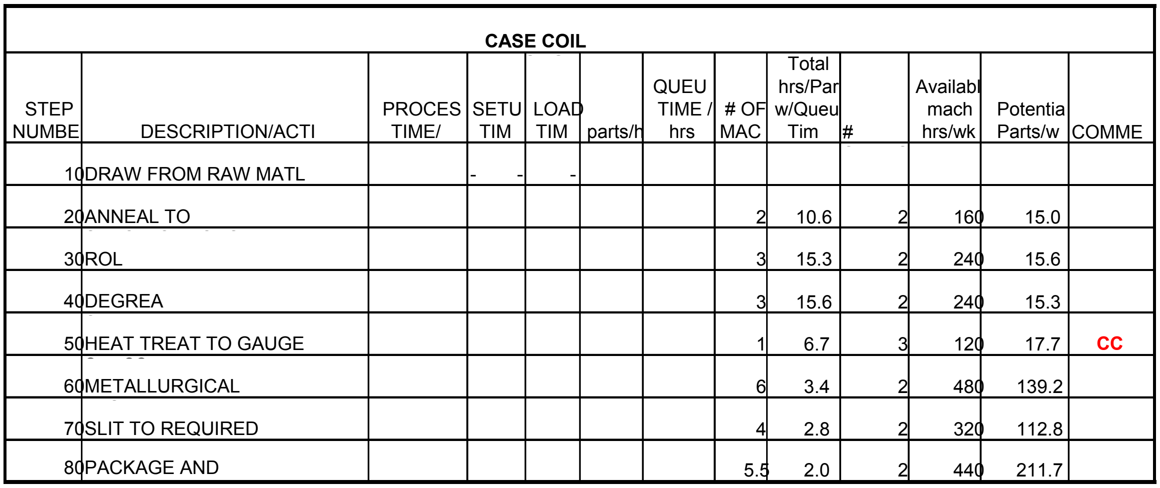
Figure 26, Case Coil - Reduce Queue Time and
Failure Rates by 50% - 6,040 min., or 100.7 hours to produce 20 units



Minutes	Completed Orders
6035	18.86
6036	18.86
6037	18.86
6038	18.86
6039	18.86
6040	20.26
6041	20.26
6042	20.26
6043	20.26
6044	20.26
6045	20.26
6046	20.26

Figure 27, Case Coil Tabular Output - Reduce Queue Time and
Failure Rates by ½ - 6,040 min., or 100.7 hours to produce 20 units

Now, let's assume that somehow Case Coil was able to obtain 2 additional rolling machines and somehow reduce anneal queue time by 5%. Leaving the failure rates and other queue times at their original values would eliminate the bottleneck at anneal by making the throughput 15.68 parts / wk. This moves the bottleneck to the heat treat process, so, a buffer is added between degrease and heat treat to control the rate material flows to the heat treat process. Also, feedback from the degrease process to sending to degrease is added to limit the demand for material at degrease to no more than the degrease WIP. Finally, feedback from the buffer to ordering through a converter called "added fraction to DBR buffer." Figure 28 shows the new values and Figure 29 the new Stella model for this situation. Running the model again we get the graph shown in figure 30.



CASE COIL												
STEP NUMBE	DESCRIPTION/ACTI	PROCES TIME/	SETU TIM	LOAD TIM	parts/h	QUEU TIME / hrs	# OF MAC	Total hrs/Par w/Queu Tim	#	Availabl mach hrs/wk	Potentia Parts/w	COMME
10	DRAW FROM RAW MATL		- -	-								
20	ANNEAL TO						2	10.6	2	160	15.0	
30	ROL						3	15.3	2	240	15.6	
40	DEGREA						3	15.6	2	240	15.3	
50	HEAT TREAT TO GAUGE						1	6.7	3	120	17.7	CC
60	METALLURGICAL						6	3.4	2	480	139.2	
70	SLIT TO REQUIRED						4	2.8	2	320	112.8	
80	PACKAGE AND						5.5	2.0	2	440	211.7	

Figure 28, Revised Case Coil Throughput Data

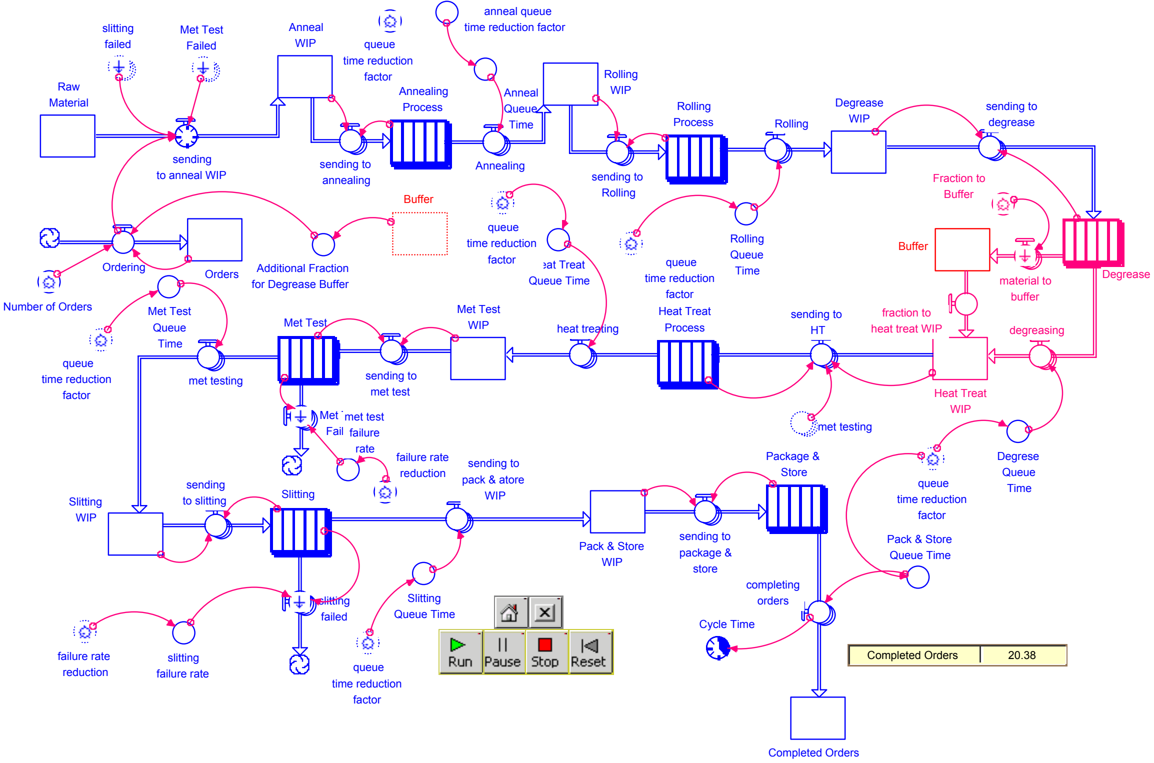


Figure 29, Stella Model for Revised Throughput Scenario

The results of these changes without changing failure rates or queue times makes a significant improvement in the overall throughput from the base case of 320.5 hours to 265.7 hours for 20 units as shown in figures 30 and 31.

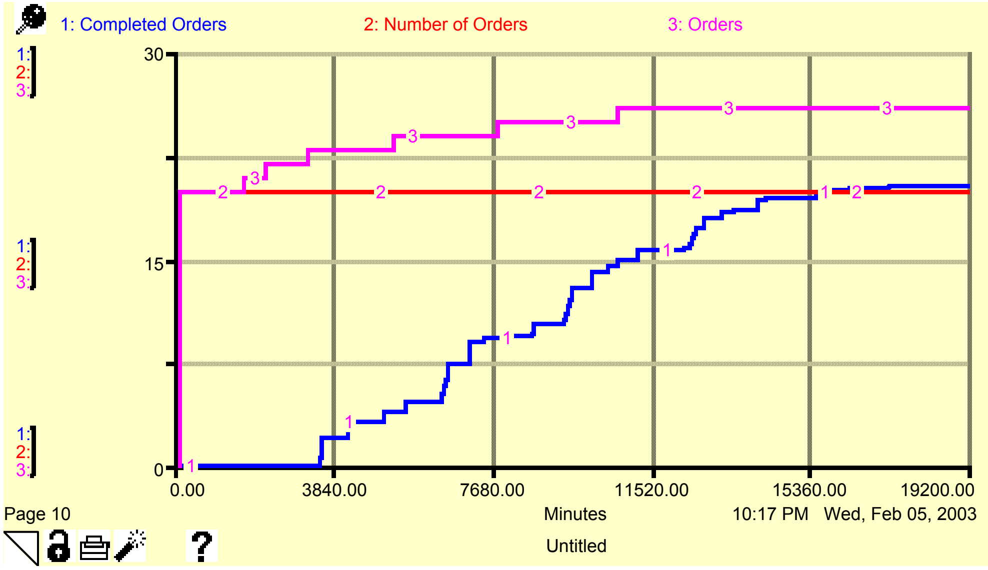
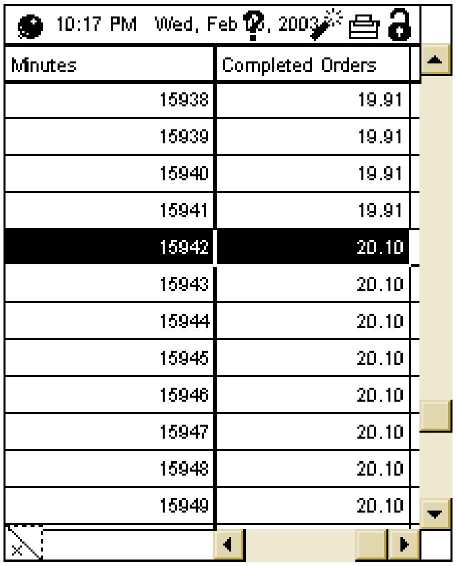


Figure 30, Added Machine Throughput Of 265.7 Hrs For 20 Units



Minutes	Completed Orders
15938	19.91
15939	19.91
15940	19.91
15941	19.91
15942	20.10
15943	20.10
15944	20.10
15945	20.10
15946	20.10
15947	20.10
15948	20.10
15949	20.10

Figure 31, Improved "Base Case" Tabular Output of Throughput of 15,942 min, or 265.7 hrs for 20 units

From these results it can be concluded that the Drum-Buffer-Rope concept of the Theory of Constraints does make significant improvements in system throughput. In addition, Stella modeling tools provide a powerful methodology to evaluate alternatives in system structure to assist in the decision process of selecting the best alternative.

DISCUSSION

The overall objective of this study was two fold: 1) use SD software to demonstrate how the TOC principles, in particular the Drum-Buffer-Rope concept can improve throughput of a production system; and 2) demonstrate how SD software, specifically Stella, can further enhance this process by adding the ability quickly evaluate various alternatives versus testing these alternatives on live production runs that may take weeks, or months. Following the 6 steps identified by Jay Forester for SD simulation, it was possible to show that the DBR concept of TOC is a valid approach to improving production throughput. The SD software made it possible to observe the effects of testing various hypotheses that were anticipated to improve performance, and arrive at a quantitative measure of the effects of these changes.

The modeling of a simple 5-step process was designed to demonstrate the effectiveness of the DBR concept. This test resulted in a 28% reduction in the cycle time for this system. Lessons learned in the construction of this model were then applied to the more complex model of the hypothetical Case Coil example. The first test of this model was to show again that the DBR concept also worked to improve throughput of this model. The base throughput time for the Case Coil system was 332.1 hrs for 20 units. Applying the DBR concept to the Critically Constrained Resources yielded a throughput time of 294.0 hrs, or an 11.5% reduction in cycle time. Next, overall failure rates in slitting and metallurgical test were reduced by 50%. This resulted in a cycle time of 190.7 hrs for 20 units, or an incremental decrease in cycle time of 63.8%. The next test was to reduce the overall queue time by 50%. This yielded another reduction of 46.1 minutes, to 144.6 hours.

Finally, following the TOC concept of exploiting the constrained process, an additional 2 rolling machines were added to the system and the anneal queue time was reduced by 5% moving the bottleneck to the Heat Treat process. Then, modifying the Stella model so that the DBR was at the degrease operation resulted in an overall cycle time of 265.7 hours. This was a 54.8-hour, or, 17% improvement in cycle time from the original base case of 320.5 hrs. From these results was concluded that the Drum-Buffer-Rope concept of the Theory of Constraints does make significant improvements in system throughput. In addition, Stella modeling tools provide a powerful methodology to evaluate alternatives in system structure to assist in the decision process of selecting the best alternative.

This project has demonstrated what it set out to accomplish. That is that by providing a way to model and simulate the system under study through System Dynamics and applying the rules of TOC to the model, alternative solutions to improve system operation can be quickly developed and analyzed. System Dynamics software further enhances this process by adding the ability quickly evaluate various alternatives versus testing these alternatives on live production runs that may otherwise take weeks, or months to perform. Had this been a real production situation, evaluation of these various alternatives would have taken several months to accomplish without the use of SD software. Whereas, a skilled Stella modeler who is familiar with the production system under study can construct a model that represents the production system in a day, or two and run various scenarios the third day. Actual model simulation times will vary with the CPU speed of the computer the simulation is run on.

Development of the various modeling scenarios for this study progressed at an average of approximately 10 hours per week over the period of 20 weeks for a total of 200 hours to develop and test the model scenarios. Significant research went into determining the correct application of conveyors, arrays, and other modeling elements during this time. The model was prepared on a 233 mHz Pentium computer using the Stella 7.0 software. In the course of this study it was discovered that the iThink Software, also by High Performance Systems, would have also worked and had more examples that were oriented toward the type of problem under study. I was able to obtain a trial copy of iThink and convert these examples to work on Stella. Student price for both software packages is about $130.00. Proof of student status is required when ordering the student software. The professional price is about $1,100.00. There are software packages for either Windows, or Macintosh computer platforms. Actual runtime on the 233 mHz Pentium computer was about 15 minutes for the complete Stella model with the DBR added.

From a software features perspective, the iThink and Stella programs are virtually identical. Each is designed to facilitate the mapping, modeling and simulating of dynamic processes. The major difference between the two products is in the supporting documentation. The iThink software is targeted at business users. Applications and sample models cover the gamut of business uses including Business Process Re-engineering, Strategic Planning, Financial Analysis, Manufacturing, Balanced Scorecard, Systems Thinking, and Organizational Learning. [18]

Stella, on the other hand, is targeted at educators and researchers. Its documentation and sample models span the curriculum from Literature to Physics, Mathematics to History, and pretty much everything in between. iThink is the best choice for working with business-oriented issues. Stella is the best match for an educational or scientific research setting. However, Stella models can be opened using iThink, and vice versa. [19]

CONCLUSION

The major conclusions that can be drawn from this analysis are that System Dynamics modeling enables application of the Theory of Constraints DBR process and exploration of alternative means of managing system constraints. This study demonstrates that while the TOC Thinking Process represents a well-structured approach to understanding how to deal with constraints in a production system, Systems Dynamics modeling provides a supplemental understanding relative to knowledge gained through the TOC Thinking Process. In addition, System Dynamics and the use of SD software can be a valuable tool in communicating with management and workers the concept of TOC and how constraints affect the system they are dealing with.

An inherent shortcoming in using the TOC Thinking Process is that it lacks the robust capability to fully capture the dynamic complexity of even a simple production system.[20] System Dynamics can overcome this shortcoming by adding the capability of experimenting with the dynamic complexity of these systems through modeling. SD modeling is also based on a way of thinking about systems from a global perspective. A primary application of TOC embodies a system thinking approach to manufacturing systems. By knowing how to think from a systems perspective, we can better understand these systems. Through better understanding, we can improve the performance of the system. Testing of TOC alternatives using System Dynamics software also provides a valuable tool to understand how system performance can be improved.

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