The efficiency of alternative control mechanisms in a MTO three-stage tandem production/inventory system

Charalampos Michaloudis[1], Patroklos Georgiadis[2]

Laboratory of Business Administration, Industrial Management Division, Department of Mechanical Engineering, Aristotle University of Thessaloniki

P.O. Box: 461, 541 24, Thessaloniki, Greece

Tel: (+30) 2310 994244, Fax: (+30) 2310 996018

e-mails: (1) hmich@auth.gr, (2) geopat@auth.gr

Abstract

In this work we develop a SD model for a make-to-order (MTO) three-stage capacitated production/inventory system. We employ a production order release mechanism affiliated with the automated pipeline inventory and order based production control system (APIOBPCS) policies family. The production rates at each stage are defined under alternative policies. One of the policies considers the human behavior in the decision making process. The robustness of the alternative policies is investigated through the dynamic response of the system under step and pulse changes in demand. Finally, the efficiency of the alternative policies is examined by means of six performance criteria.

Keywords: Production Planning and Control, Make-to-Order, Capacitated Production/Inventory System, System Dynamics

1. Introduction

Nowadays, the competitive, demanding and stochastic market requires not only to satisfy the customer demands but also to achieve it on time and in the most economic possible way. Hence it is crucial for manufacturing firms to minimize all cost sources, including production costs, stockholding costs and backorder costs. To succeed so, manufacturing firms need to keep under control work in process (WIP) while minimizing throughput times and lead times and improving due date adherence. This becomes more crucial in complex production systems (Land and Gaalman, 1996).

In a production/inventory system the shop floor can be viewed as a network of workstations each with a set of jobs queuing, waiting their turn to be processed (Haskose et al., 2004). Each workstation is defined by its capacity. The required time taken to process all of the jobs in the queue (lead time) in front of a workstation is proportional to the ratio of the amount of the backlogged work to the workstation's capacity. As denoted by the Little law (Little, 1961), the mean work in process in front of a work centre is equal to the product of the mean jobs arriving at the work centre per time unit and the mean job throughput time.

In most production systems, due to the inherent randomness and the need to anticipate congested conditions, manufacturing lead times are highly unreliable and often very long, causing WIP and finished goods inventories (FGI) levels to rise uncontrollably (Stalk et al., 1992). Many Production Planning and Control (PPC) policies have been proposed, to successfully overcome this problem. The PPC policies can either employ feedforward (e.g. MRP, MRP II) or feedback (ConWIP, Hybrid Push/Pull) mechanisms to describe the information flow in the shop floor.

In the present paper we are focusing on the production planning problem for a make-to-order (MTO) three-stage tandem capacitated production/inventory system.

In literature can be found many research papers focused in developing production planning models for capacitated manufacturing systems. Many of the proposed approaches use operations research (OR) techniques like linear programming while other are employing control theory methods for the definition of the load dependent production capacity. The production capacity is also subject to the human factor. Specifically, the less automated is a manufacturing process the more intense is the human involvement. It is noticeable that although the significance of this factor, there are rarely found in literature mechanisms incorporating the human behavior. This is probably due to the difficulty of modeling the human behavior and quantifying its impact on system's function. System Dynamics methodological approach, can successfully overcome this problem, as reported in literature (Sterman, 2000).

The contribution of the paper is twofold; firstly it introduces the System Dynamics methodological approach for capacitated production/inventory systems employing feedforward control policies and secondly it incorporates the human behavior in the decision rules that define the production rates. Specifically we examine the response of a three-stage tandem capacitated production/inventory system under alternative control policies that have been suggested in the production planning context.

The rest of the paper is organized as follows. In Section 2 we present a brief literature review of capacitated production planning and control (CPPC) policies. In Section 3 we present the production/inventory system under study. In Section 4 we develop a SD model and we present alternative production ordering rules and production rates control policies. In Section 5 we investigate the efficiency and the robustness of the control mechanisms on production rates. Finally, we wrap-up with summary and conclusions in Section 6.

2. Literature Review

During previous years there has been a remarkable research effort in developing dynamic approaches for the CPPC problem. The most commonly used approaches are operations research techniques.

Specifically there is a remarkable amount of research papers, regarding capacity planning in MRP and MRP II production systems. Karmarkar et al. (1987) describes the inability of MRP/MRP II models to couple lead times with workload of the production system. Billington et al. (1983) denotes the disability of MRP systems to treat the capacity as infinite. Enns et al. (2002) and Enns et al. (2004) developed methods to calculate lead times based on the workload in the shop floor in MRP II production systems.

An extensive literature has been developed to examine the effects of lot sizes, processing times and distribution of random variables on the performance of capacitated production systems. Asmundsson et al. (2002) in their research report, propose two different approaches; the mathematical programming for aggregate planning and the queuing simulation for performance analysis. The queuing models have shown that lead times increase nonlinearly in both mean and variance as the system capacity utilization approaches to 100%. On the other hand, mathematical models tend to face problems on the definition of the lead time. There are many approaches to overcome these problems that are described thoroughly in the literature (e.g. Hackman et al., 1989, Karmarkar, 1993).

A different approach to couple lead times with shop floor workload in production planning has been suggested by Graves (1986). Graves introduced the clearing functions in his effort to control the flow time of jobs and hence the workload in a production inventory system. Using clearing functions, he tried to detach the production system from Little's law which implied fixed lead times, and to employ adjustable production rates to variable workload. This approach was furthermore developed by other researchers, like Karmarkar (1989) and Srinivasan et al. (1988) who took into account cost factors as well as Hwang et al. (2004) who added lot sizing mechanisms on production planning. Pahl et al (2005) in their survey tried to review similar research efforts cited in the literature.

The above mentioned approaches are characterized by the lack of feedback mechanisms which is crucial for the definition of workload-orientated capacity planning control policies. To overcome this limitation, approaches based on control theory are introduced (Riddalls et al., 2002), (Tang et al., 2004), (Wikner, 2005).

Specifically, Towill (1982) developed a decision support system (DSS) for production and inventory ordering named inventory order based production control system (IOBPCS). Since then, there have been efforts for the extension of this base model. John et al. (1995) proposed the automated pipeline inventory and order based production control system (APIOBPCS), which also considers work in process inventory (WIP) and compares actual levels with a target value. Disney (2001) proposed the VMI-APIOBPCS policy which coupled the APIOBPCS model with Vendor Managed Inventory (VMI) approach. Later, Disney et al. (2003) described a two-echelon (manufacturer-distributor) APIOBPCS model and investigated the impact of the system structure upon transportation operations.

In this paper we are combining the APIOPBCS approach as described by Disney et al. (2003) with the clearing functions as proposed by Karmarkar (1989) and Srinivasan et al. (1988) and we are employing them in simulation models based on System Dynamics (SD) methodology. The developed SD-based framework is used to examine the robustness of alternative production planning approaches under various demand patterns.

3. Production/Inventory system under study

We examine an arbitrary three-stage tandem capacitated production/inventory system. The stock and flow representation of the process is presented in Figure 1.

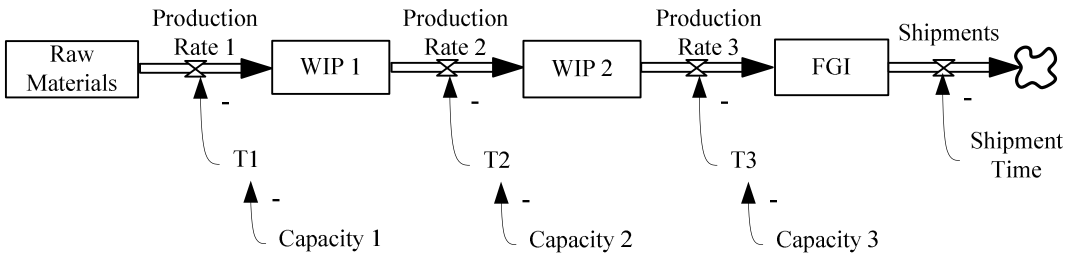

Figure 1: *Simplified stock and flow diagram of the production/inventory system*

The flows represent the *Production Rates* of the three workstations and the *Shipments* while the stocks represent the *Raw Materials* inventory, work in process inventory (*WIP*) and the finished goods inventory (*FGI*)

The production procedure starts whenever a demand arrives at the shop. The demand is translated into production orders that are backlogged in a job pool. According to the adopted order release mechanism, these orders are imported in the shop floor. Each time a demand is satisfied, an equivalent order is withdrawn from the job pool depleting the backlog level.

The *Production Rates*$_i$ depend on the manufacturing lead times T_i which are constrained by the production capacity of workstations i (*Capacity i*), where i=1, 2, 3. *Shipments* on the other hand, are defined taking into account the *Shipment Time*.

The production process assumes infinite raw materials inventory and infinite warehouse capacity for WIP and finished goods.

4. SD model

4.1. Causal loop diagram

Figure 2 represents the causal loop diagram for the production/inventory system under study.

The *Gross Production Rate 1* is determined by the availability of *Raw Materials*, the manufacturing lead time *T1* and the *Desired Production Rate* that is defined from the adopted order release mechanism described in subsection 4.2. The *Net Production Rate 1* is given by the *Gross Production Rate 1* and the first workstation's yield (*Yield 1*), which corresponds firstly to the defective manufactured products that are removed from the production and secondly to the inability of the equipment to work continuously at its maximum capacity. Manufacturing lead time *T1* is subject to the limitations of production capacity of workstation 1 as presented in subsection 4.3.

The *Net Production Rate 1* increases the first stations' work in process inventory (*WIP 1*) which is depleted by the *Gross Production Rate 2*. The latter is defined by *WIP 1* and manufacturing lead time *T2* which depends on the production capacity and inventory at workstation 2. The *Net Production Rate 2* is given by the product of *Gross Production Rate 2* and *Yield 2*. In similar way the *Gross Production Rate 3*, *Net Production Rate 3* and *T3* are defined.

Production orders depend on customer demand. All incoming orders (*Demand*) are logged in a job pool (*Backlog*) and tracked until they are shipped (*Shipments*) to customers. *Shipments* are determined by *Backlog*, *Shipment Time* and the availability of products in the finished goods warehouse (*Finished Goods Inventory*).

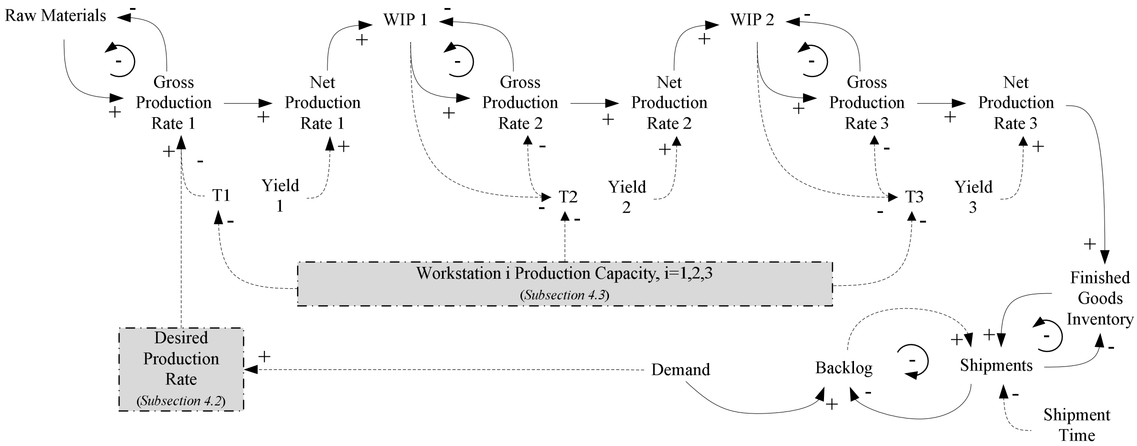

Figure 2: *Causal loop diagram of the system under study*

The equations of the model using Powersim® 2.5c software package are given in Appendix A.

4.2. Production ordering policy

The aim of a production ordering policy is to keep actual inventories, both on hand and in process, as close as possible to a desired level. The production orders are usually defined according to the customer demand and the actual levels of inventories as given in equation 1:

Production Orders = Demand + Inventory Replenishment – Work in Process (1)

The success of such a policy lies in the transparency of the information about the actual levels of demand, finished goods inventories and WIP. The automated pipeline inventory order based production control system (APIOBPCS) is a decision support system for dynamic production and inventory ordering that embodies all these information. In this paper we adopted a special case of the APIOBPCS policy as the main production order release policy of the production/inventory system. Disney et al. (2003) refer to the term APIOBPCS as the structure of the ordering decision used by the manufacturer for production scheduling. According to John et al. (1995) the APIOBPCS is representative of the ordering heuristics suggested by Sterman (1989) in decision making in supply chains. Moreover, Naim and Towill (1995) found that the APIOBPCS structure is directly analogous to Sterman's (1989) "Anchoring and Adjustment" heuristic structure used to describe the human behaviour when playing the "Beer Game".

Similarly to equation 1, in the APIOBPCS policy the production ordering decision (*Desired Production Rate*) equals to the average (or forecasted) demand plus a quantity needed for work in process inventory and finished goods inventories to adjust to a predetermined target level in a specific time period.

Specifically, the *Desired Production Rate* in a single workstation production system is calculated as following:

$$\text{Desired Production Rate} = \text{Forecasted Demand} + \frac{\text{EFGI}}{T_i} + \frac{\text{EWIP}}{T_w} \qquad (2)$$

where EFGI is the difference between actual (FGI) and target (TFGI) finished goods inventory, T_i equals the time needed for the actual FGI to adjust to its target level, EWIP is the difference between actual (WIP) and target (TWIP) work in process inventory and T_w is the time needed for the actual WIP to adjust to its target level. The demand is forecasted by first order exponential smoothing of the actual perceived demand with smoothing constant 1/ST:

Forecasted Demand = DELAYINF(Demand, ST, 1) (3)

According to Disney and Towill (2002), if the adjustment time T_w for work in process equals the adjustment time T_i for finished goods inventory, the system achieves a robust and stable response.

In our modelling approach, *Desired Production Rate* is defined incorporating in Equation 2 the amount of backlogged orders as follows:

$$\text{Desired Production Rate} = \text{Forecasted Demand} + \frac{\text{EFGI}}{T_i} + \frac{\text{EWIP}}{T_w} + \frac{\text{Backlog}}{T_b} \qquad (4)$$

where T_b is the time needed to eliminate the actual backlog.

Adding to the Figure 2 the needed causal links that represent the production ordering mechanism, we have the extended causal loop diagram of the system under study shown in Figure 3. The equations for the three-stage tandem production/inventory system using Powersim® 2.5c software package are given in Appendix B.

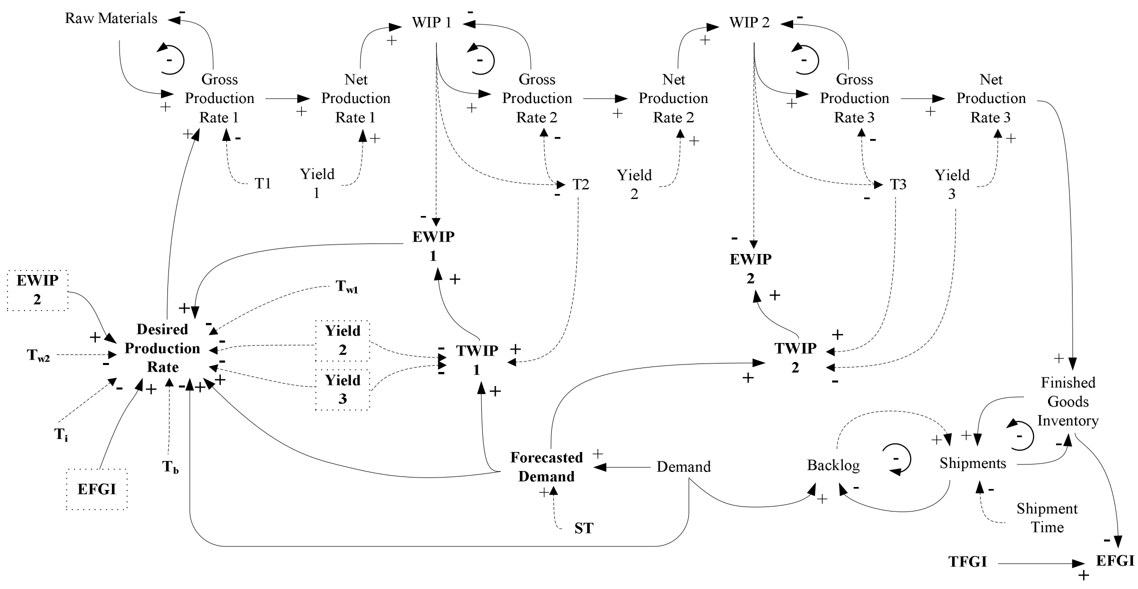

Figure 3: *Causal loop diagram of the production/inventory system*

4.3. Production Rates control policies

In research agenda there is a remarkable interest in developing production planning approaches for capacitated production systems. These approaches can either incorporate linear or non linear techniques and they can assume either stationary or variable production lead time that depends on the workload of the shop floor. In this section we present four production rate control mechanisms which are well documented in the literature and are based on OR techniques and SD methodology. We employed these approaches on the three-stage tandem capacitated production/inventory system. We denote the production rate of workstation i over the period t by P_{ti} and the work in process at the workstation i at the end of period t by W_{ti}. Finally, we denote the capacity limit of the workstation i in period t by C_{ti}.

4.3.1. Constant Proportion Clearing Function

The Constant Proportion Clearing Function, referred from now on as CPCF, was developed by Graves (1986) in an attempt to consider workload rather than single jobs, in a shop floor. Graves used a queuing model to embed flexible production rates in order to smooth the work flow. The control rule that defines the production rate is given by the following equation:

$$P_{ti} = \alpha_i \cdot W_{ti} \tag{5}$$

where α_i is a smoothing parameter with $0 < \alpha_i < 1$ which is used to denote a fixed portion of the workload which will be processed during period t. Graves refers to the smoothing parameter α_i as "clearing factor" because it specifies the volume of work which will be cleared (finished) in one time period.

If we consider the smoothing parameter α_i equal to $1/T_i$ where T_i is an exogenously defined fixed manufacturing lead time, the above model can be formulated by first order material delay as following:

$$P_{ti} = \frac{W_{ti}}{T_i} \tag{6}$$

The exogenous definition of the clearing factor and therefore of the lead time is the simplest and most common used approach in production planning and inventory management found in literature. In this approach the lead times T_i are considered constant and independent of the workload.

4.3.2. Capacitated Constant Proportion Clearing Function

The Capacitated Constant Proportion Clearing Function, referred as C-CPCF, is a linear programming approach which extends Graves' (1986) constant proportion clearing function.

Graves' model has two obvious limitations; it presumes fixed lead times and infinite production capacity. The former is a major drawback because it omits the nonlinear relationship of lead times and WIP and therefore it emerges the incapability of the model to capture the workload dependency of the production rate. On the other hand, infinite production capacity means infinitely high production rates. To overcome this disadvantage, C-CPCF approach limits the maximum production rate to a certain predetermined production capacity C_{ti}. Hence, the output of the workstation i over the period t is given by the following equation:

$$P_{ti} = \min\left(\frac{W_{ti}}{T_i}, C_{ti}\right) \quad (7)$$

4.3.3. Concave Saturating Clearing Function

The Concave Saturating Clearing Function, referred as CSCF in the remainder of the paper, is coupling lead times with work in process inventories and therefore it influences the production rates. The function originates from steady-state queuing structure as suggested by Karmarkar (1989). The use of the nonlinear model has been reported by Asmundsson et al. (2002, 2003) for aggregate production planning, Hwang et al. (2005) for efficient lot sizing mechanisms and Orcun et al. (2006) for comparing various capacity models.

The CSCF approach implies that as workload increases, throughput increases exponentially tending to a maximum capacity limit. Through simulation experiments, is documented that the CSCF approach represent better the nonlinear changes in system performance than other approaches (Orcun et al., 2006).

The Production Rate is defined by the following equation:

$$P_{ti} = \frac{W_{ti} \cdot C_{ti}}{W_{ti} + K} \quad (8)$$

where K is a parameter that defines the curvature of the clearing function. The physical definition of K in the form $\frac{K}{C_{ti}}$, could be the time needed for the production system to initially process the first job. It is obvious that if K = 0 then the production rate (throughput) equals maximum production capacity.

The described CPCF, C-CPCF and CSCF approaches are graphically presented in Figure 4.

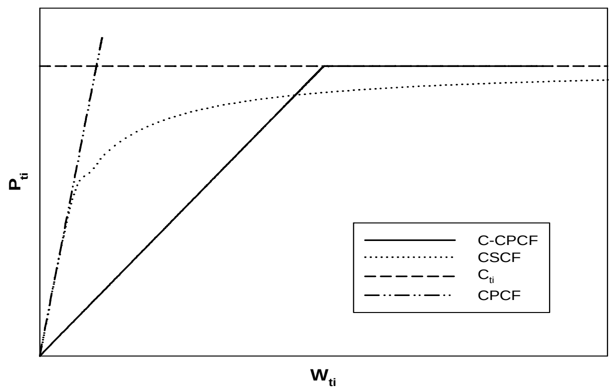

Figure 4: *Different forms of control policies (Karmarkar, 1989)*

4.3.4. Variable Capacity utilization

The approaches described in the previous sections are based on control theory methodology and thus they assumed automatic response of the production/inventory system to changes in its environment. The Variable Capacity utilization approach, referred as VC in the remainder of the paper, originates from Sterman's human behaviour modelling attempt (Sterman, 2000, pp. 608). It is a modelling approach that considers the human interaction which embeds unreliability and uncertainty to the responsiveness of the system.

In the suggested approach we define the manufacturing lead times of each workstation *i* as the ratio of the total amount of workload in front of the workstation to the feasible production of the station *i*. The feasible production at each workstation is defined as the product of the capacity utilization and the actual production capacity. Capacity utilization varies according to the total amount of inventory, production orders on the shop floor and actual production capacity. Specifically for the workstations 2 and 3 it is defined as a function of work in process and actual capacity as shown in the following equations:

$$\text{Capacity Utilization}_i = f(\text{WIP Ratio}_{i-1}/\text{Capacity Ratio}_i),\ (i=2,3) \quad (9)$$

$$\text{where WIP Ratio}_{i-1} = \text{WIP}_{i-1}/\text{Normal WIP}_{i-1},\ (i=2,3) \quad (10)$$

$$\text{and Capacity Ratio}_i = \text{Capacity}_i/\text{Normal Capacity}_i,\quad (i=2,3) \quad (11)$$

For workstation 1 the equivalent equations are the following:

$$\text{Capacity Utilization}_1 = f(\text{Raw Materials Ratio}/\text{Capacity Ratio}_1) \quad (12)$$

$$\text{where Raw Materials Ratio} = \text{Raw Materials}/\text{Normal Raw Materials} \quad (13)$$

$$\text{and Capacity Ratio}_1 = \text{Capacity}_1/\text{Normal Capacity}_1 \quad (14)$$

Normal WIP$_i$ and *Normal Capacity$_i$* variables equal to the normal work in process inventory and capacity at workstation *i* respectively.

The *Capacity Utilization* function is shown in Figure 5. Operations managers must compensate changes in the workload by adjusting the level of capacity utilization. The higher the workload, the higher the utilization rate and therefore the higher the throughput. When *WIP Ratio$_{i-1}$* equals *Capacity Ratio$_i$*, (i=2,3) utilization is unity. When workload is less than capacity, operations managers lower utilization gradually, preferring to run the backlog down rather than idling their production equipment. Whenever workload is null then utilization equals to zero, because production policy dictates that production never starts unless there is demand.

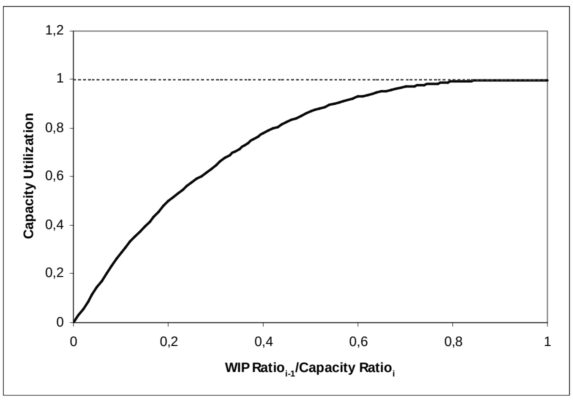

Figure 5: *Capacity Utilization Function*

Production rates of each workstation are calculated either as a first order material delay (as described in Equation 6) or as third order material delay given by the following equation:

$$P_{ti} = \frac{W_{ti}}{\frac{T_i}{3}} \tag{15}$$

According to the order of the delay, the VC approach will be referred as 1-VC or 3-VC respectively.

The causal loop diagram of VC approach is presented in Figure 6. The equations of the model using Powersim 2.5c software package, are given in Appendix C.

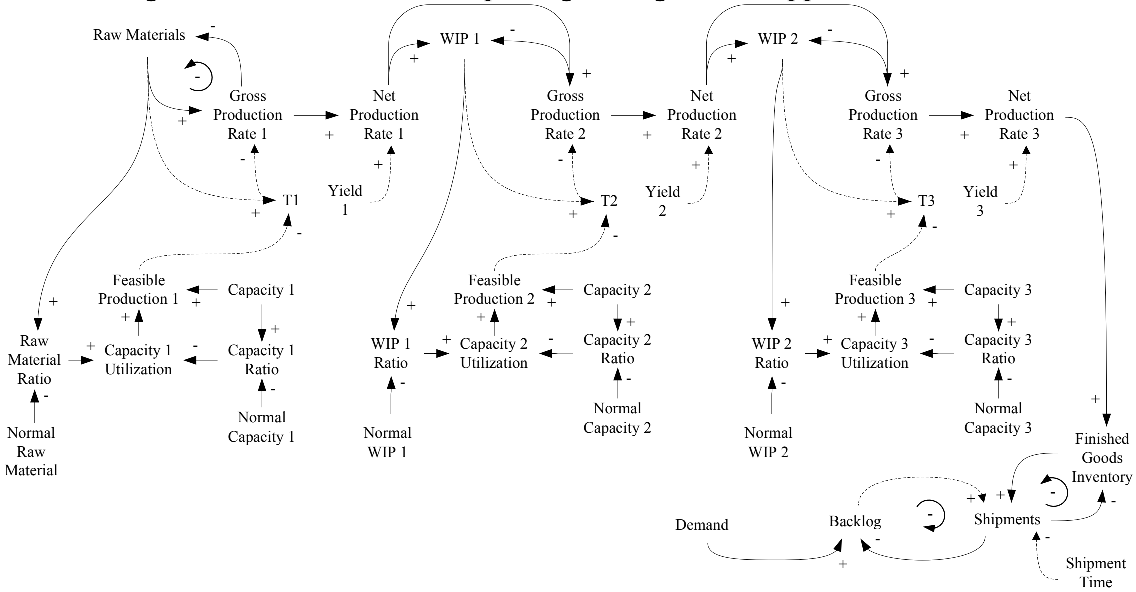

Figure 6: *Causal loop diagram of the production/inventory system with VC approach*

5. Robustness of control approaches on Production Rates

In this section we investigate the dynamic behavior of the system under the presented alternative control approaches. Firstly we investigate the production/inventory system's response to a steady demand (subsection 5.1). Demand is set to 31.25 units/time period while the upper limit of capacity in each workstation to 50 units/time period. In all simulation experiments, the simulation horizon (T) is set to 300 time periods and the time step to 0.01 time periods.

Then we investigate the robustness of alternative control approaches imposing a step change in demand of 5.5 units/time period (subsection 5.2) and of 5.5 units/time period but lasting only 30 time periods (subsection 5.3) and a pulse change in demand (subsection 5.4). The magnitude of the pulse change is set equal to the magnitude of finite step change, meaning equal to $5.5 \cdot 30=165$ units/time period. The above mentioned changes in demand applied after the system has reached its steady state.

The efficiency of CPCF, C-CPCF, CSCF and VC approaches on the system performance is examined through two different investigations. Firstly we examine the evolution of the variables *Backlog*, *Finished Goods Inventory (FGI)*, *WIP1* and *Gross Production Rate 2* through the simulation horizon. For better view of the robustness of the alternative control approaches in a vis-à-vis investigation, firstly we calibrated the critical parameters of the models in order to have the same steady state conditions and the same dynamic behavior under a steady demand. Next we examine six performance criteria for the alternative approaches. Specifically we examine the *Mean Service Rate, Mean Delivery Delay, Mean WIP1, Mean WIP2, Mean FGI* and *Mean Backlog* at the end of the simulation horizon.

The *Mean Service Rate* and the *Mean Delivery Delay* are given by the following equations:

$$\text{Mean Service Rate}=\sum_{t=0}^{T}\frac{\text{Shipments}_t \cdot \text{T}_b / \text{Backlog}_t}{T} \quad (16)$$

$$\text{Mean Delivery Delay}=\sum_{t=0}^{T}\frac{\text{Backlog}_t / \text{Shipments}_t}{T} \quad (17)$$

5.1. Steady demand

Figure 7 shows system’s response to a steady demand input.

We observe that CPCF approach responds immediately to the demand increase, augmenting the *Gross Production Rate 2* and thus balancing almost instantly the amount of *Backlog*, *FGI* and *WIP1*. Moreover, due to the low levels of *Backlog* and *FGI*, the work in process inventory is also kept in low levels.

On the other hand, CSCF approach, responds with a time lag to the demand increase. This delay causes an increase in *Backlog* and a decrease in *FGI*. Hence, due to the adopted order release mechanism, the system balances in high *WIP1* level.

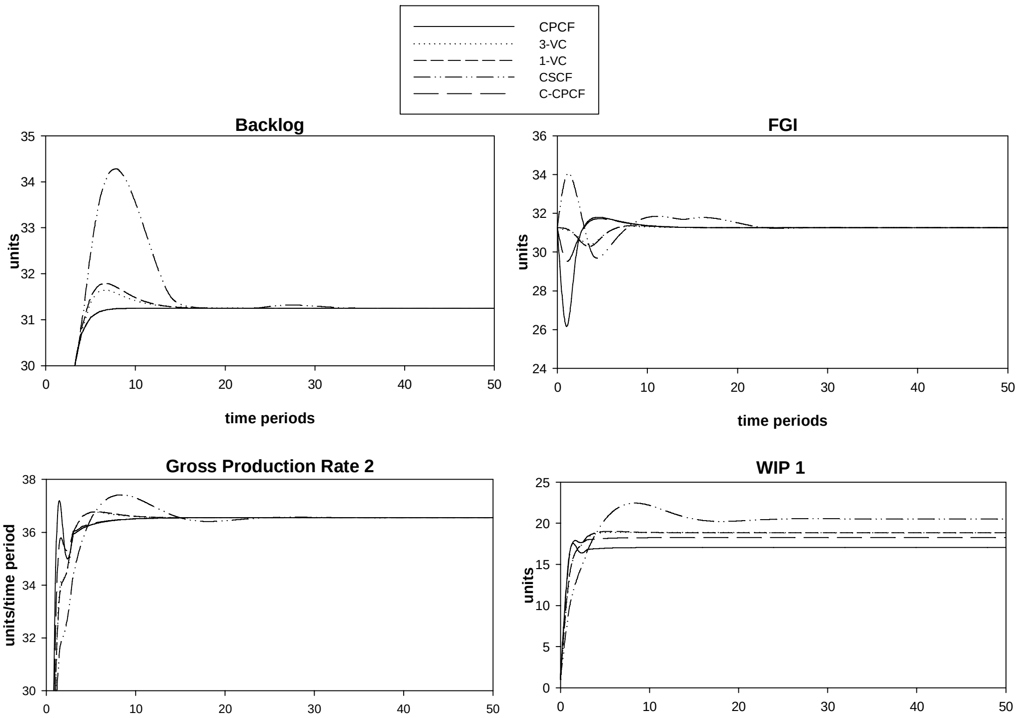

Figure 7: *Simulation results with steady demand*

In Table 1 we present the values of the six performance criteria. We use these values as a baseline to compare the efficiency of the alternative control policies under different demand patterns.

Table 1: *Performance criteria of the alternative control policies under steady demand.*

	CPCF	C-CPCF	CSCF	3-VC	1-VC
Mean Service Rate	1,88	2,00	1,88	1,88	1,88
Mean Delivery Delay (*time periods*)	1,00	1,00	1,00	1,00	1,00
Mean WIP 1 (*units*)	17,06	16,05	17,07	17,04	17,04
Mean WIP 2 (*units*)	15,43	14,42	15,34	15,35	15,36
Mean FGI (*units*)	31,24	31,28	33,21	33,07	31,24
Mean Backlog (*units*)	31,15	31,15	31,16	31,15	31,15

5.2. Step change in demand

Figure 8 shows the simulation results for a step change in demand. We observe that the responsiveness of *Backlog*, *FGI* and *Gross Production Rate 2* is similar for all control approaches except for the case of CSCF. VC approaches responsiveness is adequate enough, keeping the *Backlog* and *FGI* in low levels but balancing on rather high levels of *WIP1* compared to CPCF and C-CPCF approaches.

CSCF approach has the worst responsive behavior to the step change on demand, bearing long oscillation time periods until the system reaches the steady state. We notice again that, the total amount of workload in front of the first workstation is raised, due to the response delay of the system to the step change in demand.

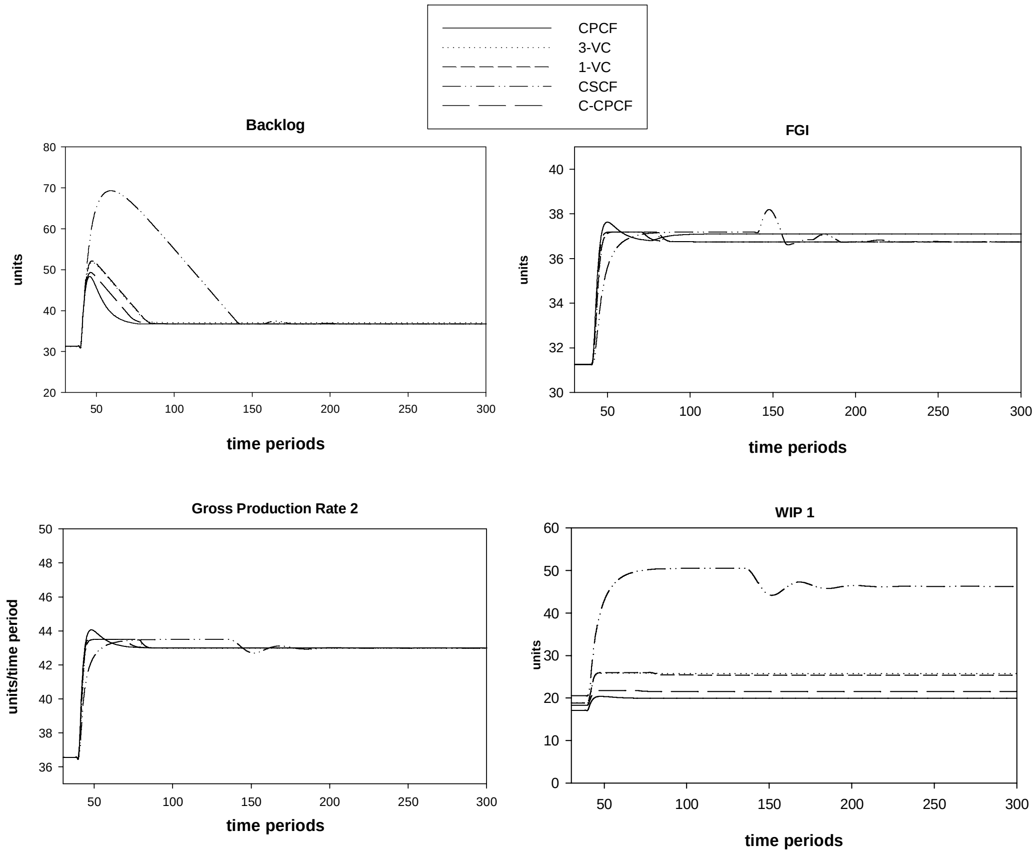

Figure 8: *Simulation results with step change in demand*

In Table 2 we present the variation of the performance criteria values when compared to the baseline (Table 1). We observe that the *Mean Service Rate* has been decreased while the *Mean Deliver Delay* and the rest four inventory indices have been increased in all alternative control policies. However C-CPCF achieves the best results in comparison to CSCF and VC approaches. Specifically C-CPCF achieves the lowest deviation from the baseline in most indices. The CPCF approach is not included in our analysis because it is the only non capacitated approach.

Table 2: *Performance criteria of the alternative control policies under step change in demand*

	CPCF	C-CPCF	CSCF	3-VC	1-VC
Mean Service Rate	-1,06%	-1,50%	-8,51%	-1,60%	-2,66%
Mean Delivery Delay	1,00%	2,00%	13,00%	2,00%	3,00%
Mean WIP 1	14,36%	15,26%	112,01%	31,22%	32,86%
Mean WIP 2	14,32%	15,33%	68,38%	26,06%	24,93%
Mean FGI	16,01%	15,15%	13,19%	13,82%	16,01%
Mean Backlog	16,85%	17,69%	30,62%	17,82%	18,81%

5.3. Finite step change in demand

Figure 9 shows the system's response to a finite step change in demand.

We observe that in CSCF approach it is possible to achieve a smooth *Gross Production Rate 2* because of the large curvature *K* of the capacity function. Due to this response, the system cannot meet the increased demand causing *FGI* to decrease and *Backlog* to increase. Moreover, since backlogged orders are accumulating in the job pool, the APIOBPCS mechanism, releases a large amount of production orders in the shop floor which increases *WIP 1*.

On the other hand, CPCF approach, responds instantly to the step change in demand. Specifically, after the demand increase, system's *Gross Production Rate 2* adjusts to the increased production orders level and thus there are not observed many backlogged orders while *FGI* equals demand. We notice that *WIP1* is also kept in low levels due to the order release mechanism and the low *Backlog*.

The VC approaches present a quite quick response to the step change in demand with *Backlog*, *FGI* and *WIP* levels being kept in satisfactory levels. We notice that the 3-VC approach compared to the other approaches shows a more unstable behavior, balancing in higher *Backlog* and *WIP* levels.

In Table 3 we present the variation of the performance criteria values when compared to the baseline (Table 1). We observe that C-CPCF approach presents the best performance when compared to the other approaches. The only weakness of this approach is the large amount of finished goods inventories that are stored throughout the simulation horizon. The lowest *Mean FGI* value is achieved by the 3-VC approach.

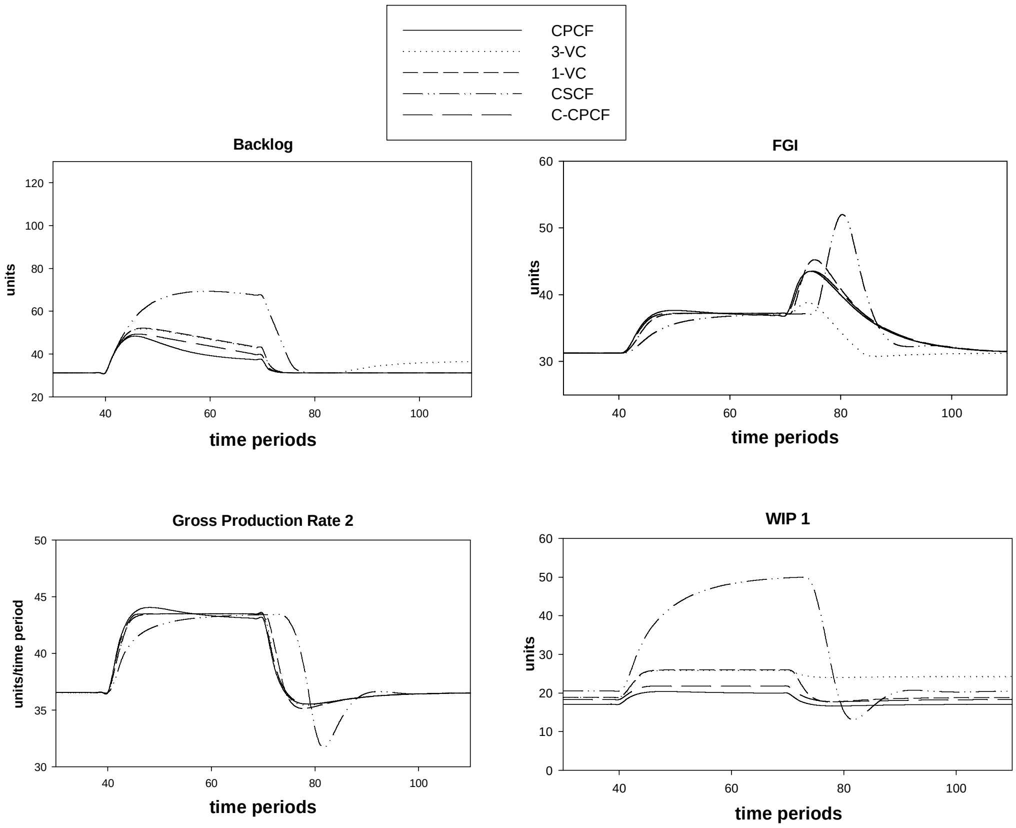

Figure 9: *Simulation results with finite time step change in demand*

Table 3: *Performance criteria of the alternative control policies under finite step change in demand.*

	CPCF	C-CPCF	CSCF	3-VC	1-VC
Mean Service Rate	-1,06%	-1,50%	-4,26%	-7,98%	-2,13%
Mean Delivery Delay	1,00%	2,00%	7,00%	9,00%	3,00%
Mean WIP 1	1,64%	1,74%	13,59%	25,18%	3,93%
Mean WIP 2	1,62%	1,80%	8,08%	20,52%	2,93%
Mean FGI	3,59%	3,52%	2,68%	-2,33%	3,59%
Mean Backlog	3,37%	4,11%	9,95%	11,01%	5,07%

5.4. Pulse change in demand

Figure 10 shows the simulation results to a pulse change in demand.

The CPCF approach seems to achieve better responsiveness than the other approaches. Almost immediately after the demand impulse, *Gross Production Rate 2* increases to cope with the augmented production orders. However, this production planning policy is the only one with no capacity limitation and thus we notice that the *Gross Production Rate 2* increases to a higher level compared to the other approaches. Moreover the total volume of backlogged orders and the values of *WIP1* are significantly lower.

On the other hand, 3-VC, 1-VC, CSCF and C-CPCF approaches, due to the capacity limitation are unable to meet the increased demand causing *Backlog* to rise in high levels. As a result, the APIOBPCS mechanism releases a large amount of production orders to the shop floor leading in high values of *WIP 1*. This problem is more lucid in

CSCF approach where the total volume of *WIP 1* during the simulation horizon, is higher than the other three approaches.

In Table 4 the variation of the six performance criteria values from the baseline (Table 1) under pulse change in demand is presented. Once more the C-CPCF approach presents the best performance when compared to the alternative control policies. Specifically C-CPCF control policy achieves the lowest *Mean Service Rate*'s value deviation from the baseline and the lowest *Mean Delivery Delay*, *Mean WIP 1*, *Mean WIP 2* and *Mean Backlog* indices levels increase. However the best *Mean FGI* index value is achieved by the 3-VC approach which also decreases the amount of stored finished goods inventories in comparison to the baseline.

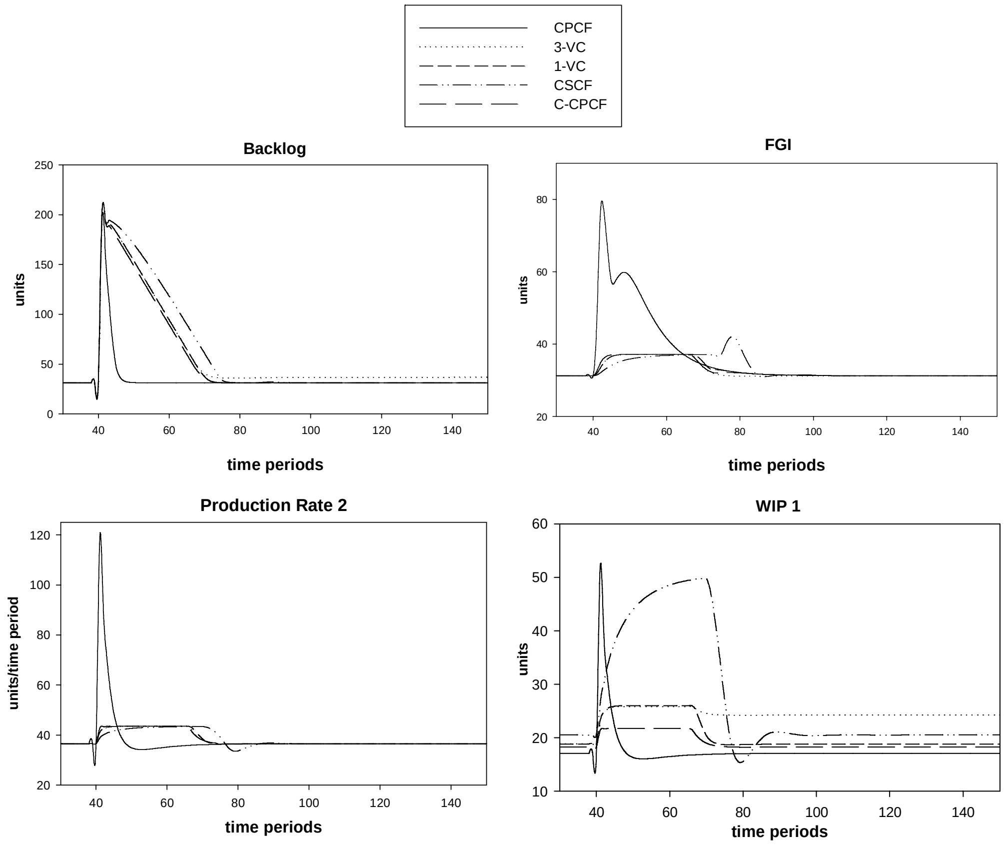

Figure 10: *Simulation results with pulse demand change*

Table 4: *Performance criteria of the alternative control policies under pulse change in demand.*

	CPCF	C-CPCF	CSCF	3-VC	1-VC
Mean Service Rate	-0,53%	-6,00%	-7,45%	-12,77%	-6,38%
Mean Delivery Delay	3,00%	22,00%	29,00%	31,00%	24,00%
Mean WIP 1	1,64%	1,74%	13,01%	25,35%	3,81%
Mean WIP 2	1,62%	1,80%	7,89%	20,65%	2,86%
Mean FGI	5,95%	1,89%	1,57%	-3,21%	1,95%
Mean Backlog	5,62%	27,93%	34,56%	36,15%	29,44%

6. Summary and Conclusions

In this work we incorporated feedback mechanisms for capacitated production planning and control problem in a make to order three-stage tandem production/inventory system. We reviewed some of the most common approaches suggested by the literature to define the production rates. Initially we cited a production order release mechanism affiliated with the APIOBPCS policies family. Thereafter, we presented several production rate control policies used for production planning, with most of them employing workload-dependent lead time control mechanisms. Along with the cited policies, we proposed another approach that considers the human behavior in the decision making process to define the production rates. We then employed the examined approaches in the system under study. We investigated the efficiency of the examined approaches on the systems' performance, through the dynamic responsiveness of the system to a range of demand patterns and by means of six performance criteria.

In the vis-à-vis investigation of the examined approaches, the simulation results showed similar responsiveness of the system to most of the approaches. Concave Saturating Clearing Function (CSCF) approach was the only one that responded slowly to changes in demand pattern, leading to high *Backlog* and *WIP 1* levels and low *FGI* levels. The proposed VC approaches showed satisfactory responsiveness even though they incorporated a stochastic behavior in the system. However, CPCF approach achieved the best values of the performance criteria.

An extension of this work could be the examination of the described approaches along with other control mechanisms in complex production/inventory systems, employing push, pull and hybrid push/pull control policies.

Appendix A: Equations required for the system presented in Figure 2

Variable	Equations	Units	Initial Values
Backlog	$dt \cdot \text{Demand} - dt \cdot \text{Shipments}$	units	0
Finished Goods Inventory	$dt \cdot \text{Net Production Rate 3} - dt \cdot \text{Shipments}$	units	31.25
Raw Materials	$-dt \cdot \text{Gross Production Rate 1}$	units	10^{10}
WIP 1	$dt \cdot \text{Net Production Rate 1} - dt \cdot \text{Gross Production Rate 2}$	units	1
WIP 2	$dt \cdot \text{Net Production Rate 2} - dt \cdot \text{Gross Production Rate 3}$	units	1
Demand	As defined in section 5	units/time period	NA
Gross Production Rate 1	MAX(MIN(Raw Materials/T1, Desired Production Rate),0)	units/time period	NA
Gross Production Rate 2	Subject to Production Rates control policy (Subsection 4.3)	units/time period	NA
Gross Production Rate 3	Subject to Production Rates control policy (Subsection 4.3)	units/time period	NA
Net Production Rate 1	$\text{Gross Production Rate 1} \cdot \text{Yield 1}$	units/time period	NA
Net Production Rate 2	$\text{Gross Production Rate 2} \cdot \text{Yield 2}$	units/time period	NA
Net Production Rate 3	$\text{Gross Production Rate 3} \cdot \text{Yield 3}$	units/time period	NA
Shipments	MIN(Finished Goods Inventory/Shipment Time, Backlog/Shipment Time)	units/time period	NA
Yield 1	Constant	dimension-less	0.87
Yield 2	Constant	dimension-less	0.90
Yield 3	Constant	dimension-less	0.95
T1	Subject to Production Rates control policy (Subsection 4.3)	time periods	NA
T2	Subject to Production Rates control policy (Subsection 4.3)	time periods	NA
T3	Subject to Production Rates control policy (Subsection 4.3)	time periods	NA

Appendix B: Equations required for the production ordering system presented in Figure 3

Variable	Equations	Units	Initial Values
Forecasted Demand	DELAYINF(Demand,ST,1)	units/time period	NA
Desired Production Rate	$\frac{\text{Forecasted Demand}}{\text{Yield1} \cdot \text{Yield2} \cdot \text{Yield3}} + \frac{\text{EWIP1}}{T_{w1}} + \frac{\text{EWIP2}}{T_{w2}} + \frac{\text{EFGI}}{T_i} + \frac{\text{Back log}}{T_b}$	units/time period	NA
EWIP1	TWIP1-WIP1	units	NA
EWIP2	TWIP2-WIP2	units	NA
EFGI	TFGI - Finished Goods Inventory	units	NA
TWIP1	$\frac{\text{Forecasted Demand}}{\text{Yield2} \cdot \text{Yield3}} \cdot T2$	units	NA
TWIP2	$\frac{\text{Forecasted Demand}}{\text{Yield3}} \cdot T3$	units	NA
TFGI	constant	units	0
ST	constant	time periods	8
T_{w1}	constant	time periods	2
T_{w2}	constant	time periods	2
T_i	constant	time periods	2
T_b	Equals total manufacturing lead time (T1+T2+T3)	time periods	NA

Appendix C: Equations required for the VC approach presented in Figure 6

Variable	Equations	Units	Initial Values
Gross Production Rate 2	MAX(MIN(DELAYMTR(Net Production Rate 1,T2/n,n,0), Feasible Production 2),0)	units/time period	n=1 or 3
Gross Production Rate 3	MAX(MIN(DELAYMTR(Net Production Rate 2,T3/n,n,0), Feasible Production 3),0)	units/time period	n=1 or 3
T1	Raw Materials / Feasible Production 1	time periods	NA
T2	WIP1 / Feasible Production 2	time periods	NA
T3	WIP2 / Feasible Production 3	time periods	NA
Feasible Production i	Capacity i · Capacity Utilization i	units/time period	i= 1, 2, 3
Capacity Utilization 1	f(Raw Materials Ratio / Capacity Ratio 1)	%	NA
Capacity Utilization 2	f(WIP Ratio 1 / Capacity Ratio 2)	%	NA
Capacity Utilization 3	f(WIP Ratio 2 / Capacity Ratio 3)	%	NA
Raw Materials Ratio	Raw Materials / Normal Raw Material	Dimension-less	NA
WIP Ratio i-1	WIP i-1 / Normal WIP i-1	Dimension-less	i=2,3
Capacity i Ratio	Capacity i / Normal Capacity i	Dimension-less	i=1, 2, 3
Capacity i	constant	units/time period	50 (i=1,2,3)
Normal Capacity i	constant	units/time period	50 (i=1,2,3)
Normal Raw Material	constant	units	NA
Normal WIP i-1	constant	units	i=2,3

References

Asmundsson J, Rardin RL, Uzsoy R. 2003. An experimental comparison of linear programming models for production planning utilizing fixed lead time and clearing functions. Research Report, School of Industrial Engineering, Purdue University, West Lafayette.

Asmundsson J, Uzsoy R, Rardin RL. 2002. An alternative modeling framework for aggregate production planning. Research Report, School of Industrial Engineering, Purdue University, West Lafayette.

Billington PJ, McClain JO, Thomas LJ. 1983. Mathematical programming approaches to capacity-constrained mrp systems: Review, formulation and problem reduction. *Management Science* **29(**10): 1126-1137.

Disney SM. 2001. The production and inventory control problem in vendor managed inventory supply chains. *Ph.D. Thesis, Cardiff Business School, Cardiff University.*

Disney SM, Towill DR. 2002. A discrete transfer function model to determine the dynamic stability of a vendor managed inventory supply chain, *International Journal of Production Research* **40**(1): 179-204.

Disney SM, Potter AT, Gardner BM. 2003. The impact of vendor managed inventory on transport operations. *Transportation Research Part E* **39**: 363-380.

Enns ST, Choi S. 2002. Use of GI/G/1 queuing approximations to set tactical parameters for the simulation of mrp systems. *Proceeding of the 34th Conference on Winter Simulation: Exploring New Frontiers,* 1123-1129.

Enns ST, Suwanruji P. 2004. Work load responsive adjustment of planned lead times. *Journal of Manufacturing Technology Management* **15(**1): 90-100.

Graves SC. 1986. A tactical planning model for job shops. *Operations Research* **34**: 522-533.

Hackman ST, Leachman RC. 1989. A general framework for modeling production. *Management Science* **35**: 478-495.

Haskose A, Kingsman BG, Worthington D. 2004. Performance analysis of make-to-order manufacturing systems under different workload control regimes. *International Journal of Production Economics* **90**: 169-186.

Hwang S, Uzsoy R. 2004. A single-product dynamic lot sizing model with work in process and congestion. Technical Report, School of Industrial Engineering, Purdue University, West Lafayette.

John S, Naim MM, Towill DR. 1995. Dynamic analysis of a WIP compensated decision support system. *International Journal of Manufacturing System Design* **1(**4): 283-297.

Karmarkar US, Kekre S, Kekre S. 1987. Capacity analysis of a manufacturing cell. *Journal of Manufacturing Systems* **6**(3): 165-175.

Karmarkar US. 1989. Batching to minimize flow times on parallel heterogeneous machines. *Management Science* **35**: 607-613.

Karmarkar US. 1993. Manufacturing lead times, order release and capacity loading. *Logistics of Production and Inventory, Handbooks in Operations Research and Management Science* **4**: 287-329.

Land MJ, Gaalman G. 1996. Workload control concepts in job shop. A critical assessment. *International Journal of Production Economics* **46-47**: 535-548.

Little JDC. 1961. A proof of the queuing formula $L=\lambda W$. *Operations Research* **9**: 383-389.

Naim MM, Towill D.R. 1995. *What's in the pipeline? Second International Symposium on Logistics, Nottingham, UK.*

Orcun S, Uzsoy R, Kempf K. 2006. Using system dynamics simulations to compare capacity models for production planning. *Proceeding of the 2006 Winter Simulation Conference.*

Pahl J, Voß S, Woodruff DL. 2005. Production planning with load dependent lead times. *4OR: A Quarterly Journal of Operations Research* **3**: 257-302.

Riddalls CE, Bennett S. 2002. Production-inventory system controller design and supply chain dynamics. *International Journal of Systems Science* **33**(3): 181-195.

Srinivasan A, Carey M, Morton TE. 1988. Resource pricing and aggregate scheduling in manufacturing systems. *Working Paper, GSIA, Garnegie-Mellon University.*

Stalk Jr. G, Hout TM.. 1992. *Competing against time.* FreePress: New York.

Sterman JD. 1989. Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science* **35**(3), 321-339.

Sterman JD. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World.* Irwin, McGraw-Hill: Boston, MA.

Tang O, Naim MM. 2004. The impact of information transparency on the dynamic behavior of a hybrid manufacturing/remanufacturing system. *International Journal of Production Research* **42**(19): 4135-4152.

Towill DR. 1982. Dynamic analysis of an inventory and order based production control system. *International Journal of Production Research* **20**(6): 671-687.

Wikner J. 2005. Dynamic analysis of a production-inventory model. *Kybernetes* **34**(6): 803-823.