Production Planning and Control in Flow Shop Operations using Drum Buffer Rope Methodology: A System Dynamics Approach

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This paper aims to introduce System Dynamics (SD) in applying Drum Buffer Rope (DBR) methodology of Theory of Constraints (TOC) in a three-stage flow shop system that produces a single product. To the best of our knowledge, although there are a lot of TOC applications using discrete simulation in production scheduling with DBR methodology, there are not any TOC application of DBR methodology in production scheduling using System Dynamics.

We firstly present a conceptual model of the production planning and control and raw material procurement processes of a flow shop, based on the concept of the Capacity Constraint Resource (CCR), which is the corner stone of the TOC philosophy. Then, we present the stock and flow diagram of the system under study. According to the results of an illustrative example, it reveals that the driving force of the production and raw materials procurement processes of the flow shop is its CCR schedule. The system response to pulse and wavy changes in demand is examined as well. Moreover, by means of the simulation results, the efficiency of DBR production scheduling approach is contrasted with the well known anchoring and adjustment approach of Sterman.

Keywords: Theory of Constraints; Capacity Constraint Resource; Drum Buffer Rope; Real Time methodology; Flow shop; Production process; Raw materials procurement process; System Dynamics.

1 Introduction

Theory of Constraints (TOC) was first developed by Eli Goldratt in the mid-1980s. In 1984 Goldratt and Cox published their novel titled “The Goal” (Goldratt and Cox, 1984). In this novel the hero is a plant manager, who managed to overcome the threat of imminent closure of his factory transforming the firm to economically healthy. The book resulted in various implementations of the concepts presented and the wide development of the TOC all over the world. According to Goldratt, TOC is an overall theory for running an organization. The corner stone of this theory is the performance of the constraint of the system. A key definition of constraint stated by Goldratt is: *“Constraints is anything that limits a system from achieving higher performance versus its goal”*. Although at that time the term constraint was synonymous with the term bottleneck, during 1985 the distinction between a bottleneck and a Capacity Constraint

Resource (CCR) became clear defining that CCR can be a non-bottleneck constraint which, on the average, has excess capacity (Goldratt, 1988).

In 1985 the time buffer concept was developed and its proper use gave the schedule a surprising immunity against disruptions. The Drum-Buffer-Rope (DBR) approach was formulated and explained in the book The Race (Goldratt and Fox, 1986). Time buffer usage leaded to the formulation of Buffer Management. Tracking the time buffer leads to the process improvements (Goldratt, 1988).

Applying TOC principles in process improvements, it was realized that this process is characterized by a continuous improvement approach. Moreover, it was realized that besides the resource and material constraints, there are also managerial/policy constraints like batch sizing rules, resource utilization guidelines and setup rules. In 1994 Goldratt developed a generic approach named Thinking Process (TP) for investigating, analyzing and solving complex problems created by policy constraints.

Nowadays TOC has two major components. The first component is a philosophy which consists of the five focusing steps of *on-going improvement*, the *DBR scheduling methodology* and the *buffer management information system*. The second component of TOC is the *TP approach*. In addition, TOC prescribes new *performance measurements* which are quite different from those of the traditional cost-accounting system.

The steps of performing the TOC process of *on-going improvement* in a system are:

1. Identify the system constraint(s).

2. Decide how to exploit the system constraint(s).

3. Subordinate everything else to the above decision.

4. Elevate the system constraint(s).

5. If, in the previous steps, the constraint(s) have been broken, go back to step 1, but don't let inertia become the system constraint.

To make sure that the critical resources do not stop working, TOC introduced the use of time-buffers before them. The magnitude of them is determined in terms of time and their main purpose is to prevent the system from stopping because of statistical fluctuations.

The *DBR scheduling methodology* is managed through the use of time buffers. The drum is the system schedule or the pace at which the constraint works. Rope provides communication between critical control points to ensure their synchronization. Buffer is strategically placed inventory to protect the system's output from the variations that occur in the system. The DBR methodology synchronizes resources and material utilization in an organization. Time buffers contain inventory and protect constraint schedule from the effects of disruptions at non-constraint resources. The use of time buffers as an information system to effectively manage and improve throughput is refereed as *buffer management*. It provides information based on planned and actual performance and is used for monitoring the inventory in front of a protected resource (Schragenheim and Ronen, 1990).

The TOC *performance measurements* are operational and financial. The operational measures are the following:

1. Throughput (T), which is the rate at which an organization generates revenue through sales. If the system produces something which has not been sold, it is not considered throughput.

2. Inventory (I) is defined as the investment of the system in purchasing things that it intends to sell. Thus, this definition excludes the added value of labor and overhead for work in process.

3. Operating Expense (OE) is the expenditure of the system in order to turn inventory into throughput (Ronen and Starr, 1990).

The financial measures used in TOC are the following:

1. Net profit (NP), which equals T minus OE.

2. Return on Investment (ROI), which equals NP divided by I.

3. Cash flow (CF), which is an “on-off” type measurement, that represents whether the system has enough cash to survive (Rahman, 1998).

To the best of our knowledge, although there are a lot of TOC applications using discrete simulation in production scheduling with DBR methodology, there are not any TOC application of DBR methodology in production scheduling using System Dynamics (SD). Thus, this is the first attempt to simulate a production system combining the concepts of DBR methodology of TOC with SD methodology.

The rest of the paper is organized as follows. The section 2 presents the literature review of applying the TOC principles of DBR scheduling methodology and the respective performance measures in manufacturing systems. The section 3 refers to the developed SD model; the conceptual model and its stock-flow diagram. The section 4 presents an illustrative example and experimentation of the developed model and the section 5 refers to the system’s response to demand changes. The section 6 presents an experimentation of the developed model adopting the anchoring and adjustment approach for its production and materials procurement processes. The efficiency of the two approaches presented in sections 5 and 6 is compared in section 7. Finally, in section 8 we wrap-up with the conclusions and directions for future research.

2 Literature Review

A vast majority of articles focus on the DBR methodology. Schragenheim and Ronen provide a detailed description of the working principle of DBR logistic system and the use of time-buffers for uninterrupted scheduling (Schragenheim and Ronen, 1990, Schragenheim and Ronen, 1991). Other articles present the application of DBR in various production environments (Mahapatra and Sahu, 2006, Schragenheim *et al.*, 1994, Russel and Fry, 1997, Lambrecht and Segaert, 1990). Besides, other articles describe actual applications of DBR in manufacturing firms (Pegels and Watrous, 2005, Riezebos *et al.*, 2003, Umble *et al*, 2001, Chaudhari and Mukhopadhyay, 2003, Guide and Ghishelli, 1995, Duclos and Spencer, 1995, Guide, 1996).

More over some articles present the use of various TOC performance measures in shop floor production systems as a means for process improvement (Russell and Fry, 1997). Other articles describe real world applications of TOC performance measures in manufacturing firms (Satish *et al.,* 2005, Chaudhari and Mukhopadhyay, 2003). Various articles compare the application of DBR system with the traditional systems like JIT and MRP systems in production environments by using various performance measures (Ronen and Starr, 1990, Cook, 1994, Duclos and Spencer, 1995). Mabin and Balderstone discussed 81 successful TOC applications (Mabin and Balderstone, 2003), while Satish *et al.* presented simulation-based comparison of TOC and traditional accounting performance measures in industry (Satish *et al.,* 2005).

3 SD model

3.1 Conceptual Model

The conceptual model presented in this article applies the DBR methodology of TOC in a make to order, three operations flow shop. The production system produces a single product, purchases one type of raw material on specific order quantities and it has in the second operation a capacity constraint resource (CCR).

The generic causal loop diagram of the model is shown in figure 1. Level variables are shown in capitals. Since the CCR is the resource that constraints the performance of the system, its schedule is the driving force for the production planning which has to be made by ignoring the capacity of all the non-constraint resources. Thus, the required duration to produce the demand at the shop's CCR operation up to its end operation (*Required Production Duration CCR Downwards*) is firstly calculated.

By subtracting *Required Production Duration CCR Downwards* and *Min Planned Production Time Buffer* from the *Planned Lead Time* of the demand, which is the duration of time the order has to wait for its fulfillment, the planned time available for the production of the demand at the production stages of the shop before the CCR one (*Planned CCR Production Start Time*) is calculated. Thus, the CCR production plan is set by means of a pipeline delay. The input to this delay is *Demand*, its duration is set equal to *Planned CCR Production Start Time* and its output is the *Planned CCR Production Rate*. The *Planned CCR Production Rate* increases the *CCR Production Backlog* which is depleted by *CCR Production Rate*. Besides, *CCR Production Rate* is limited by *CCR Production Backlog*, the capacity of the CCR operation (*CCR Capacity*) and the work in process inventory in stage 1 (*WIP1*).

Three loops (loop 1, loop 2 and loop 3) control the *Production Rate 1*. Specifically, *Production Rate Rope* is the pipeline delay of *CCR Production Rate*. *Production Rate Rope* is the rope of the DBR logic for the production process. We set this rope by using the Real Time methodology for the order production scheduling (Russell and Fry, 1997); i.e. materials are released into the gateway operation of the shop at the rate at which they are processed by the CCR operation. *Production Rate 1* is limited by *Production Rate Rope*, *Capacity 1* and *Material on Hand* whereas the current production time buffer (*Production Time Buffer*) is higher than its minimum required value (*Min Planned Production Time Buffer*). In case that *Production Time Buffer* is less than *Min Planned Production Time Buffer*, the *Production Rate 1* is equal to *Capacity 1* considering the availability of *Material on Hand*. *Production Rate 1* increases *WIP1*, which is depleted by *CCR Production Rate*. Loop 2 is similar to loop 1 and controls the *Production Rate 1* and the *Material on Hand* and the material inventory that has been ordered and not yet delivered (*Material in Transit*). *Material Order Rope* is the pipeline delay of *CCR Production Rate*. *Material Order Rope* is the rope of the

DBR logic for the raw material procurement process. We set this rope by using the Real Time methodology; i.e. the material inventory is monitored for order at the rate at which the products are processed by the CCR operation of the shop. According to loop 3, when *Production Time Buffer* is lower than its respective minimum value (*Min Planned Production Time Buffer*), the *Production Rate 1* gets higher value than the *CCR Production Rate* which is set by means of the *Production Rate Rope*.

The raw material procurement process is controlled by three loops (loop 2, loop 4 and loop 5). Specifically, in case *Material Order Rope* is positive, *Material Order* is limited by *Material Order Quantity* whereas the current material time buffer (*Material Time Buffer*) is less than its minimum required value (*Min Planned Material Time Buffer*). Whenever *Material Time Buffer* is higher than *Min Planned Material Time Buffer, Material Order* is equal to zero. Note that *Material Time Buffer* is the sum of *Material on Hand* and *Material in Transit* expressed in time units of the shop's CCR operation. *Material Order* increases *Material in Transit*, which is depleted by *Material In Transit Decrease*. Besides, *Material In Transit Decrease,* which is equal to *Material Procurement Rate,* increases *Material on Hand,* which is depleted by *Material Usage Rate*.

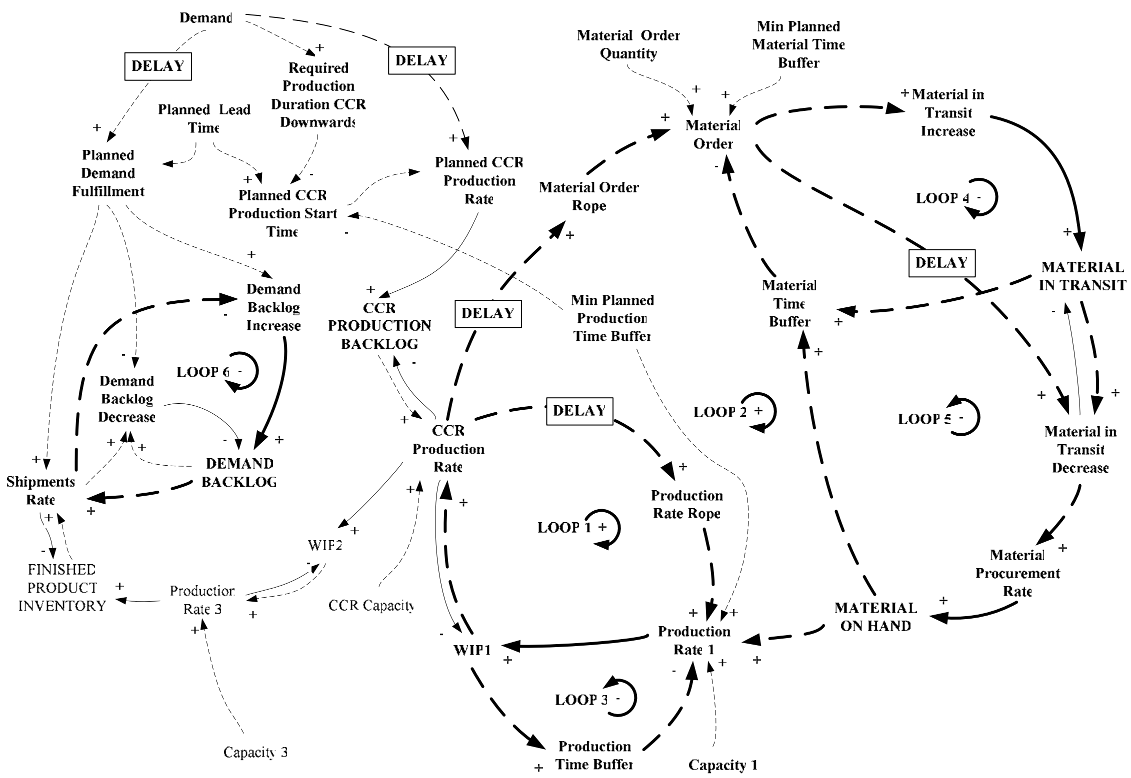


Figure 1: Generic causal loop diagram of the developed model

Planned Demand Fulfillment is the pipeline delay of *Demand*. The demand fulfillment process is controlled by loop 6. Specifically, *Demand Backlog Increase* increases *Demand Backlog*, which is depleted by *Demand Backlog Decrease.* In case *Shipments Rate* of the product is less than *Planned Demand Fulfillment, Demand Backlog Increase* gets a positive value. Otherwise, *Demand Backlog Decrease* gets a positive value and delayed fulfillment of the demand takes place.

3.2 Stock and flow diagram

The stock and flow diagram of the developed model is shown in figure 2 and it includes the following 7 stock variables:

- CCR_PROD_BACKLOG: *CCR Production Backlog*.

- DEM_BACKLOG: *Demand Backlog.*

- MATERIAL: *Material Inventory on Hand*.

- MATERIAL IN TRANSIT: This is *Material in Transit*.

- WIP_1: Work in process inventory of operation 1 (*WIP1*).

- WIP_2: Work in process inventory of operation 2 (*WIP2*).

- F_PR_INV: Inventory in finished products (*Finished Product Inventory*).

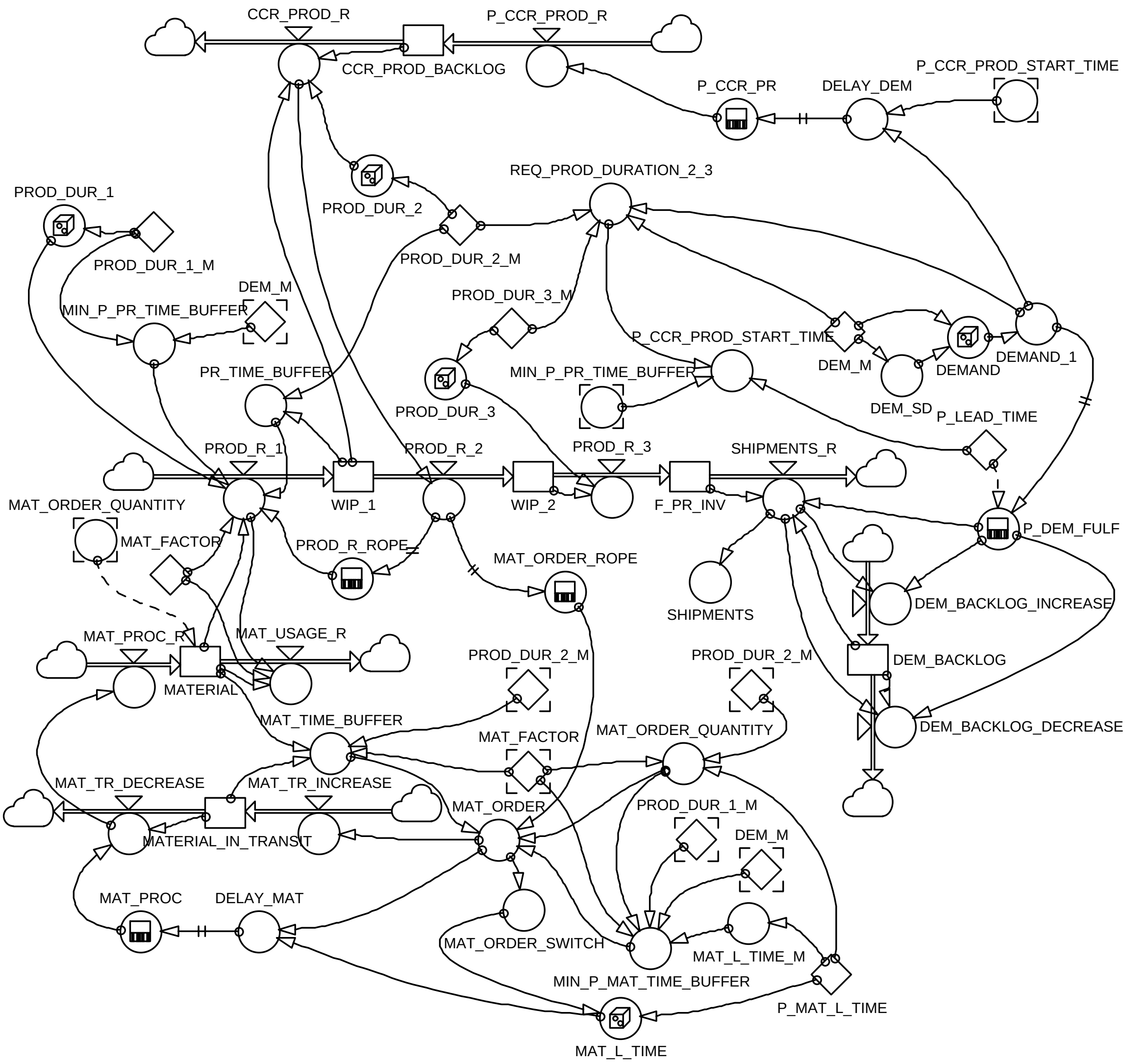


Figure 2: Stock and flow diagram of the developed model

The number of items produced in the production stages of the shop are Poisson distributed. Thus, the respective production durations are exponential distributed. Note that for the production planning process the durations of the shop's operations are equals to their mean values. However, throughout the simulation of the actual production process they are exponential distributed.

Besides, for the raw material procurement scheduling process, the material delivery lead time is equal to its mean value. However, throughout the simulation of the actual procurement process, this duration is uniformly distributed resulting in a highly fluctuation material procurement process.

4 Illustrative example and experimentation

We consider a numerical example concerning a single product flow shop with 3 operations. Each operation of the flow shop is considered as a queueing model M/M/1, in which the number of arrivals in an interval is Poisson distributed with mean equal to λ (which is the mean of the normally distributed *Demand*), the production duration follows an exponential distribution with parameter μ_i (where $1/\mu_i$ stands for the mean duration of the operation i) and λ is less than μ_i. Thus, the production line of the flow shop is considered as a series of 3 queueing models M/M/1 (one model for each operation of the shop). The mean duration of each of the two non-CCR operations (i.e. operations 1 and 3) is set equal to 0.0625 days/item. The mean duration of the CCR operation (operation 2) is set equal to 0.125 days/item. The *Demand* of the product follows a normal distribution with mean equal to 7.5 items/day and standard deviation equal to the ¼ of its mean value.

The *Required Production Duration CCR Downwards* is calculated by means of average time values as shown in equation 1. Considering that the duration of operation 2 and the total time of waiting before operation 3 and production at operation 3 follow exponential distributions with known means and standard deviations (Hillier and Lieberman, 1995), this mean duration is calculated as the sum of the two mean time values times the current demand value.

$$\mathrm{RPD} = \left(\frac{1}{\mu_2} + \frac{1}{\mu_3 - \lambda_3}\right) \cdot \mathrm{D} \qquad \text{(eq. 1)}$$

where,

RPD: Required Production Duration from the CCR up to the end operation of the shop (days)

$\frac{1}{\mu_i}$: Mean of the production duration of the operation i, that is exponential distributed (days/item)

$\frac{1}{\mu_3 - \lambda_3}$: Mean of the waiting time before operation 3 and production duration at the operation 3, that is exponential distributed (days/item)

λ_3: Mean of arrivals before the operation 3, that is Poisson distributed (item/day)

D: Demand (items)

Besides, the *Minimum Planned Production Time Buffer* is set equal to 3 times the average lead time to the CCR according to the common practice (Schragenheim, Ronen, 1990). Thus, it is set equal to 3 times the mean value of production duration before the CCR operation (i.e. for operation 1) for the mean value of *Demand* during one timestep of the model. The *Production Time Buffer* is expressed in time units of the CCR operation of the shop. The *Planned Lead Time*, which is the demand due date, is 10 days. For the production of 1 item of the product, 2 kg of raw material are required. The duration of the delay used for the *Production Rate Rope* is set equal to 4 timesteps.

The material delivery lead time is 3 days and its actual value follows a random distribution between the values 3 and 6. *Material Order Quantity* is set equal to 3 times the material required to fulfill the average material demand of the CCR operation during the material delivery lead time. Therefore, it is set equal to 144 kg (i.e. 3*2(kg/item)*8 (items/day)*3(days)). The *Minimum Planned Material Time Buffer* (similarly to the *Minimum Planned Production Time Buffer*) is set equal to 3 times the mean value of duration before the CCR operation (i.e. for procurement of raw material and for production at operation 1) for the mean value of *Demand* during one timestep of the model (Schragenheim, Ronen, 1990). Note that the number of materials orders necessary to cover the respective material quantity is set equal to the smallest integer greater than or equal to its original estimated value. The *Material Time Buffer* is expressed in time units of the shop's CCR operation. The duration of the delay used for the *Material Order Rope* is set equal to 4 timesteps.

The initial values of all the levels are zero, except the initial value of *Material Inventory* which is set equal to 2 times the *Material Order Quantity*; i.e. 288 kg. The model developed in simulation software Powersim® 2.5c. The time unit used is 1 day, the timestep used is 0.25 days and the duration of simulation runs is 3,000 days.

In figure 3 we show the time evolution of the work in process and finished product inventories. The inventory before the CCR operation of the shop (WIP_1), although fluctuates, is usually higher than its minimum planned value (that is roughly 0.35 days or 5.65 items) following the DBR methodology. Thus, it is not constraining the CCR production rate. Besides, the inventory level of the CCR operation (WIP_2) is kept low, meaning that the following operation does not constraint the operation of the shop. Thus, the finished product inventory is kept constantly high.

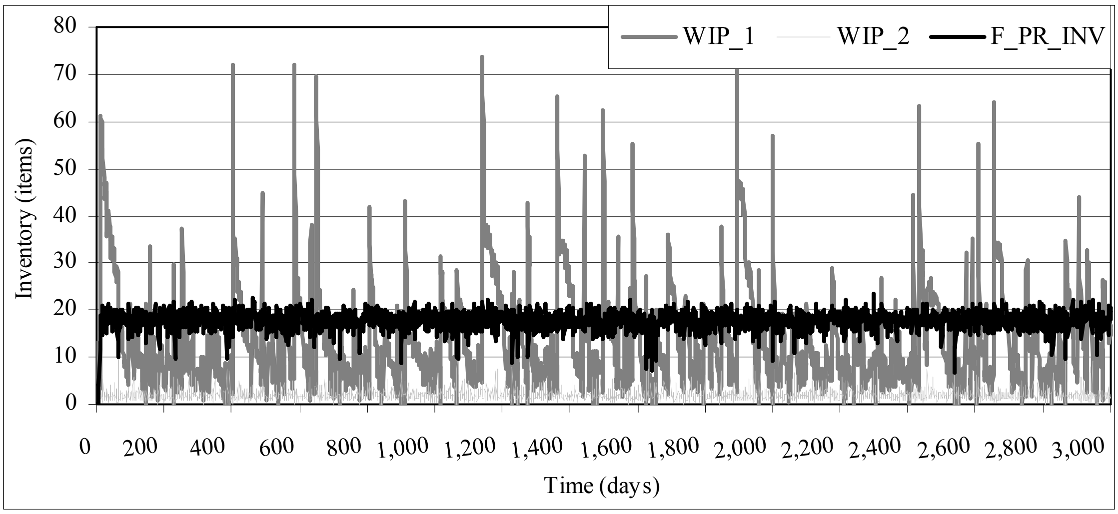


Figure 3: Work in process and finished product inventories

As it is shown in table 1, the planned demand fulfillment and the shipments have the same average value of 7.466 items/day. Besides, the equality of the planned demand fulfillment and the shipments values results in zero demand backlog and divergence throughout the simulation and therefore the average values of the demand backlog and the divergence are zero as it is shown in table 1. Besides, the average value of raw material inventory is 71.292 kg, of WIP_1 is 13.580 items, of WIP_2 is 2.026 items and of finished product inventory is 17.792 items.

Table 1: Average values of the performance measures of the simulation results

Performance measure	Average value (units)
Demand Backlog	0
Planned Demand Fulfillment	7.466 (items/day)
Shipments	7.466 (items/day)
Divergence	0
Raw Material Inventory	71.292 (kg)
WIP_1	13.580 (items)
WIP_2	2.026 (items)
Finished Product Inventory	17.792 (items)

5 System's response to demand changes

Firstly, we tested the structural validity of the model starting from its dimensional consistency. Then we conducted extreme-condition tests checking whether the model behaves realistically even under extreme policies.

In the following subsections we present the response of developed system to changes in demand when using the DBR scheduling approach. Specifically, we investigate the response of CCR production rate to pulse and wavy changes in demand.

5.1 Pulse change in demand

As it is shown in figure 4, in case of the normally distributed demand with mean equal to 7.5 items/day, the CCR production rate is normally distributed in a respective way. However, as it is depicted in figure 5, in the case of an additional pulse demand with magnitude of 1,000 items/day, appearing on the 400th day, the CCR production rate at the days following the pulse demand gets its maximum possible value (which fluctuates due to the variability of the respective production duration) in order to satisfy the increased demand.

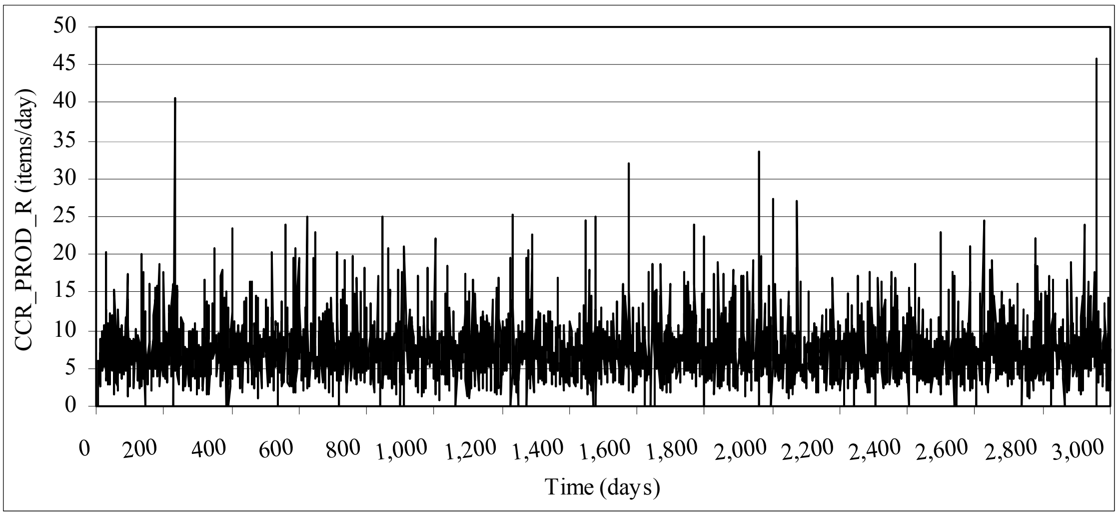


Figure 4: CCR production rate in the case of the normally distributed demand

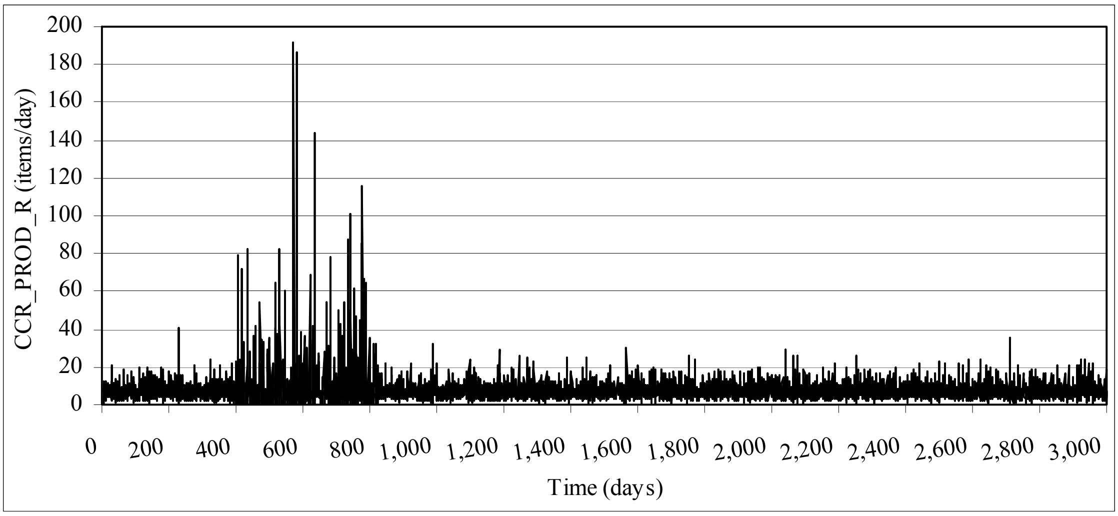


Figure 5: CCR production rate in the case of the normally distributed with the additional pulse demand

5.2 Wavy change in demand

We consider a wavy (sinusoidal) change in demand with mean 7.5 items/day, amplitude of 1.5 items/day and period of 500 days. The response of the CCR production rate is depicted in figure 6, showing the same wavy change with that of demand.

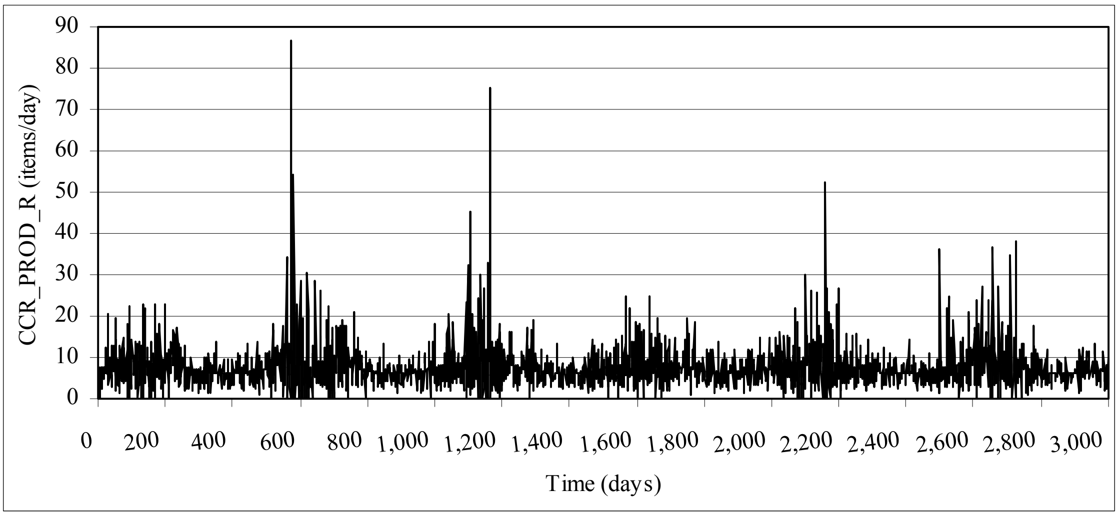


Figure 6: CCR production rate in the case of the wavy demand

6 Anchoring and adjustment approach - Stock and flow diagram and experimentation

To estimate the efficiency of the developed approach, we contrast it with the well-known anchoring and adjustment (AA) approach (Sterman, 2000, Disney *et al.,* 2003). The stock and flow diagram of the developed model adopting the AA approach is shown in figure 7. It includes the following 6 stock variables:

- DEM_BACKLOG: *Demand Backlog.*

- MATERIAL: *Material Inventory on Hand*.

- MATERIAL IN TRANSIT: This is *Material in Transit*.

- WIP_1: Work in process inventory of operation 1 (*WIP1*).

- WIP_2: Work in process inventory of operation 2 (*WIP2*).

- F_PR_INV: Inventory in finished products (*Finished Product Inventory*).

Using the same parameter settings as described in section 4, the *Desired Production Rate* (DESIRED_PROD_R) is calculated as a sum of the *Expected Demand* plus the discrepancies of the *Finished Product Inventory*, the *WIP1* and *WIP2* divided by the respective adjustment times (Disney *et al.,* 2003). The *Expected Demand* is a first-order information delay of *Demand* with average delay time *T*. The estimation of delay time *T* corresponds to the least Mean Squared Error (MSE) calculated in a series of tests performed for various values of delay time.

The values of the parameters *T1*, *T2* and *T_MAT_INV* that are used to calculate the desired values of *WIP1*, *WIP2* and *Material* respectively and the values of the four adjustment times for the adjustment of *WIP1* (WIP_1_AD_TIME), *WIP2* (WIP_2_AD_TIME), *Finished Product Inventory* (F_PR_INV_AD_TIME) and *Material* and *Material in Transit* (MAT_INV_AD_TIME) respectively are estimated through the analysis of the simulation results of various combinations of them. The result of this analysis is the selection of two scenarios presented in table 2 for the values of the respective parameters.

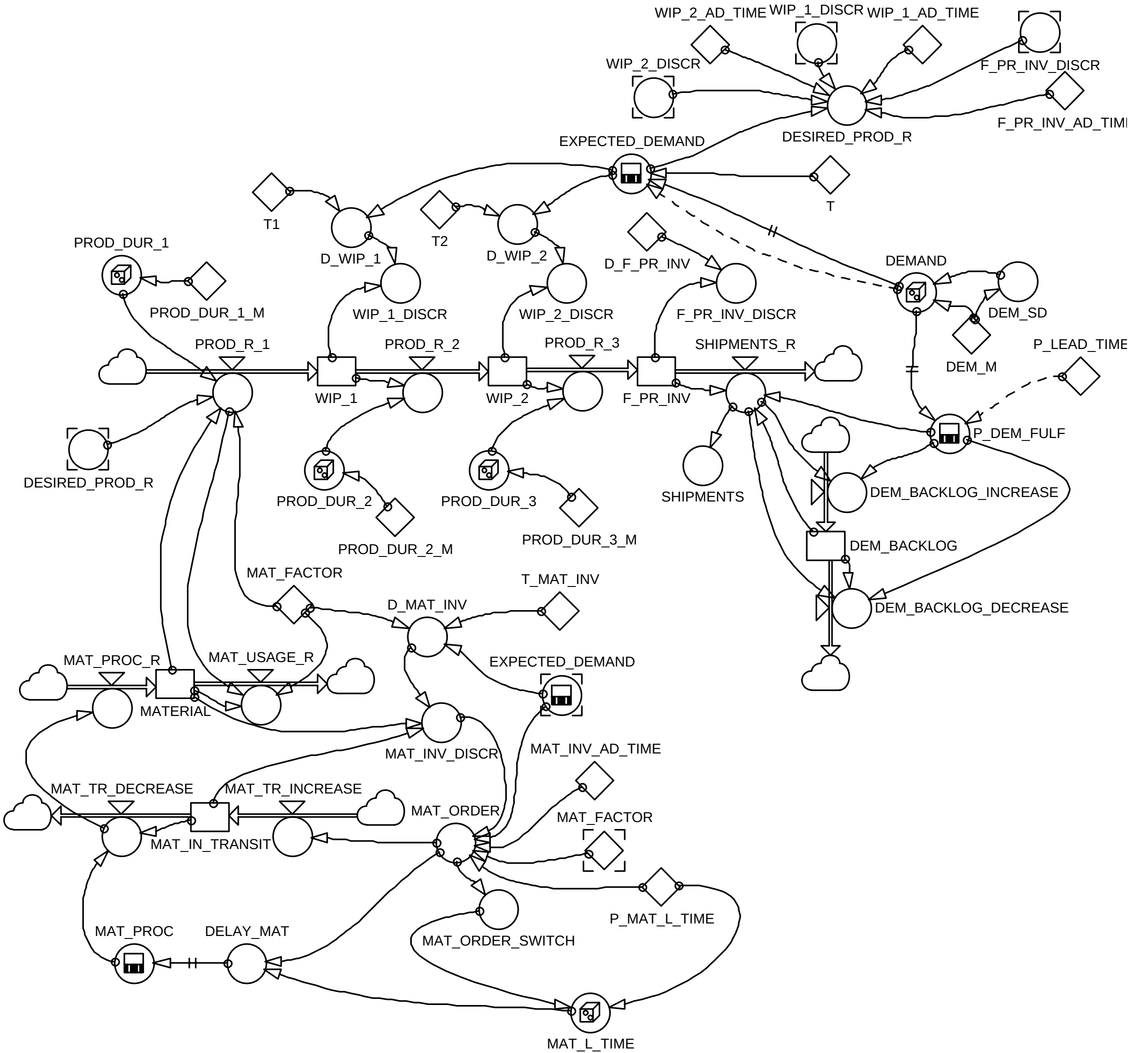


Figure 7: Stock and flow diagram of the developed AA approach model

Table 2: Values of the parameters of the developed AA approach model

Parameter	Value (units)	
	Scenario A	Scenario B
T	*	*
T1	2	5
T2	2	5
T_MAT_INV	2	5
WIP_1_AD_TIME	5	2
WIP_2_AD_TIME	5	2
F_PR_INV_AD_TIME	5	2
MAT_INV_AD_TIME	5	2

* T=23 days (in case of the normally distributed demand)
T=1 day (in case of the wavy demand)

7 Comparing the DBR approach with the AA approach

The efficiency comparison of the developed DBR production planning and control approach with the AA approach is performed under four alternative demand patterns. Specifically, the demand is considered to follow a normal distribution with or without an additional pulse demand, or to follow a wavy change with or without an additional pulse demand.

7.1 Normal demand

We consider a normal demand as stated in section 4 (i.e. with mean equal to 7.5 items/day and standard deviation equal to the ¼ of its mean value). As it is shown in table 3 both the DBR and the AA approach result in zero demand backlog meaning that all the planned fulfillment of demand is satisfied on time. The same result comes out from the zero divergence of the two approaches and from their equity of planned demand fulfillment and shipments. The simulation results of the two approaches differ in the average values of the inventories of raw material, WIP1, WIP2 and finished products. Specifically, as it is shown in table 3, the DBR approach gives extremely lower average raw material inventory than the AA approach in both scenarios studied. Besides, the DBR approach gives lower average finished product inventory and almost the same WIP2 with the AA approach in both scenarios. Furthermore, the DBR approach results in higher WIP1 according to the fact that this is the inventory before the CCR operation of the shop and it is desired to be high enough in order to prevail the starving of the CCR operation.

Table 3: Average values of the performance measures of the simulation results in the case of the normally distributed demand

Performance measure (units)	Average value			(1) / (2)	
	DBR approach (1)	AA approach (2)			
		Scenario A	Scenario B	Scenario A	Scenario B
Demand Backlog (items)	0	0	0		
Planned Demand Fulfillment (items/day)	7.466	7.466	7.466	1	1
Shipments (items/day)	7.466	7.466	7.466	1	1
Divergence (items/day)	0	0	0		
Raw Material Inventory (kg)	71.292	778.754	329.984	0.092	0.216
WIP_1 (items)	13.580	2.368	2.388	5.735	5.686
WIP_2 (items)	2.026	1.998	2.016	1.014	1.005
Finished Product Inventory (items)	17.792	24.409	70.050	0.729	0.254

In the case of an additional pulse demand as stated in section 5.1 (i.e. with magnitude of 1,000 items/day appearing on the 400th day), the average values of the performance measures of the simulation results are shown in table 4. It's worth mentioning the extremely lower raw material inventory kept in the DBR approach. Besides, as it is shown in figure 8, in the case of the additional pulse demand the CCR production rate following the pulse demand is higher at the DBR approach than at the AA approach (scenario A). Besides, as it is shown in figure 9, in the DBR approach the raw material inventory fluctuates more uniformly than in scenario A in the AA approach. Note that the response of the CCR production rate and raw material inventory is similar for the scenario B of the AA approach.

Table 4: Average values of the performance measures of the simulation results in the case of the normally distributed with the additional pulse demand

Performance measure (units)	Average value			(1) / (2)	
	DBR approach (1)	AA approach (2)			
		Scenario A	Scenario B	Scenario A	Scenario B
Demand Backlog (items)	68.618	8.286	2.884	8.281	23.791
Planned Demand Fulfillment (items/day)	7.799	7.799	7.799	1	1
Shipments (items/day)	7.799	7.799	7.799	1	1
Divergence (items/day)	1.485	0.560	0.464	2.654	3.199
Raw Material Inventory (kg)	67.148	839.777	344.670	0.080	0.195
WIP_1 (items)	13.330	2.702	3.109	4.933	4.287
WIP_2 (items)	2.293	2.198	2.373	1.043	0.966
Finished Product Inventory (items)	15.811	24.151	70.436	0.655	0.224

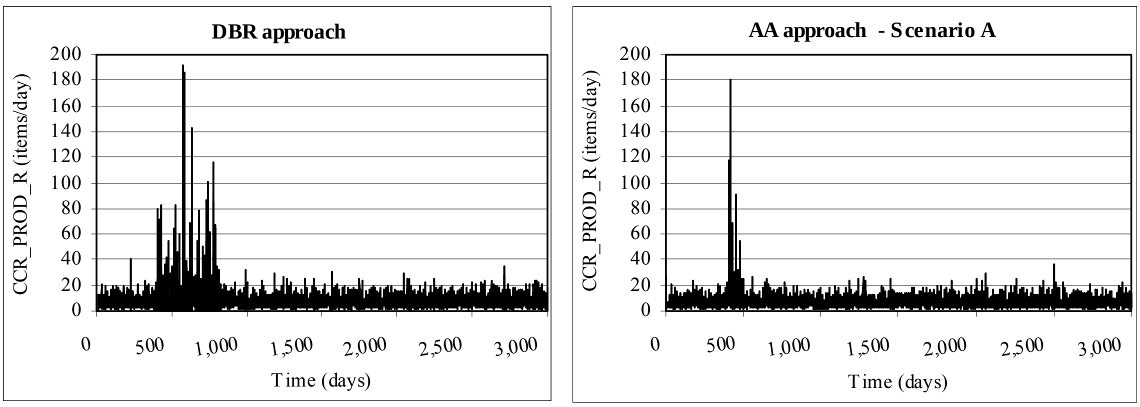
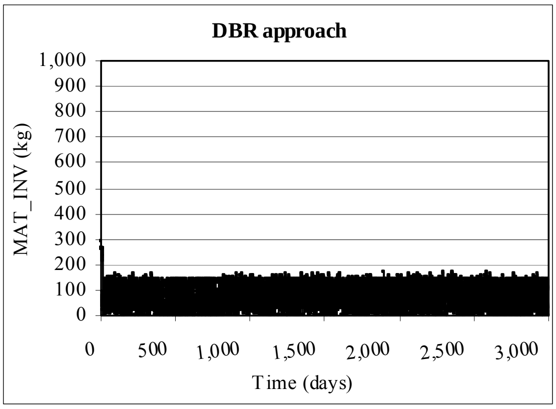


Figure 8: CCR production rate in the case of the normally distributed with the additional pulse demand



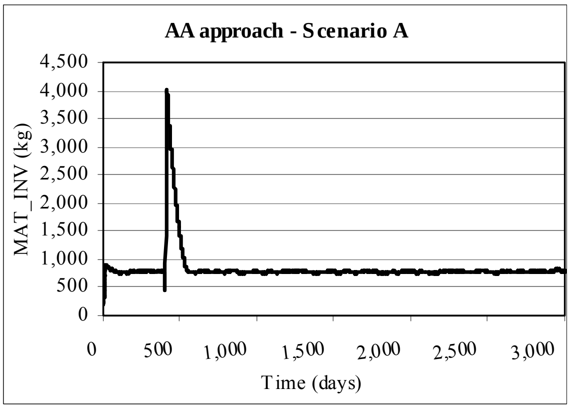


Figure 9: Raw Material Inventory in the case of the normally distributed with the additional pulse demand

7.2 Wavy demand

We consider a wavy (sinusoidal) demand as stated in section 5.2 (i.e. with mean 7.5 items/day, amplitude of 1.5 items/day and period of 500 days). As it is shown in table 5 both the DBR and the AA approach result in almost the same average of the demand backlog, planned demand fulfillment, shipments and divergence. Besides, the DBR approach gives extremely lower average raw material inventory than the AA approach in both scenarios studied. Moreover, the DBR approach gives lower average finished product inventory and almost the same WIP2 with the AA approach in both scenarios. Besides, the WIP1 is higher at the DBR approach, as it is also resulted in the case of normally distributed demand.

Table 5: Average values of the performance measures of the simulation results in the case of the wavy demand

Performance measure (units)	Average value			(1) / (2)	
	DBR approach (1)	AA approach (2)			
		Scenario A	Scenario B	Scenario A	Scenario B
Demand Backlog (items)	0.030	0	0		
Planned Demand Fulfillment (items/day)	7.475	7.475	7.475	1	1
Shipments (items/day)	7.475	7.475	7.475	1	1
Divergence (items/day)	0.046	0	0		
Raw Material Inventory (kg)	70.475	778.510	329.786	0.091	0.214
WIP_1 (items)	13.283	2.421	2.436	5.486	5.453
WIP_2 (items)	2.059	2.022	2.033	1.018	1.013
Finished Product Inventory (items)	17.254	24.132	69.915	0.715	0.247

In the case of an additional pulse demand as stated in section 5.1 (i.e. with magnitude of 1,000 items/day appearing on the 400th day), the average values of the performance measures of the simulation results are shown in table 6. It's worth mentioning the extremely lower raw material inventory kept in the DBR approach. Besides, the responses of the CCR production rate and the raw material inventory are in both scenarios similar with the case of normally distributed demand as they are depicted in figures 8 and 9.

Table 6: Average values of the performance measures of the simulation results in the case of the wavy demand with the additional pulse

Performance measure (units)	Average value			(1) / (2)	
	DBR approach (1)	AA approach (2)			
		Scenario A	Scenario B	Scenario A	Scenario B
Demand Backlog (items)	55.802	37.434	10.626	1.491	5.252
Planned Demand Fulfillment (items/day)	7.809	7.809	7.809	1	1
Shipments (items/day)	7.809	7.809	7.809	1	1
Divergence (items/day)	1.512	0.777	0.587	1.947	2.576
Raw Material Inventory (kg)	67.931	3,473.808	2,495.145	0.020	0.027
WIP_1 (items)	12.154	2.729	2.855	4.454	4.257
WIP_2 (items)	2.318	2.177	2.245	1.065	1.033
Finished Product Inventory (items)	15.367	22.340	68.701	0.688	0.224

8 Summary and conclusions

This paper was aimed to introduce System Dynamics in applying the DBR methodology of TOC in a manufacturing process. Based on the concept of the CCR, which is the corner stone of the TOC philosophy, we presented the conceptual model of the production planning and control and raw material procurement processes of a flow shop system. We also presented the stock and flow diagram for a three-operation flow shop system and an illustrative example and we investigated the system's response in pulse and wavy changes in demand. Besides, by means of the simulation results, the efficiency of DBR production scheduling approach was contrasted with the well known AA approach. The results in all alternative demand patterns examined show that the DBR approach manages to keep in average lower finished product and raw material inventories whereas it keeps the same shipments with the AA approach. Besides, the DBR approach keeps higher inventory before the CCR operation of the shop than the AA approach, in order to prevail the CCR operation starving.

The novelty of the specific paper is based on the fact that the driving force of the production and raw material procurement processes of the flow shop is its CCR operation. The developed model may easily be extended to include more than 3 operations at the flow shop. Besides, it may be extended to employ the performance measures used in TOC methodology.

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