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Simulation Modeling and Optimization of Multi-Echelon Supply Chains

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ABSTRACT

This paper presents a study of the elements of the four tier supply chain (beer game) model and the initial analysis of the effects of its parameters. One of the most commonly applied methodologies to study the various aspects of the beer game model is the control theoretic approach, which focuses on linear modeling. However, System dynamic simulation, used in this research, is ideal for mapping complex interactions among design parameters and for studying non-linear outputs through "What If" analysis. Furthermore, most of the previous research into the effects of parameter values of production control systems was focused on single echelons, whereas this Paper studies the effects on the dynamic performance of a whole supply chain. Production and inventory control systems seldom exist in isolation, but are connected in series and in parallel to form a complex supply chain. Significant benefits can be gained by doing what is best for the overall supply chain rather than what is best solely for the single echelon. Focusing on the design of a single echelon in isolation without reference to the rest of the supply chain can lead to poor performance overall. It is believed that "A sequence of locally optimized systems cannot guarantee a global optimum." Therefore, the whole supply chain should be taken as a single entity and the best parameter values should be derived with respect to the performance of the whole. This is a contribution to continuing research on modeling and optimization of multi-echelon supply chains, giving practitioners and academicians a practical into exploring the impact of different design parameters on the dynamic response of the inventory and order rate of supply chains.

Keywords: Supply Chain Modelling, Simulation, Optimizations, Beer Game Model

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1. Introduction

This paper presents a study of the elements of the four tier supply chain (beer game) model and the analysis of the effects of its parameters. Most of the previous research into the effects of parameter values of production control systems was focused on single echelons (John et all 1994, Riddalls et al 2002), whereas this research studies the effects on the dynamic performance of a whole supply chain. Production and inventory control systems seldom exist in isolation, but are connected in series and in parallel to form a complex supply chain. Significant benefits can be gained by doing what is best for the overall supply chain rather than what is best solely for the single echelon. Focusing on the design of a single echelon in isolation without reference to the rest of the supply chain can lead to poor performance overall. Riddalls et al (2000) also pointed out, "*A sequence of locally optimized systems cannot guarantee a global optimum."* Therefore, the whole supply chain should be taken as a single entity and the best parameter values should be derived with respect to the performance of the whole.

The remainder of this paper is organized as follows. The next section provides brief survey of the related literature. In section 3, the methodology is introduced and then the supply chain simulation model is presented in section 4. After that, analysis is presented in section 5 and section 6 concludes.

2. Review of Results in the Literature

The two main design objectives for the robust production and inventory control system are good inventory recovery and attenuation of demand rate fluctuation on the ordering rate (Sarimveis et al., 2008). However, these performance objectives can be conflicting. A trade-off between good inventory recovery and fine rejection of random demand disturbances needs to be explored. To do this, the performance measures discussed above coupled with graphical techniques are used to investigate the impact of design parameters on the performance of the system. Sterman (1987) assumed, through his beer game model, that Tw $\geq$ Ti, because managers always put more emphasis on their inventory levels than the pipeline. Sterman argues this is reasonable since inventory discrepancies are much more immediately apparent to managers than the variances in the pipeline. John et al (1994) found that for a deterministic input in a single echelon of the APIOBPCS model, Ti = Tp, Tw=Ta=2Tp is a 'good' design. This setting was derived using classical control theory and simulation. This combination avoids unnecessary fluctuations in the inventory and order rate whilst the recovery time is not excessively long. Mason-Jones et al. (1997) explored parameter settings for pipeline feedback that ensures good control of material flow in a four echelon supply chain. They found that the setting of the design parameters for inventory, pipeline, and forecasting is directly related to the production or process lead time. They found that Ti = Tp = Tw and Ta = 2 Tp are the best settings for the four echelon beer game model. Disney et al. (1997) used Laplace-transform transfer-functions and simulation and in order to achieve a trade-off between controlling the bullwhip effect and inventory variances, they proposed that Ti = 4, Tw = 15, Ta = 8 is a good design. Riddalls and Bennett (2002) studied the stability boundaries of a single echelon of the APIOBPCS with a pure time delay to model the production delay. Most notably, they found that the ratio of Ti to Tw plays the most important role in determining stability; for good dynamic behaviour (swift response, no overshoot, small inventory discrepancy, non-oscillatory behaviour) systems with Ti = Tw behave best and are most stable, i.e. furthest from instability. This finding confirmed the similar earlier finding of Sterman (1989). Riddalls and Bennett concluded that, "it is important to make inventory and WIP adjustments in similar proportions, otherwise one will overcorrect for the other, leading to oscillations." They showed how small increases in Tw, relative to Ti result in much poorer responses in the sense of greater oscillations. They also emphasised that larger values of Ti are undesirable as they lead to slower responses and larger inventory depletion.

3. Methodology

System dynamics is an approach to understanding complex systems, using modeling and simulation techniques capable of modeling feedback loops explicitly and evaluating the dynamics of complex processes and systems. If difference equations are used to model a system, as in the model presented here, then the model can be implemented in a spreadsheet to simulate the system in operation, for example (Shukla et al, 2009). This requires a reasonably good knowledge of spreadsheet modeling as well as difference equations. It is also very time consuming and prone to errors as the spreadsheet can soon become quite intricate and ultimately unwieldy. Proprietary software packages have been developed to be more user-friendly and functionally powerful for the task of systems dynamics modeling and simulation, especially in their user-interface. One package that is used commonly for system dynamics modeling is MATLAB® (e.g. Coppini et al., 2009), which has its origins in the traditional control engineering community. The particular system dynamics software used in this research is *iThink*®. This has been developed more for the business community rather than for control engineers, so it should be suitable for supply chain managers and designers. Models are built in *iThink*® using *flows* (e.g. of products from a factory to an inventory), *stocks* to model simple inventories or process delays such as a factory between flows, *connectors* to provide information flows (e.g. feedback of actual inventory levels for comparison with desired levels) and *converters* to apply gain factors or other formulae to variables – see Figure 1.

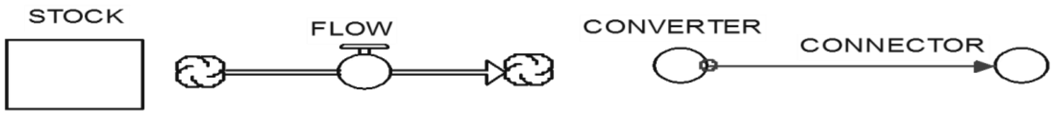

Figure 1: Building blocks of *iThink* software.

4. Multi-echelon supply chain model

Figure 2 presents the simulation model of the 4-echelon supply chain produced in *iThink*®. At the material flow level, each echelon consists of one inventory and one time delay, i.e. factory or other facility. Each echelon operates independently based on demand from downstream (towards the end-customer). At echelon-n, the input to the factory or other facility at time period *t* is the order rate ($ORATE^n_t$), which is determined by feeding forward the exponentially smoothed sales ($SSALES^n_t$), i.e. the demand forecast, and the actual end-customer demand, i.e. the smoothed sales from the retailer ($SSALES^1_t$), and feeding back the error in the inventory and the work-in-progress, with the aim of keeping the inventory at the desired level. The error in the inventory ($EINV^n_t$) is the difference between the desired inventory level ($DINV^n$) and the actual inventory level ($AINV^n_t$). Here, like Disney, S.M. and Towill, D.R. (2003), $DINV^n$ is kept constant and equal to original demand. The work-in-progress (WIP^n_t) is the accumulation of orders that have been placed on the echelon but not yet completed and the desired WIP is $DWIP^n_t$. The error in the WIP ($EWIP^n_t$) is the difference between the desired $DWIP^n_t$ and the actual WIP^n_t . Ti is a divisor applied to the inventory deficit to control the rate of recovery and *Tw* similarly controls the WIP replenishment rate.

Demand needs to be forecast at each tier before applying it in scheduling and there are potentially many methods to do this. Simple exponential smoothing is used in the APIOBPCS model used here. This is justified as it is the basis of much industrial practice and the approach used in other published models, e.g. (Mason-Jones and Towill, 1997) (Coppini et al., 2009) (Shukla et al, 2009) and (Hussain et al, 2016). In *iThink*® the built-in function SMTH1 calculates the first-order exponentially-smoothed value, with the smoothing constant (*Ta*) representing the time to average sales and the average age of data in the forecast. The value of *Ta* determines the degree of smoothing applied to the demand and is subject to $0 \leq 1/Ta \leq 1$.

$COMRATE^n_t$ is the completion (output) rate of the factory or facility at echelon-n. As a simple time delay (*Tp*) is used to model the lead time, $COMRATE^n_t$ is simply equal to $ORATE^n_{t\text{-}Tp}$. The actual inventory $AINV^n_t$ is the accumulation of stock determined by $COMRATE^n_t$ minus $SALES^n_t$

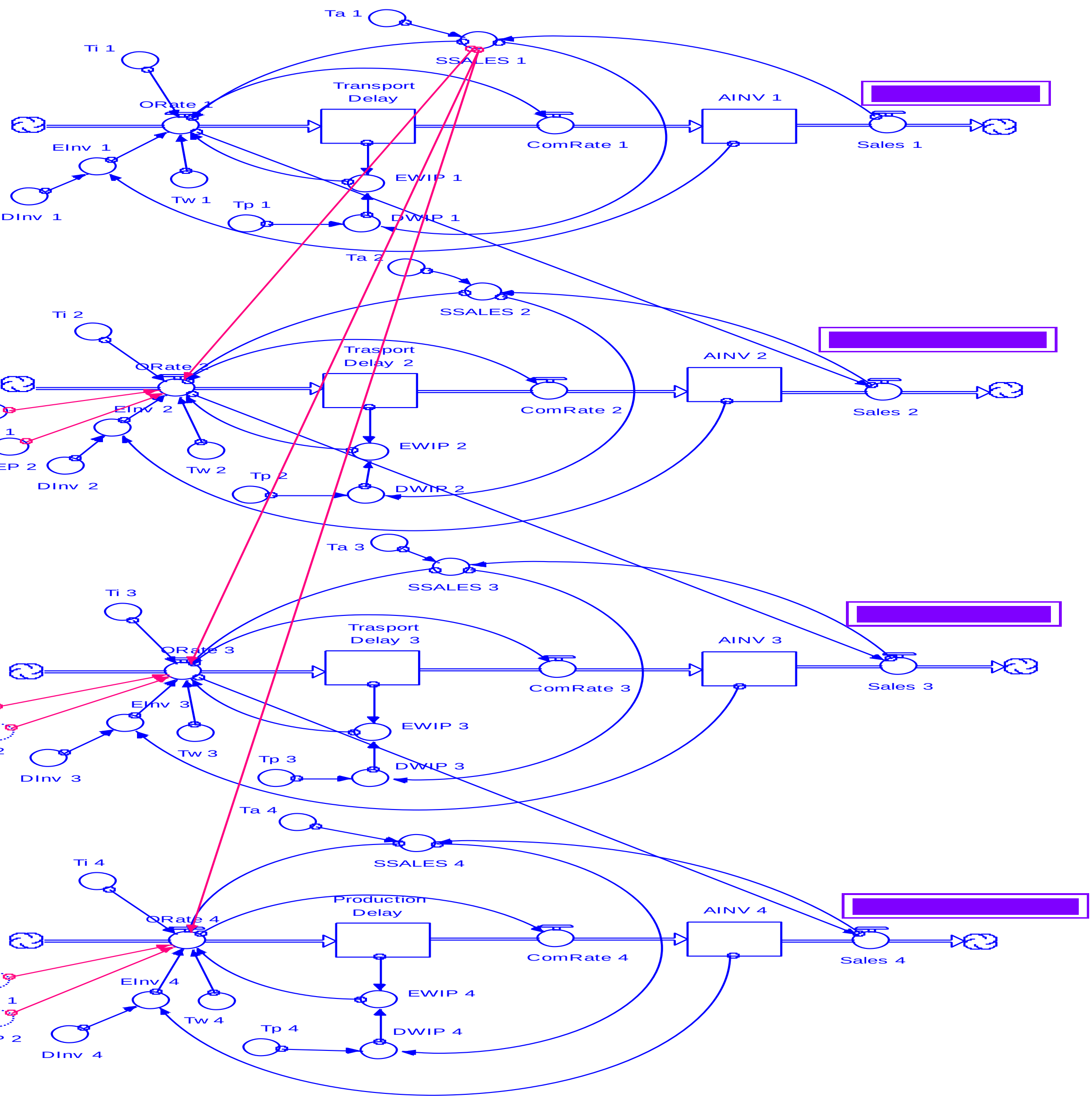

Figure 2: *iThink* model of information enriched multi-echelon supply chain

In summary, at echelon n:

for n=1: $SALES^{1}_{t}$ = the actual end-customer demand data (1)

for n>1: $SALES^{n}_{t} = ORATE^{n-1}_{t}$ (2)

$SSALES^{n}_{t} = SSALES^{n}_{t-1} + (SALES^{n}_{t} - SSALES^{n}_{t-1})/Ta^{n}$ (3)

for n>1: $ORATE^{n}_{t} = SSALES^{1}_{t} + EINV^{n}_{t}/Ti^{n} + EWIP^{n}_{t}/Tw^{n}$ (4)

for n=1: $ORATE^{1}_{t} = SSALES^{1}_{t} + EINV^{1}_{t}/Ti^{1} + EWIP^{1}_{t}/T$ (5)

$COMRATE^{n}_{t} = ORATE^{n}_{t-Tp}$ (6)

$AINV^{n}_{t} = AINV^{n}_{t-1} + COMRATE^{n}_{t} - SALES^{n}_{t}$ (7)

$DINV^{n} = SALES^{n}_{0}$ (8)

$EINV^{n}_{t} = DINV^{n} - AINV^{n}_{t}$ (9)

$DWIP^{n}_{t} = Tp^{n} \times SSALES^{n}_{t}$ (10)

$EWIP^{n}_{t} = DWIP^{n}_{t} - WIP^{n}_{t}$ (11)

5. Analysis

The test signal is a 20 % step increase in demand from 100 to 120 per week and the simulation is run for 100 weeks as this is enough to capture most of the steady-state responses. Three factors are considered, Ti, Tw and Ta at four levels as defined in Table 1. The appropriate orthogonal arrays of experiments are the L_{16} arrays in Table 2 where the columns are mutually orthogonal.

Factors	Level 1	Level 2	Level 3	Level 4
Ti	4	6	8	10
Tw	4	6	8	10
Ta	2	4	8	12

Table 1. Parameters & their levels

Experimental Run	Ti	Tw	Ta
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	3
6	2	2	4
7	2	3	1
8	2	4	2
9	3	1	1
10	3	2	2
11	3	3	3
12	3	4	4
13	4	1	4
14	4	2	3
15	4	3	1
16	4	4	2

Table 2. L16 Arrays

Those that go beyond this are simply regarded as 'very long' and unacceptable (well into the region of unacceptable parameter values), although care is taken to check that they do indeed settle on target. A deterministic step input evaluates the system's ability to cope with sudden but maintained change. The response to a step change in demand is of importance not only because it gives a shock to the system but additionally it is an input that is easily visualized and reveals the basic dynamic characteristics of the system (Bonney et al., 1994) and (Hussain et al., 2012). The order rate step responses for the sixteen different combinations of design parameters are given in Figure 3-5.The responses have been divided into two distinct groups. The first group (**Figures 3**) comprises responses that are clearly stable, without highly oscillatory behavior or large peak overshoots that could be described as over-reaction. The second group does display this excessive over- reaction in its peak responses and possibly oscillatory behavior, i.e. the responses are tending towards instability and are certainly unacceptable for the management of the inventory and production control system.

The second group comprises experiments 1-4 and 7-9 and Table 2 shows that they use small values for Ti, i.e. Ti = 4 or 6, with the exception of experiment 9 for which Ti=8. In general, it is well understood in control engineering that oscillatory behavior, leading to instability or over-reaction, can be introduced by feedback loops. With the small values of Ti the feedback of the error in the inventory has a greater effect as $EINV_t = (DINV_t - AINV_t)/Ti$ is larger, i.e. there is an increased gain in the loop and this provides an explanation for the over-reaction and oscillatory behavior seen in the second group. Experiments 5 and 6 do not experience such behavior, so it can be deduced that the particular values of the other parameters counteract and control this effect. This leads to the general finding that small values of Ti can produce feedback that is too lively unless tempered by suitable values of the other parameters. In stark contrast, experiments 5 and 6 actually produce particularly good results two of maximum order rate values and middling values for their duration of deficit and rise time, i.e. they yield a very good compromise. Experiment 6 actually satisfies the conditions for the best settings found by Mason-Jones et al. (1997) and Hussain and saber (2012); Tp = Ti, Ti = Tw, and Ta = 2 Tp.

Experiment 9 has Ti=8 and the other experiments with this value do not fall into the second group. It is noted that the other parameter values for experiment 9 are the lowest levels, i.e. Tw = 4 and Ta = 2 and this once again gives an explanation for the over-reaction type behavior seen based on the argument that they are creating strong or higher gain feedback loops. The responses for experiment 9 are somewhat different to the others in the second group as the maximum magnitude of the oscillations in the inventory are much lower and much closer to those seen in the first group.

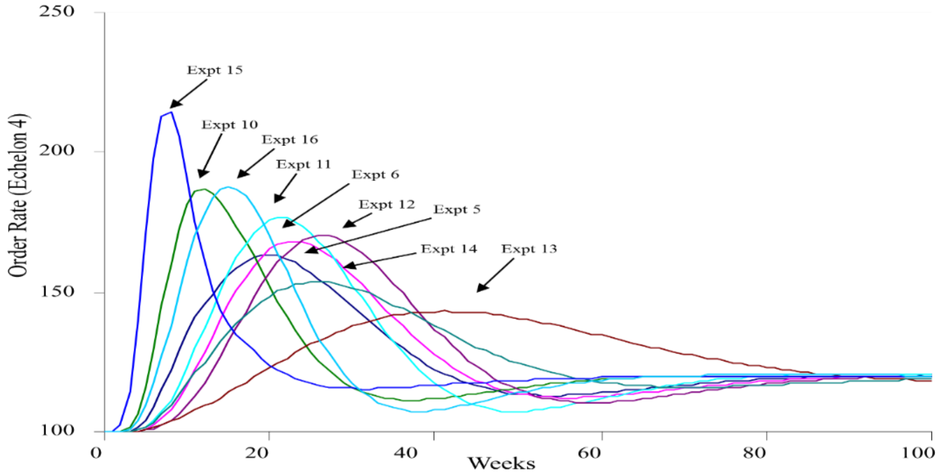

Figure 3. Stable Response

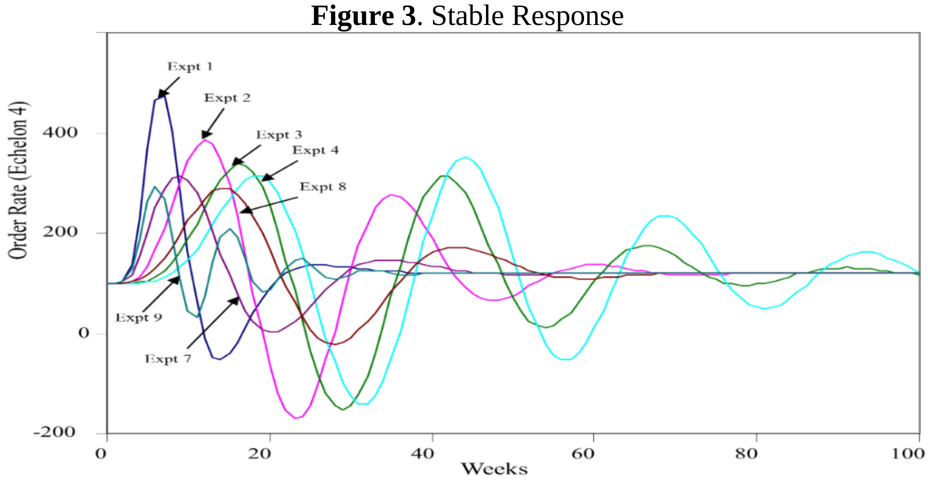

Figure 4. Acceptable response

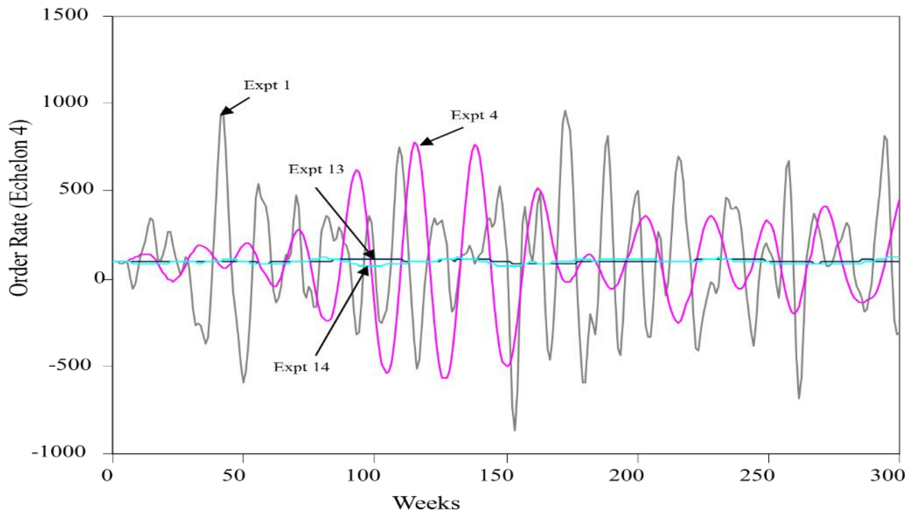

Figure 5. Unstable response

6. Discussion & Conclusion

A simulation model of the APIOBPCS production and inventory control system has been developed, using iThink, to understand the effects of its parameters on its dynamic responses; this model combines the *make to stock* and *make to order* control strategies. Four APIOBPCS models have been linked to create a four-tier supply chain model of the beer game. The effects of the APIOBPCS parameter values across the whole chain, rather than a single echelon have been studied. Taguchi's Orthogonal Arrays has been used to derive a sample that is representative of the parameter-value space being investigated without having to simulate every parameter-value combination, i.e. the number of experiments is greatly reduced.

It has been demonstrated that parameter values that give very poor dynamics across the whole supply chain do not necessarily yield poor dynamics within a single echelon, so it is essential to consider the whole supply chain when setting parameter values. The condition Ti = Tw = Tp and Ta = 2Tp found by Mason-Jones et al. (1997) to be a condition for a good or best response across the supply chain, was borne out by the results presented here, although for the 'best' result the parameter values were very close to this condition rather than absolutely satisfying it. Riddalls and Bennett (2001) reported that the condition Ti = Tw avoids oscillatory behavior in the dynamic responses of the order rate and inventory and this has been borne out here, except when Ti = Tw is very small (4 in the experiment here) in which case the over-lively inventory feedback, due to the small Ti, caused very large oscillations and, indeed, the worst response; this means that the Ti = Tw condition is subject to Ti not being very small. It has been noted also that a large Ti can produce too slow a response, again confirming the findings of Riddalls and Bennett (2001). The close agreement between the findings of Riddalls and Bennett (2001) and Hussain et al (2011) provides a degree of verification of the iThink simulation model implemented here.

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