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A System Dynamics Analysis of the Effects of Capacity Limitations in a Multi-Level Production Chain

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Abstract

In a production chain machines, man power, space and other resources are limiting the available capacity to produce a certain output in a given time. The paper investigates different ways of modeling such a limited production chain.

One way is to build a chain of single levels, each with a first-order-delay and a capacity constraint of its own. Usually this modeling is substituted by a single level with a n-order-delay (n>1) having a capacity constraint. A second simplification is a single level having a capacity restriction and a first-order-delay with a longer delay time.

It can be shown that in case the limit is achieved the behavior of the different production chain models are different to eachother. The paper presents the structure of the underlying system dynamics models and their behavior for certain scenarios. Finally the restrictions of black-box-delay-functions, available in different system dynamics modeling software packages, are discussed in general, focusing on their functionality and the risk of misinterpretation.

Content

1 The Multi-Level Production Chain System

1.1 Theoretical Background and Practical Relevance

A production process that is split into several sub-processes, depending on eachother, can be called a *production chain* (see Dyckhoff 1998, p. 101). If the production sub-processes can be arranged in separate stations the chain is called a multi-level production chain (MLPC). In a wider sense, larger logistic systems fulfill similar tasks. Such systems are called *supply chains* (see Disney/Naim/Towill 1997, p. 174-176; Towill 1996, p. 29). But this paper focuses only on production chains.

In practice most of the output of industrialized fabrication is manufactured in production chains. Even very simple products are produced in MLPCs because of economic efficiency reasons (e.g. economics of scale). Jirik (1999), König (1997), Bazargan-Lari (1996), Dankert (1994), Sushil (1991) and Schulze (1988) give an overview about today's factory layout.

Since some years there is a remarkable trend to build up not only MLPCs within a single enterprise, but to incorporate production processes beforehand with the own ones to an *integrated MLPC network* that crosses the juridical boundaries of at least two companies (see Bellmann 1996, and Dyckhoff 1996).

The objectives of the majority of the MLPC models are the optimization of the material flow under uncritical circumstances (see Lanzenauer von/Pilz-Glombik 2000; Zäpfel/Wasner 2000; Günther/Blömer 1997; Kurbel 1978; Forrester 1961) and the examination of backlog in unlimited production or supply chains (see Fung 1999; Lee/Padmanabhan/Whang 1997).

Some authors introduce some new aspects of MLPCs simulation. Chen (1999) gives attention to the information flows within such systems. Dyckhoff (1998a) connects production chain themes with environmental matters.

1.2 Limitations in MLPCs

In all production chains the control of the material flow in time and in numbers is a necessity (see Evans/Naim/Towill 1998; Disney/Naim/Towill 1997a). The control has to ensure that the right parts (in the sense of products at different states of fabrication) have to be at the right time at the right place, where they can be manufactured into new products. The single sub-processes can be arranged in different orders – one after the other, parallel or in form of a network (see fig. 1). A more complex order requires a more complex control system.

The most important influencing factors of that control system are:

1. the **amount of products** that should be produced,
2. the **amount and quality of additional goods** that are necessary to produce these products,
3. the **quality of the parts**,
4. the correct **spatial allocation** of the parts,
5. the correct **temporal allocation** of the parts, and
6. the time a part rests at a production station in average (**average duration time**).

The parts symbolize the input of a production station, the products represent its output (and becoming parts for the next station). In the context of this paper additional goods is defined as material or service that is necessary for production, but not fabricated in the observed system. This material or service is bought by the logistic division and delivered to the production station, where it is consumed. Of course there is always an easy way to let the system work without any problems. If we install and fill large input and output storages combined with large production capacity reserves the system is robust against all quantitative interferences to the material flow.

But according to the economic constraints (e.g. maximization of profit, minimization of requested resources or maximization of customer utility) this material flow can not be realized. It would be to expansive. The relationship between cost accounting and complex production structures has been analyzed for instance by Schmalenbach (1909) and Kistner/Luhmer (1977).

In most cases the amount of products that should be produced (= the production plan) is determined by the sales division. The production division's only control on this variable is to set some ranges in which the plan can alter.

The inflow of additional goods has to be maintained by the logistic division. The special problems that take place in just-in-time production systems are named by Kalagnanam/Lindsay (1996).

The quality of the parts produced by production stations in advance depends highly on the skills and motivation of the interacting staff (see Mukherjee/Lapré/van Wassenhove 1998; Kübel 1997; Mandal/Howell/Sohal, 1996).

The spatial and temporal allocation of the parts has to be controlled by the production division itself. The problems that can occur here are problems of the internal transport and the storage of parts when the following production station is unable to bring in the arriving parts directly (see Lee/Padmanabhan/Whang 1997; Lee/Padmanabhan/Whang 1997a; Naim/Towill 1995).

The last point is highly related to the average duration time. Even if the production time is constant, more capacity decreases the average duration time by an increase of products in process. Hamilton (1980) and Kellerer (1958) investigated the problems of measuring the average duration time.

In sum, the production plan, given by the sales division, defines the quantitative objective of the production division. The resulting material flows can be limited in the production chain by:

1. the capacity of the internal transportation,
2. the capacity of storages between two stations, and
3. the capacity of each production station itself.

Dynamic models containing such limitations are rare. Gavirneni/Kapuscinski/Tayur (1999), Meyer/Ausubel (1999), Mason-Jones/Naim/Towill (1997), and Jeong/Maday (1996) portray models and simulations with limiting constraints.

2 The Modeling of a System Dynamics MLPC Model

2.1 General Underlying Assumptions of the MLPC Model

The system dynamics model of the multi-level production chain that is used in this paper has the following assumptions.

1. A basic product needs three steps (production sub-processes) to become a final product.
2. The is no waste production. Therefore to assemble one final product only one basic product is needed.
3. At all production stations there is a constant requirement for machines, labor and parts used to transform an incoming product into an outgoing product. This linear production technology will not be changed within the observed time horizon.
4. At all time the logistic system of the enterprise is able to support the production system with all additional goods at every amount and quality needed. The handling of this bottleneck is the task of the logistic division of the enterprise, but not of the production division.
5. The assembled product is a embeddable high-quality capital commodity with a fixed production procedure.

2.2 The Structure of the MLPC Model

The structure of such a multi-level production chain can be described as a row of level variables connected with eachother by some rates. The stocks represent the production stations in which the arriving products are transformed into a new semifinal product. The flows stand for the transport of the products from one station to the next. Figure 1 shows two illustrations of production chains. The first is a simple line production, the second is a convergent chain.

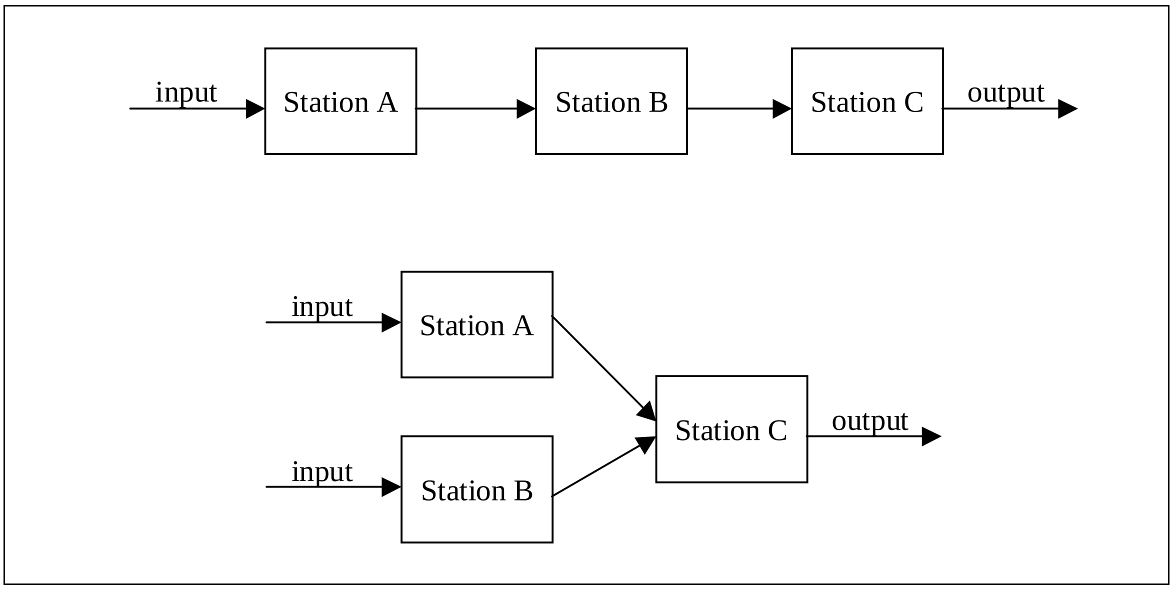

Fig. 1: Two Possible Production Chains

The system's boundaries are defined by the inflow of basic products to the first production level and the outflow of final products from the last production level. With the exception of integrated MLPC networks basic products can be seen as goods already produced and available on an external of internal market at a certain price. The final product typically flows into a sales storage ready to be sold to a customer. Any quality check and rework is not part of the production chain anymore.

Observing the behavior of a production chain a model is needed that creates a continuous flow of data about the material status of all stocks and flows (see Olsmats/Edghill/Towill 1998; Towill/Hafeez/Ferris 1993). Baines/Harrison (1999), Mildenberger (1998), and Forrester (1961) explain the general utility of the system dynamics approach for modeling and analyzing MLPCs in the requested way.

Figure 2 displays the system dynamics structure of the MLPC of scenario 1 as a row of first-order delays (see equations L-04, L-06, L-08, and L-01). The structure in the second scenario is identical, with the exception of the final numeral in the variable names. Initially the MLPC is completely empty, according to the fabrication start of a new lot in reality.

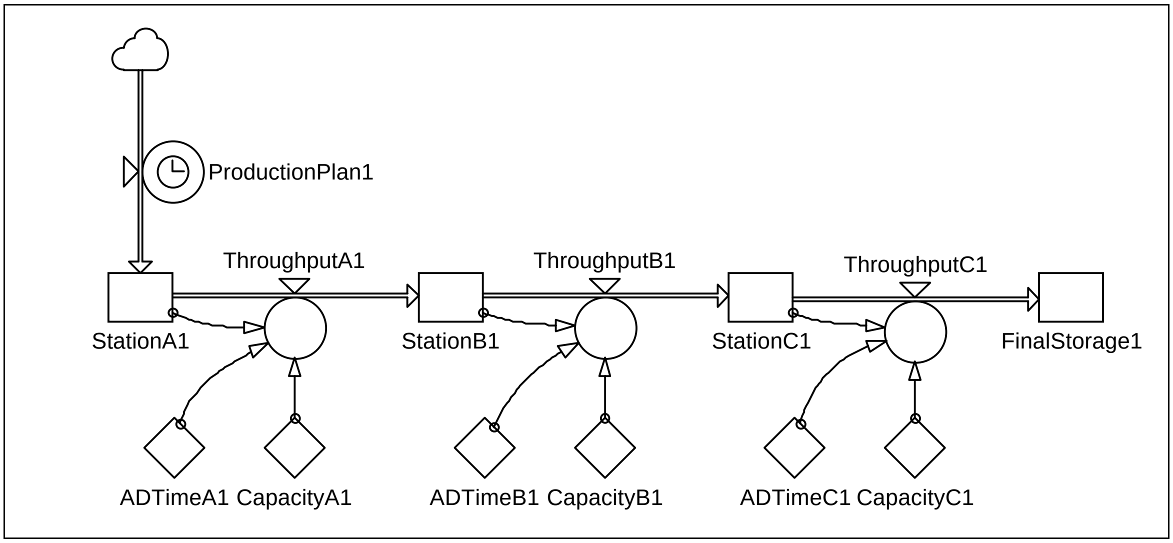

Fig. 2: Model Structure of the MLPC Model with Several First-Order Delays

L-04 $StationA1_t$ Init = 0 [units]
= $StationA1_{t-1}$
+ $ProductionPlan1_t$
- $ThroughputA1_t$

L-06 $StationB1_t$ Init = 0 [units]
= $StationB1_{t-1}$
+ $ThroughputA1_t$
- $ThroughputB1_t$

L-08 $StationC1_t$ Init = 0 [units]
= $StationC1_{t-1}$
+ $ThroughputB1_t$
- $ThroughputC1_t$

L-01 $FinalStorage1_t$ Init = 0 [units]
= $FinalStorage1_{t-1}$
+ $ThroughputC1_t$

The average duration time is the same at all stations. Different duration phases would change the quantitative results, but not the qualitative statement of the paper.

C-02 ADTimeA1 [h]
= 5

C-04 ADTimeB1 [h]
= 5

C-06 ADTimeC1 [h]
= 5

Figure 3 presents the system dynamics structure of the MLPC as one third-order delay (see equations L-03, R-09, and C-01). There the average duration time *ADT3* is set to 15 hours, consistent with equations C-02, C-04, and C-06).

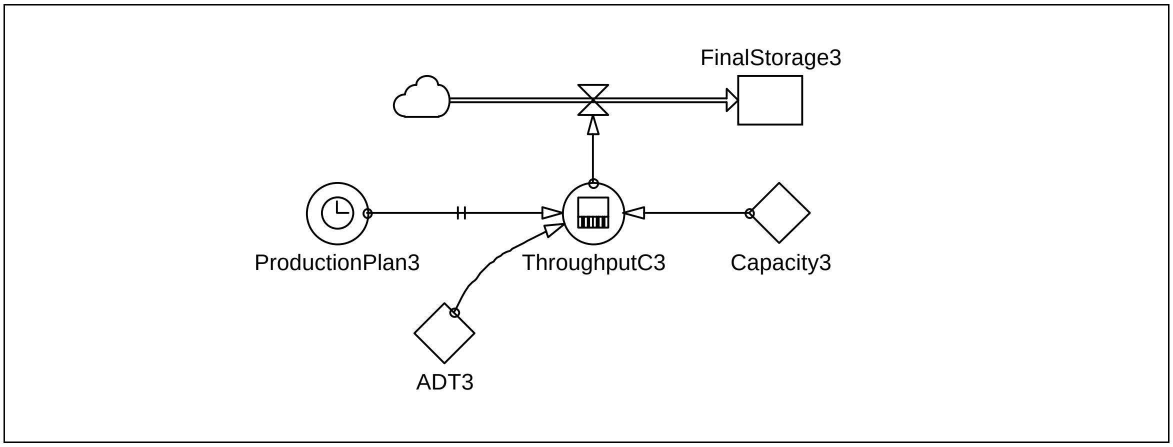

Fig. 3: Model Structure of the MLPC Model with One High-Order Delay

L-03	$FinalStorage3_t$	Init = 0	[units]
	= $FinalStorage3_{t-1}$		
	+ $ThroughputC3_t$		
R-09	$ThroughputC3_t$		[units / h]
	= FLOOR(MIN(DELAYMTR($ProductionPlan3_t$, ADT3,3,0), Capacity3))		
C-01	ADT3		[h]
	= 15		

2.3 Implementation of Limitations in the System Dynamics Model

The modeled MLPC is limited in its production capacity. For programming reasons, in scenario 1 this maximum is set on a multiple of the maximal possible production plan (see equations C-09, C-11, and C-13). Therefore the results are equal to the unlimited case. Because half done products can not be hand over to the next station the flows are rounded down to nearest integer (see equations R-03 to R-09).

R-03	$ThroughputA1_t$	[units / h]
	= FLOOR(MIN(($StationA1_t$ / ADTimeA1), CapacityA1))	
R-04	$ThroughputA2_t$	[units / h]
	= FLOOR(MIN(($StationA2_t$ / ADTimeA2), CapacityA2))	
R-05	$ThroughputB1_t$	[units / h]
	= FLOOR(MIN(($StationB1_t$ / ADTimeB1), CapacityB1))	
R-06	$ThroughputB2_t$	[units / h]
	= FLOOR(MIN(($StationB2_t$ / ADTimeB2), CapacityB2))	
R-07	$ThroughputC1_t$	[units / h]
	= FLOOR(MIN(($StationC1_t$ / ADTimeC1), CapacityC1))	
R-08	$ThroughputC2_t$	[units / h]
	= FLOOR(MIN(($StationC2_t$ / ADTimeC2), CapacityC2))	
R-09	$ThroughputC3_t$	[units / h]
	= FLOOR(MIN(DELAYMTR($ProductionPlan3_t$, ADT3,3,0), Capacity3))	

C-08 Capacity3 [units / h]
= 25

C-09 CapacityA1 [units / h]
= 250

C-10 CapacityA2 [units / h]
= 25

C-11 CapacityB1 [units / h]
= 250

C-12 CapacityB2 [units / h]
= 25

C-13 CapacityC1 [units / h]
= 250

C-14 CapacityC2 [units / h]
= 25

The storage and transportation capacities are unlimited. A combination of limitations causes multiple disturbances in the material flow, which can be an aim of further research (see Cachon/Zipkin 1999).

Of course capacity is no constant per se, but in reality all capacity changes, rather they are of increasing or decreasing nature, need investments. All according decisions are depending on long-run strategy, which are not relevant in this paper (see Cachon/Lariviere 1999; Funk/Hax/Potthoff 1984).

3 Simulation and Results

3.1 The Simulated Scenarios

The time horizon is five weeks, divided into 5 working days per week and 8 working hours per day. In total the simulation runs through 200 time periods.

There are three scenarios simulated:

1. Unlimited production capacities (see fig. 2),
2. Fixed production capacities modeled as several first-order delays (see fig. 2), and
3. Fixed production capacities modeled as one high-order delay (see fig. 3).

In all scenarios the growth of the production plan will quickly break through the initially available capacities (= 20 units). After three weeks the demand is reduced to a level below the maximal capacity. Equation R-01 and figure 4 show the production plan for the first scenario as an example for all identical production plans.

R-01 $ProductionPlan1_t$ [units / h]
= STEP(30, 16) - STEP(22, 136)

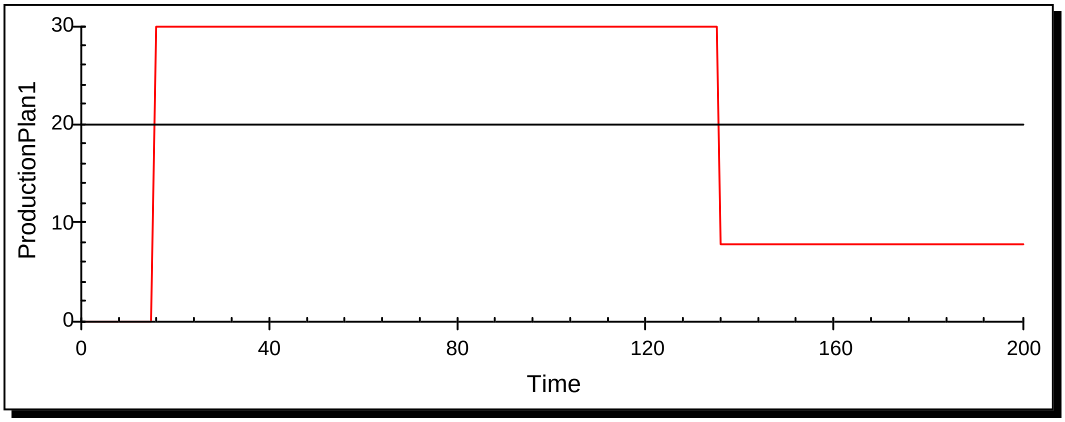

Fig. 4: The Production Plan

The reason for a seasonal growth depends on the fact that a permanent one would deepen any occurring problem constantly. The system would explode. Betz (1999) expresses the special economic relevance of such seasonal alternations.

3.2 Simulation Results and Analysis

The simulation focus only on the physical aspects of the material flow. The information flows are ignored. The economic consequences are objectives for further research. See Lehmann (1998) and Czeranowsky (1992) for the special costs of capacity changes.

Figure 5 illustrates the material flows within the MLPC in the scenario 1 and 2. The variables *ThroughputA1*, *ThroughputB1*, and *ThroughputC1* stand for scenario 1. The variables *ThroughputA2*, *ThroughputB2*, *ThroughputC2* belong to scenario 2. Because of the achieved limits in scenario 2 the MLPC needs more time to reach the new equilibrium. In scenario 1 it is achieved at time step 167, in scenario 2 at time step 199 (= 4 days later).

A second result of figure 5 is the dependency of the lateness on the number of stations in the production chain. More stations would increase the lateness tremendously.

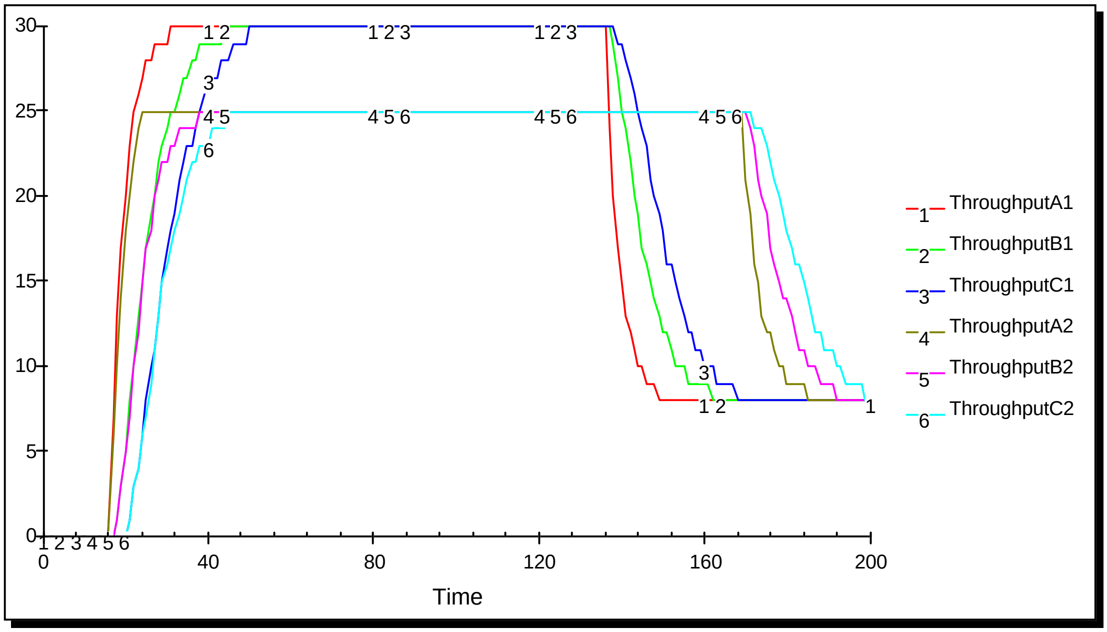

Fig. 5: The Material Flows in Scenario 1 and 2

In figure 6 the throughputs of all three scenarios from the station C to the final storage are compared with eachother. The unlimited *ThroughputC1* marks the undisturbed reference mode. In the first week all three models react approximately in the same way. Then the limits in scenario 2 and 3 force the *ThroughputC2* and *ThroughputC3* to stay at the same level. The difference occur when the *ThroughputC1* crosses the *ThroughputC2* respectively *ThroughputC3*. From that point on (time step 145) scenario 1 and 3 are equal to eachother, with the exception of mathematical rounding differences.

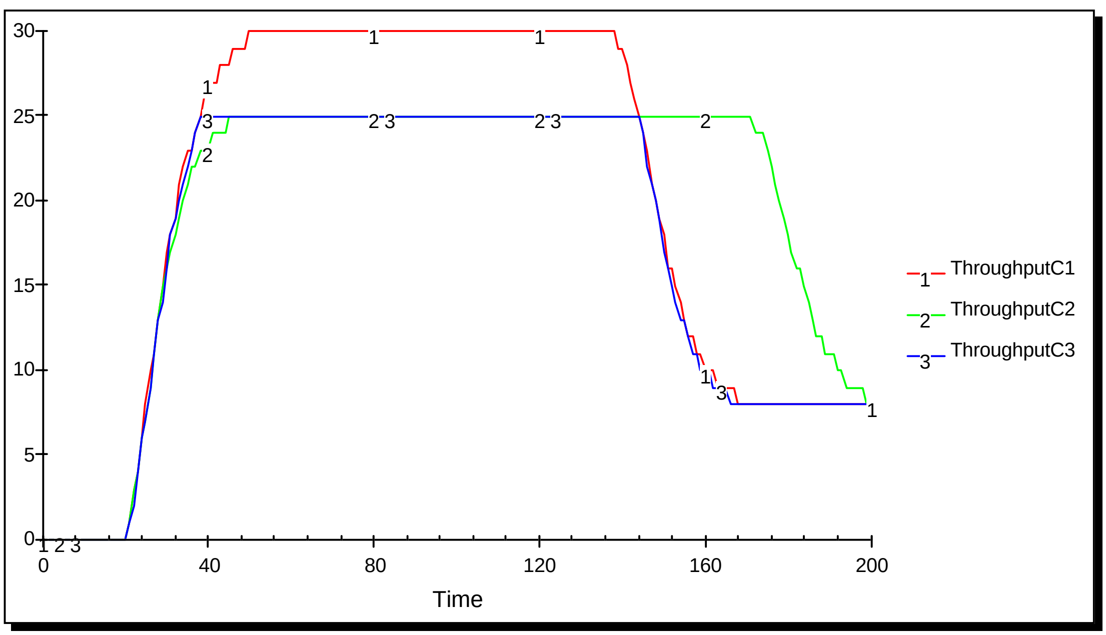

Fig. 6: The Final Throughputs

Figure 7 presents the consequences of that behavior. The final storage values in scenario 1 and 2 are the same. The reason is that both scenarios get to the new equilibrium in the bounds of the simulation horizon. Not at the same time, but they do. The change of behavior of scenario 3 in time step 145 causes that scenario 3 achieves the same equilibrium, but to early to produce the same amount of products. The final results are 3,980 units in scenario 1 and 2, scenario 3 ends with 3,471 units.

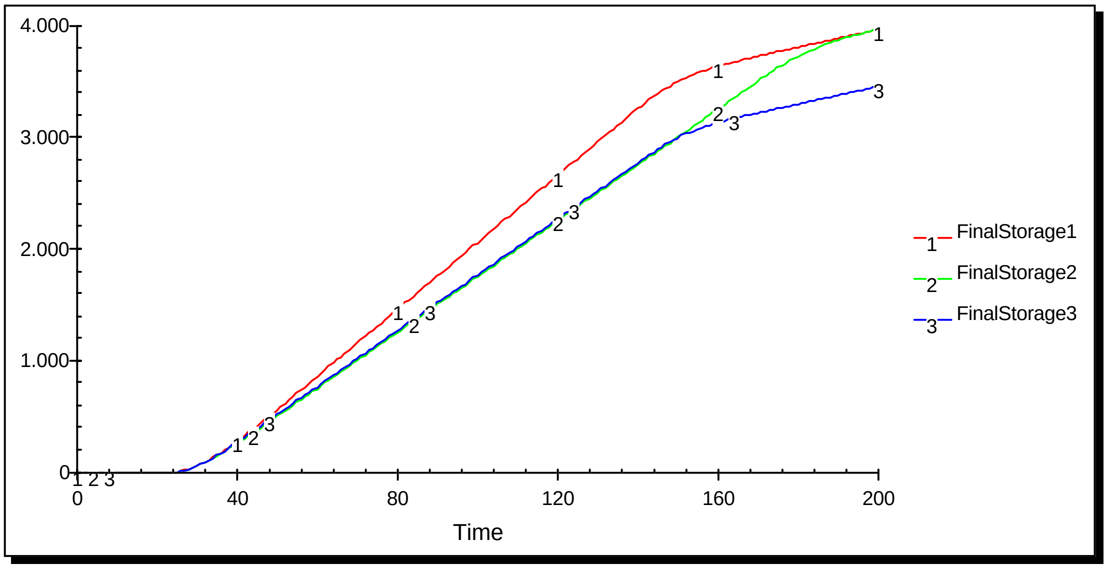

Fig. 7: The Accumulated Final Storage Values

Figure 8 presents the delivery backlogs that would occur if the production plan is equal to the customers order behavior. The two numerals right after the variable name indicate the two scenarios that are compared with eachother.

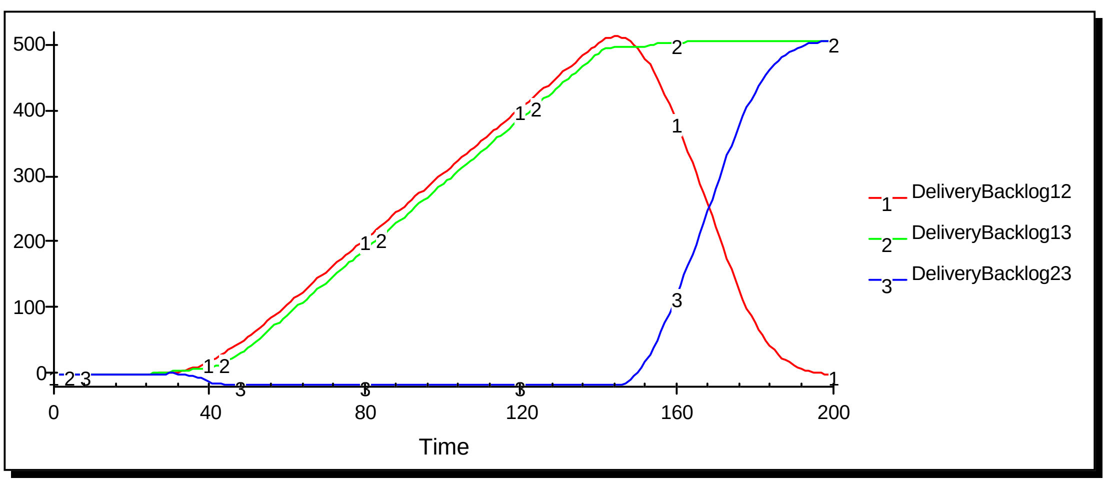

Fig. 8: Delivery Backlog

4 Restrictions of the Use of Block-Box-Functions

As seen in the simulations above, the high-order delay structure causes incorrect results just before reaching the limit and from that point on when the capacity restriction is crossed. An enlargement of the time horizon is unable to correct this failure. The reason is that one n-order delay is equal to n rowed first-order delays only if there is no internal limit passed through.

There are two methods to model such structures – building one first-order delay after the other, or using a pre-modeled delay-function, which is available in all modern simulation software packages. The second way has some advantages – for instance shorter modeling time and smaller models. But the pre-modeled function acts like a black-box. One send some data into the black-box and receives a certain output. There is no data about what happens in the black-box.

As a conclusion one can say that the use of high-order delay-functions is recommended only if one knows the internal behavior before modeling. The simulations above show clearly that this is not easy to decide. In all other cases the explicit modeling of series of first-order delays is unavoidable.

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6 Equations

L-01 $FinalStorage1_t$ Init = 0 [units]
= $FinalStorage1_{t-1}$
+ $ThroughputC1_t$

L-02 $FinalStorage2_t$ Init = 0 [units]
= $FinalStorage2_{t-1}$
+ $ThroughputC2_t$

L-03 $FinalStorage3_t$ Init = 0 [units]
= $FinalStorage3_{t-1}$
+ $ThroughputC3_t$

L-04 $StationA1_t$ Init = 0 [units]
= $StationA1_{t-1}$
+ $ProductionPlan1_t$
- $ThroughputA1_t$

L-05 $StationA2_t$ Init = 0 [units]
= $StationA2_{t-1}$
+ $ProductionPlan2_t$
- $ThroughputA2_t$

L-06 $StationB1_t$ Init = 0 [units]
= $StationB1_{t-1}$
+ $ThroughputA1_t$
- $ThroughputB1_t$

L-07 $StationB2_t$ Init = 0 [units]
= $StationB2_{t-1}$
+ $ThroughputA1_t$
- $ThroughputB2_t$

L-08 $StationC1_t$ Init = 0 [units]
= $StationC1_{t-1}$
+ $ThroughputB1_t$
- $ThroughputC1_t$

L-09 $StationC2_t$ Init = 0 [units]
= $StationC2_{t-1}$
+ $ThroughputB1_t$
- $ThroughputC2_t$

R-01 $ProductionPlan1_t$ [units / h]
= STEP(30, 16) - STEP(22, 136)

R-02 $ProductionPlan2_t$ [units / h]
= STEP(30, 16) - STEP(22, 136)

R-03 $ThroughputA1_t$ [units / h]
= FLOOR(MIN(($StationA1_t$ / ADTimeA1), CapacityA1))

R-04 $ThroughputA2_t$ [units / h]
= FLOOR(MIN(($StationA2_t$ / ADTimeA2), CapacityA2))

R-05 $ThroughputB1_t$ [units / h]
= FLOOR(MIN(($StationB1_t$ / ADTimeB1), CapacityB1))

R-06 $ThroughputB2_t$ [units / h]
= FLOOR(MIN(($StationB2_t$ / ADTimeB2), CapacityB2))

R-07 $ThroughputC1_t$ [units / h]
= FLOOR(MIN(($StationC1_t$ / ADTimeC1), CapacityC1))

R-08 $ThroughputC2_t$ [units / h]
= FLOOR(MIN(($StationC2_t$ / ADTimeC2), CapacityC2))

R-09 $ThroughputC3_t$ [units / h]
= FLOOR(MIN(DELAYMTR($ProductionPlan3_t$, ADT3,3,0), Capacity3))

A-01	$DeliveryBacklog12_t$	[units]
	= $FinalStorage1_t - FinalStorage2_t$	
A-02	$DeliveryBacklog13_t$	[units]
	= $FinalStorage1_t – FinalStorage3_t$	
A-03	$DeliveryBacklog23_t$	[units]
	= $FinalStorage2_t – FinalStorage3_t$	
A-04	$ProductionPlan3_t$	[units]
	= STEP(30, 16) - STEP(22, 136)	
C-01	ADT3	[h]
	= 15	
C-02	ADTimeA1	[h]
	= 5	
C-03	ADTimeA2	[h]
	= 5	
C-04	ADTimeB1	[h]
	= 5	
C-05	ADTimeB2	[h]
	= 5	
C-06	ADTimeC1	[h]
	= 5	
C-07	ADTimeC2	[h]
	= 5	
C-08	Capacity3	[units / h]
	= 25	
C-09	CapacityA1	[units / h]
	= 250	
C-10	CapacityA2	[units / h]
	= 25	
C-11	CapacityB1	[units / h]
	= 250	
C-12	CapacityB2	[units / h]
	= 25	
C-13	CapacityC1	[units / h]
	= 250	
C-14	CapacityC2	[units / h]
	= 25	