Information Sharing in Supply Chains: A Systemic Approach[1]

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Abstract
In a supply chain system, movements in the end-customer demand is amplified throughout the chain as one moves from the lowest echelon (retailer) to upper echelons (wholesaler, distributor, factory). It is reported that this amplification, which is known as the bullwhip effect, can significantly be reduced by sharing the end-customer demand information. In this paper, we first introduce a four-echelon supply chain model, add penalty variables to it, and simulate the model under two conditions; with and without sharing the end-customer demand information. We observe similar results as reported by other researchers; sharing the end-customer demand information has a strong effect in decreasing the amplification, which also results as decreased penalty values. We then introduce a new approach that requires sharing of further information and run the model with the new decision making heuristic based on this new approach. According to the simulation runs, the decision making heuristic suggested in this paper results in further improvement.

Keywords: supply chains; inventory management; bullwhip effect; inventory control heuristic; information sharing; systemic approach.

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1. Introduction

Stock management systems in general and inventory management systems in particular are subject to oscillations (Barlas and Ozevin, 2004; Yasarcan and Barlas, 2005; Yasarcan, 2010 and 2011). A supply chain management system consists of multiple echelons, two or more inventory management systems, connected in series[2]. Therefore, it is only natural to observe oscillations in supply chain management systems. Moreover, these oscillations usually amplify as one moves from a lower echelon to an upper stage, which is known as the bullwhip effect (see for example Barlas and Gunduz, 2011; Sterman, 1989). Some good inventory control heuristics can eliminate oscillations (Yasarcan and Barlas, 2005; Yasarcan, 2011). However, even in this case, a movement (i.e. fluctuation) in the end-customer demand would create fluctuations throughout the whole supply chain. Similar to the case with oscillations, these movements would usually amplify as one moves from a lower echelon to an upper stage (Barlas and Gunduz, 2011).

According to Barlas and Gunduz (2011), it is not possible to completely eradicate "the bullwhip effect (amplification of orders along the supply chain)". However, they also report that it can significantly be reduced by sharing the end-customer demand information. In this paper, our main aim is to introduce a new and advanced inventory management heuristic for supply chains, which is developed based on a systemic approach. For this purpose, we first introduce a four-echelon supply chain model, add penalty variables to it, and simulate the model under two conditions; with and without sharing the end-customer demand information. We observe similar results as reported by Barlas and Gunduz (2011); sharing the end-customer demand information has a strong effect in decreasing the amplification, which also results as decreased penalty values. We then introduce the new heuristic that requires sharing of further information. According to the simulation runs, the decision making heuristic suggested in this paper results in further improvement.

2. The Model Structure and Equations

The stock-flow diagram of our four-echelon supply chain model, which serves as a platform to compare different heuristics, is given in Figure 1. Note that this diagram mainly represents the physical structure of the said supply chain. The output variables of the control heuristics, *<Desired Orders 1>*, *<Desired Orders 2>*, *<Desired Orders 3>*, and *<Desired Orders 4>*, are the input variables to this structure and they are written in bold italic big characters.

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[2] In Sterman (1989), there is an example supply chain consisting of a retailer (the lowest echelon), wholesaler, distributor, and factory (the uppermost echelon).

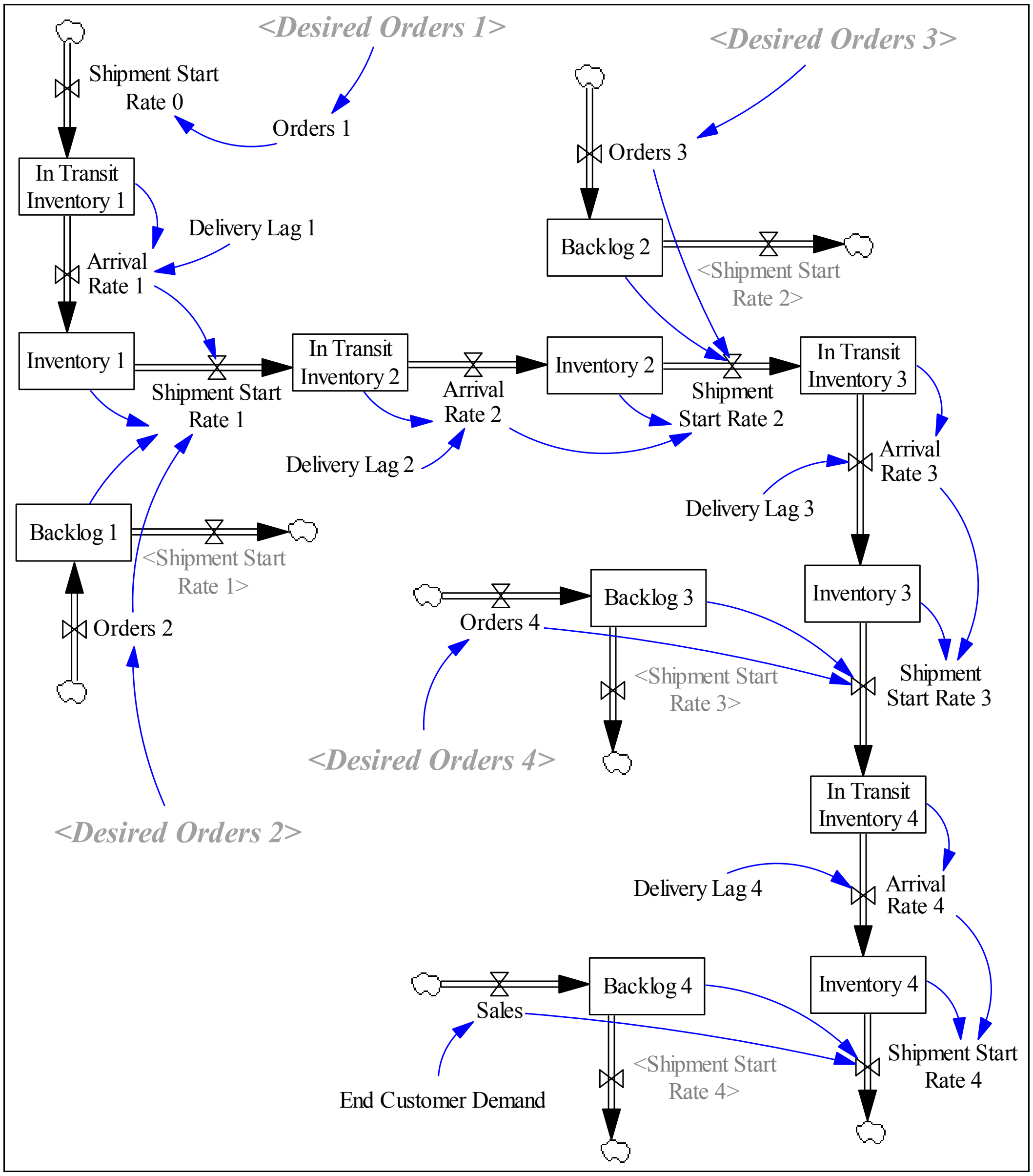

Figure 1: Stock-flow diagram of the supply chain

The stock equations of the model structure in Figure 1 are given as follows:

$$Backlog\ 1_0 = 0 \quad [items] \tag{1}$$

$$Backlog\ 1_{t+DT} = Backlog\ 1_t + (Orders\ 2 - Shipment\ Start\ Rate\ 1) \times DT \quad [items] \tag{2}$$

$$Backlog\ 2_0 = 0 \quad [items] \tag{3}$$

$$Backlog\ 2_{t+DT} = Backlog\ 2_t + (Orders\ 3 - Shipment\ Start\ Rate\ 2) \times DT \quad [items] \tag{4}$$

$$Backlog\ 3_0 = 0 \quad [items] \tag{5}$$

$$\mathit{Backlog\ 3}_{t+DT} = \mathit{Backlog\ 1}_t + \left(\mathit{Orders\ 4} - \mathit{Shipment\ Start\ Rate\ 3}\right) \times DT \quad [\mathit{items}] \tag{6}$$

$$\mathit{Backlog\ 4}_0 = 0 \quad [\mathit{items}] \tag{7}$$

$$\mathit{Backlog\ 4}_{t+DT} = \mathit{Backlog\ 4}_t + \left(\mathit{Sales} - \mathit{Shipment\ Start\ Rate\ 4}\right) \times DT \quad [\mathit{items}] \tag{8}$$

$$\mathit{In\ Transit\ Inventory\ 1}_0 = 0 \quad [\mathit{items}] \tag{9}$$

$$\begin{aligned} &\mathit{In\ Transit\ Inventory\ 1}_{t+DT} = \\ &\quad \mathit{In\ Transit\ Inventory\ 1}_t + \left(\mathit{Shipment\ Start\ Rate\ 0} - \mathit{Arrival\ Rate\ 1}\right) \times DT \quad [\mathit{items}] \end{aligned} \tag{10}$$

$$\mathit{In\ Transit\ Inventory\ 2}_0 = 0 \quad [\mathit{items}] \tag{11}$$

$$\begin{aligned} &\mathit{In\ Transit\ Inventory\ 2}_{t+DT} = \\ &\quad \mathit{In\ Transit\ Inventory\ 2}_t + \left(\mathit{Shipment\ Start\ Rate\ 1} - \mathit{Arrival\ Rate\ 2}\right) \times DT \quad [\mathit{items}] \end{aligned} \tag{12}$$

$$\mathit{In\ Transit\ Inventory\ 3}_0 = 0 \quad [\mathit{items}] \tag{13}$$

$$\begin{aligned} &\mathit{In\ Transit\ Inventory\ 3}_{t+DT} = \\ &\quad \mathit{In\ Transit\ Inventory\ 3}_t + \left(\mathit{Shipment\ Start\ Rate\ 2} - \mathit{Arrival\ Rate\ 3}\right) \times DT \quad [\mathit{items}] \end{aligned} \tag{14}$$

$$\mathit{In\ Transit\ Inventory\ 4}_0 = 0 \quad [\mathit{items}] \tag{15}$$

$$\begin{aligned} &\mathit{In\ Transit\ Inventory\ 4}_{t+DT} = \\ &\quad \mathit{In\ Transit\ Inventory\ 4}_t + \left(\mathit{Shipment\ Start\ Rate\ 3} - \mathit{Arrival\ Rate\ 4}\right) \times DT \quad [\mathit{items}] \end{aligned} \tag{16}$$

$$\mathit{Inventory\ 1}_0 = 0 \quad [\mathit{items}] \tag{17}$$

$$\mathit{Inventory\ 1}_{t+DT} = \mathit{Inventory\ 1}_t + \left(\mathit{Arrival\ Rate\ 1} - \mathit{Shipment\ Start\ Rate\ 1}\right) \times DT \quad [\mathit{items}] \tag{18}$$

$$\mathit{Inventory\ 2}_0 = 0 \quad [\mathit{items}] \tag{19}$$

$$\mathit{Inventory\ 2}_{t+DT} = \mathit{Inventory\ 2}_t + \left(\mathit{Arrival\ Rate\ 2} - \mathit{Shipment\ Start\ Rate\ 2}\right) \times DT \quad [\mathit{items}] \tag{20}$$

$$\mathit{Inventory\ 3}_0 = 0 \quad [\mathit{items}] \tag{21}$$

$$\mathit{Inventory\ 3}_{t+DT} = \mathit{Inventory\ 3}_t + \left(\mathit{Arrival\ Rate\ 3} - \mathit{Shipment\ Start\ Rate\ 3}\right) \times DT \quad [\mathit{items}] \tag{22}$$

$$\mathit{Inventory\ 4}_0 = 0 \quad [\mathit{items}] \tag{23}$$

$$\mathit{Inventory\ 4}_{t+DT} = \mathit{Inventory\ 4}_t + \left(\mathit{Arrival\ Rate\ 4} - \mathit{Shipment\ Start\ Rate\ 4}\right) \times DT \quad [\mathit{items}] \tag{24}$$

Four of the flow equations of the model structure in Figure 1 are given as follows:

$$\textit{Arrival Rate 1} = \text{DELAY3I}(\textit{Shipment Start Rate 0}, \textit{Delivery Lag 1}, 0) \quad [\textit{items/day}] \tag{25}$$

$$\textit{Arrival Rate 2} = \text{DELAY3I}(\textit{Shipment Start Rate 1}, \textit{Delivery Lag 2}, 0) \quad [\textit{items/day}] \tag{26}$$

$$\textit{Arrival Rate 3} = \text{DELAY3I}(\textit{Shipment Start Rate 2}, \textit{Delivery Lag 3}, 0) \quad [\textit{items/day}] \tag{27}$$

$$\textit{Arrival Rate 4} = \text{DELAY3I}(\textit{Shipment Start Rate 3}, \textit{Delivery Lag 4}, 0) \quad [\textit{items/day}] \tag{28}$$

DELAY3I is a macro function of Vensim software. It represents a third order material delay structure. The first element in the function is the input, the second element is the delay time, and the third element is the initial value. For more information on this function, see Yasarcan (2011).

The rest of the flow equations are given as follows:

$$\textit{Orders 2} = \text{MAX}(\textit{Desired Orders 2}, 0) \quad [\textit{items/day}] \tag{29}$$

$$\textit{Orders 3} = \text{MAX}(\textit{Desired Orders 3}, 0) \quad [\textit{items/day}] \tag{30}$$

$$\textit{Orders 4} = \text{MAX}(\textit{Desired Orders 4}, 0) \quad [\textit{items/day}] \tag{31}$$

$$\textit{Sales} = \textit{End Customer Demand} \quad [\textit{items/day}] \tag{32}$$

$$\textit{Shipment Start Rate 0} = \textit{Orders 1} \quad [\textit{items/day}] \tag{33}$$

$$\textit{Shipment Start Rate 1} = \text{MIN}(\textit{Arrival Rate 1} + \textit{Inventory 1}/DT, \textit{Orders 2} + \textit{Backlog 1}/DT) \quad [\textit{items/day}] \tag{34}$$

$$\textit{Shipment Start Rate 2} = \text{MIN}(\textit{Arrival Rate 2} + \textit{Inventory 2}/DT, \textit{Orders 3} + \textit{Backlog 2}/DT) \quad [\textit{items/day}] \tag{35}$$

$$\textit{Shipment Start Rate 3} = \text{MIN}(\textit{Arrival Rate 3} + \textit{Inventory 1}/DT, \textit{Orders 4} + \textit{Backlog 3}/DT) \quad [\textit{items/day}] \tag{36}$$

$$\textit{Shipment Start Rate 4} = \text{MIN}(\textit{Arrival Rate 4} + \textit{Inventory 4}/DT, \textit{Sales} + \textit{Backlog 4}/DT) \quad [\textit{items/day}] \tag{37}$$

All other parameters and variables of the model structure in Figure 1 are given as follows:

$$\textit{Delivery Lag 1} = \textit{Delivery Lag 2} = \textit{Delivery Lag 3} = \textit{Delivery Lag 4} = 8 \quad [\textit{days}] \tag{38}$$

$$End\ Customer\ Demand = \begin{cases} 0, & \text{if } t < 5 \\ \text{RANDOM UNIFORM}(50, 150, \text{seed}), & \text{if } t \geq 5 \end{cases} \quad \left[\frac{items}{day}\right] \tag{39}$$

$$Orders\ 1 = \text{MAX}(Desired\ Orders\ 1, 0) \quad [items/day] \tag{40}$$

Note that we assumed identical inventory control structures for each echelon (see Figure 1 and equations 1-40).

3. Penalty Formulations

The stock-flow diagram of the penalty formulations is given in Figure 2. We calculate penalty for an echelon by simply accumulating the inventory and backlog values for that echelon. Note that the model equations 34-37 do not allow the inventory and backlog belonging to the same echelon to be greater than zero at the same instance in simulated time.

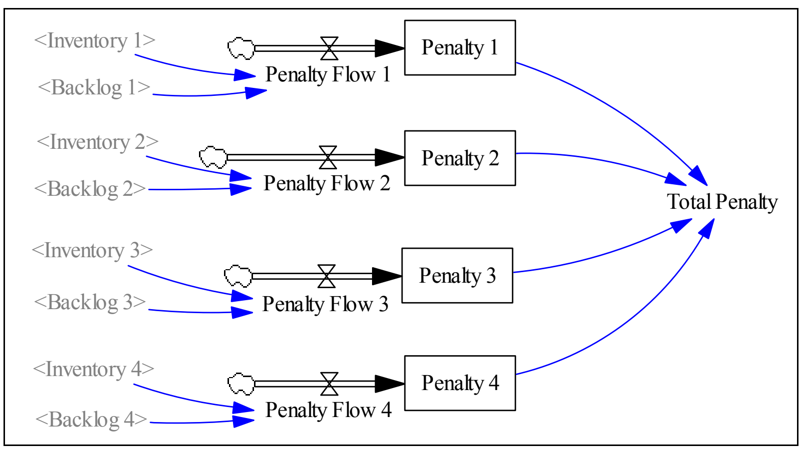

Figure 2: Stock-flow diagram of the penalty formulations

The stock equations of the penalty formulations are given as follows:

$$Penalty\ 1_0 = 0 \quad [items \cdot day] \tag{41}$$

$$Penalty\ 1_{t+DT} = Penalty\ 1_t + Penalty\ Flow\ 1 \times DT \quad [items \cdot day] \tag{42}$$

$$Penalty\ 2_0 = 0 \quad [items \cdot day] \tag{43}$$

$$Penalty\ 2_{t+DT} = Penalty\ 2_t + Penalty\ Flow\ 2 \times DT \quad [items \cdot day] \tag{44}$$

$$Penalty\ 3_0 = 0 \quad [items \cdot day] \tag{45}$$

$$Penalty\ 3_{t+DT} = Penalty\ 3_t + Penalty\ Flow\ 3 \times DT \quad [items \cdot day] \tag{46}$$

$$Penalty\ 4_0 = 0 \quad [items \cdot day] \tag{47}$$

$$Penalty\ 4_{t+DT} = Penalty\ 4_t + Penalty\ Flow\ 4 \times DT \quad [items \cdot day] \tag{48}$$

The flow equations of the penalty formulations are given as follows:

$$Penalty\ Flow\ 1 = Inventory\ 1 + Backlog\ 1 \quad [items] \tag{49}$$

$$Penalty\ Flow\ 2 = Inventory\ 2 + Backlog\ 2 \quad [items] \tag{50}$$

$$Penalty\ Flow\ 3 = Inventory\ 3 + Backlog\ 3 \quad [items] \tag{51}$$

$$Penalty\ Flow\ 4 = Inventory\ 4 + Backlog\ 4 \quad [items] \tag{52}$$

The equation of the main performance variable is given as follows:

$$Total\ Penalty = Penalty\ 1 + Penalty\ 2 + Penalty\ 3 + Penalty\ 4 \quad [items \cdot day] \tag{53}$$

Note that *Backlog 1*, *Backlog 2*, *Backlog 3*, *Backlog 4*, *Inventory 1*, *Inventory 2*, *Inventory 3*, and *Inventory 4* are already defined in section 2 (equations 1-8 and 17-24).

4. Heuristic 1: No Information Sharing

The stock-flow diagram of heuristic 1 is given in Figure 3. This heuristic assumes no information-sharing. As a result of this assumption, the input to the expectation formation process at echelon$_i$ is the orders that it receives from its direct customer that is echelon$_{i+1}$. The input to the expectation formation process at echelon$_4$, which is the lowest echelon in our four-echelon supply chain model, is the variable named *Sales*. Note that *Sales* is equal to *End Customer Demand* (see Figure 1 and Equation 32).

The stock equations of heuristic 1 are given as follows:

$$Supply\ Line\ 1_0 = 0 \quad [items] \tag{54}$$

$$Supply\ Line\ 1_{t+DT} = Supply\ Line\ 1_t + (Orders\ 1 - Arrival\ Rate\ 1) \times DT \quad [items] \tag{55}$$

$$Supply\ Line\ 2_0 = 0 \quad [items] \tag{56}$$

$$Supply\ Line\ 2_{t+DT} = Supply\ Line\ 2_t + \left(Orders\ 2 - Arrival\ Rate\ 2\right) \times DT \quad [items] \tag{57}$$

$$Supply\ Line\ 3_0 = 0 \quad [items] \tag{58}$$

$$Supply\ Line\ 3_{t+DT} = Supply\ Line\ 3_t + \left(Orders\ 3 - Arrival\ Rate\ 3\right) \times DT \quad [items] \tag{59}$$

$$Supply\ Line\ 4_0 = 0 \quad [items] \tag{60}$$

$$Supply\ Line\ 4_{t+DT} = Supply\ Line\ 4_t + \left(Orders\ 4 - Arrival\ Rate\ 4\right) \times DT \quad [items] \tag{61}$$

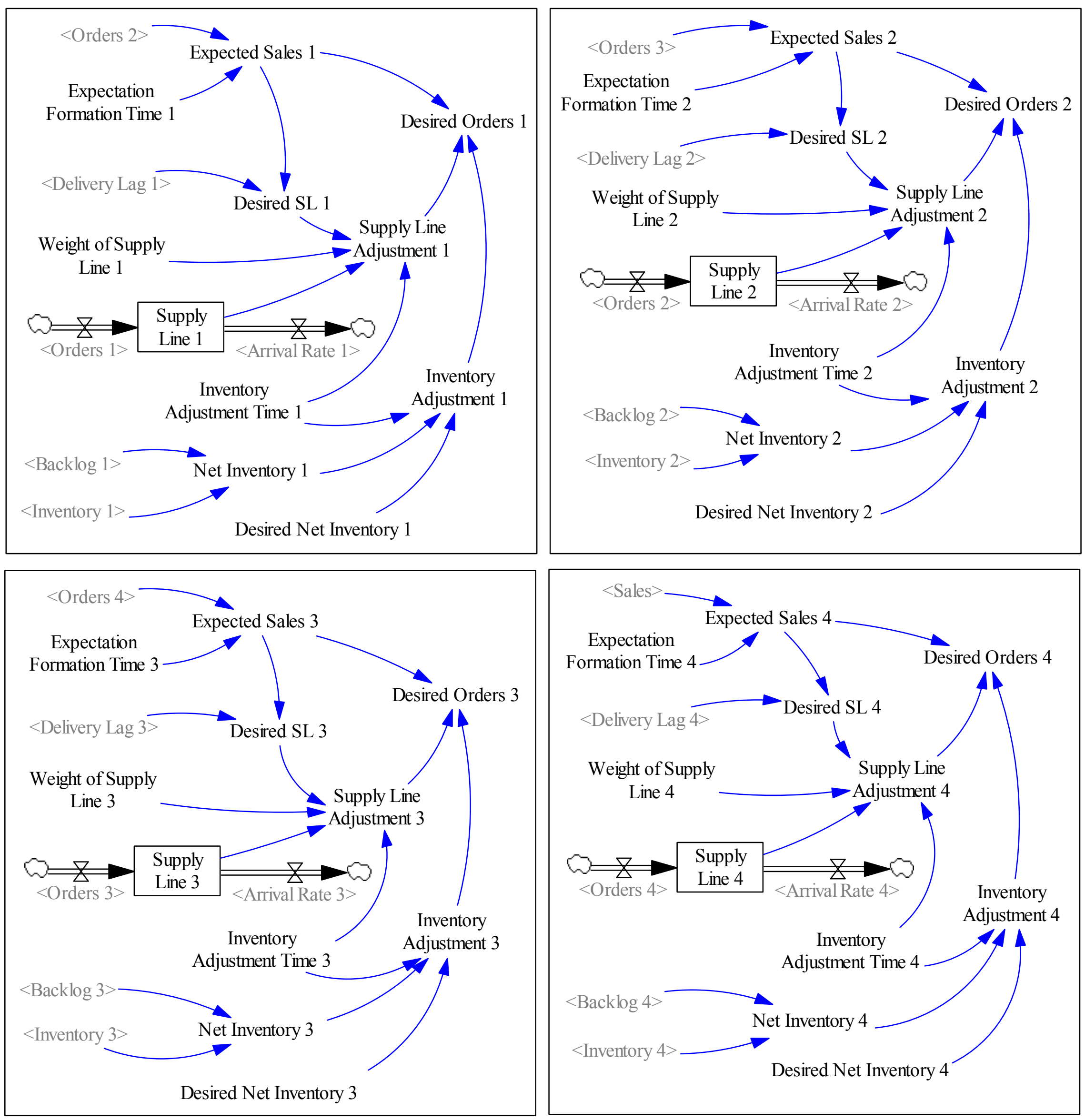

Figure 3: Stock-flow diagram of heuristic 1 (no information sharing)

The flows in Figure 3 (*Orders 1*, *Orders 2*, *Orders 3*, *Orders 4*, *Arrival Rate 1*, *Arrival Rate 2*, *Arrival Rate 3*, and *Arrival Rate 4* are already defined in section 2 (equations 40, 29-31, 25-28). The other variables and parameters that are also defined in section 2 are *Backlog 1*, *Backlog 2*, *Backlog 3*, and *Backlog 4* (equations 1-8); *Inventory 1*, *Inventory 2*, *Inventory 3*, and *Inventory 4* (equations 17-24); *Delivery Lag 1*, *Delivery Lag 2*, *Delivery Lag 3*, and *Delivery Lag 4* (Equation 38); and *Sales* (Equation 32).

The output variables of heuristic 1, which are input variables to the structure given in Figure 1, are given as follows:

$$Desired\ Orders\ 1 = \left\{ \begin{array}{l} Expected\ Sales\ 1 \\ +\ Inventory\ Adjustment\ 1 \\ +\ Supply\ Line\ Adjustment\ 1 \end{array} \right\} \quad \left[\frac{items}{day} \right] \tag{62}$$

$$Desired\ Orders\ 2 = \left\{ \begin{array}{l} Expected\ Sales\ 2 \\ +\ Inventory\ Adjustment\ 2 \\ +\ Supply\ Line\ Adjustment\ 2 \end{array} \right\} \quad \left[\frac{items}{day} \right] \tag{63}$$

$$Desired\ Orders\ 3 = \left\{ \begin{array}{l} Expected\ Sales\ 3 \\ +\ Inventory\ Adjustment\ 3 \\ +\ Supply\ Line\ Adjustment\ 3 \end{array} \right\} \quad \left[\frac{items}{day} \right] \tag{64}$$

$$Desired\ Orders\ 4 = \left\{ \begin{array}{l} Expected\ Sales\ 4 \\ +\ Inventory\ Adjustment\ 4 \\ +\ Supply\ Line\ Adjustment\ 4 \end{array} \right\} \quad \left[\frac{items}{day} \right] \tag{65}$$

The other variables of heuristic 1 are given as follows:

$$Expected\ Sales\ 1 = \mathrm{SMOOTH3}(Orders\ 2, Expectation\ Formation\ Time\ 1) \quad \left[\frac{items}{day} \right] \tag{66}$$

$$Expected\ Sales\ 2 = \mathrm{SMOOTH3}(Orders\ 3, Expectation\ Formation\ Time\ 2) \quad \left[\frac{items}{day} \right] \tag{67}$$

$$Expected\ Sales\ 3 = \mathrm{SMOOTH3}(Orders\ 4, Expectation\ Formation\ Time\ 3) \quad \left[\frac{items}{day} \right] \tag{68}$$

$$Expected\ Sales\ 4 = \mathrm{SMOOTH3}(Sales, Expectation\ Formation\ Time\ 4) \quad \left[\frac{items}{day} \right] \tag{69}$$

"SMOOTH3" is another macro function of the "Vensim" simulation software and represents a third-order information delay. The first element in the function is both the input and initial value, and the second element is the length of the delay.

$$Desired\ SL\ 1 = Delivery\ Lag\ 1 \times Expected\ Sales\ 1 \quad [items] \tag{70}$$

$$Desired\ SL\ 2 = Delivery\ Lag\ 2 \times Expected\ Sales\ 2 \quad [items] \tag{71}$$

$$Desired\ SL\ 3 = Delivery\ Lag\ 3 \times Expected\ Sales\ 3 \quad [items] \tag{72}$$

$$Desired\ SL\ 4 = Delivery\ Lag\ 4 \times Expected\ Sales\ 4 \quad [items] \tag{73}$$

$$Inventory\ Adjustment\ 1 = \frac{(Desired\ Net\ Inventory\ 1 - Net\ Inventory\ 1)}{Inventory\ Adjustment\ Time\ 1} \quad \left[\frac{items}{day}\right] \tag{74}$$

$$Inventory\ Adjustment\ 2 = \frac{(Desired\ Net\ Inventory\ 2 - Net\ Inventory\ 2)}{Inventory\ Adjustment\ Time\ 2} \quad \left[\frac{items}{day}\right] \tag{75}$$

$$Inventory\ Adjustment\ 3 = \frac{(Desired\ Net\ Inventory\ 3 - Net\ Inventory\ 3)}{Inventory\ Adjustment\ Time\ 3} \quad \left[\frac{items}{day}\right] \tag{76}$$

$$Inventory\ Adjustment\ 4 = \frac{(Desired\ Net\ Inventory\ 4 - Net\ Inventory\ 4)}{Inventory\ Adjustment\ Time\ 4} \quad \left[\frac{items}{day}\right] \tag{77}$$

$$Net\ Inventory\ 1 = Inventory\ 1 - Backlog\ 1 \quad [items] \tag{78}$$

$$Net\ Inventory\ 2 = Inventory\ 2 - Backlog\ 2 \quad [items] \tag{79}$$

$$Net\ Inventory\ 3 = Inventory\ 3 - Backlog\ 3 \quad [items] \tag{80}$$

$$Net\ Inventory\ 4 = Inventory\ 4 - Backlog\ 4 \quad [items] \tag{81}$$

$$\begin{aligned} &Supply\ Line\ Adjustment\ 1 = \\ &\qquad Weight\ of\ Supply\ Line\ 1 \times \frac{(Desired\ SL\ 1 - Supply\ Line\ 1)}{Inventory\ Adjustment\ Time\ 1} \quad \left[\frac{items}{day}\right] \end{aligned} \tag{82}$$

$$\begin{aligned} &Supply\ Line\ Adjustment\ 2 = \\ &\qquad Weight\ of\ Supply\ Line\ 2 \times \frac{(Desired\ SL\ 2 - Supply\ Line\ 2)}{Inventory\ Adjustment\ Time\ 2} \quad \left[\frac{items}{day}\right] \end{aligned} \tag{83}$$

$$\begin{aligned} &Supply\ Line\ Adjustment\ 3 = \\ &\qquad Weight\ of\ Supply\ Line\ 3 \times \frac{(Desired\ SL\ 3 - Supply\ Line\ 3)}{Inventory\ Adjustment\ Time\ 3} \quad \left[\frac{items}{day}\right] \end{aligned} \tag{84}$$

$$\text{Supply Line Adjustment 4} = \text{Weight of Supply Line 4} \times \frac{(\text{Desired SL 1} - \text{Supply Line 4})}{\text{Inventory Adjustment Time 4}} \quad \left[\frac{items}{day}\right] \tag{85}$$

The constants/parameters of heuristic 1 are given as follows:

$$\text{Desired Net Inventory 1} = \text{Desired Net Inventory 2} = 0 \quad [items] \tag{86}$$

$$\text{Desired Net Inventory 3} = \text{Desired Net Inventory 4} = 0 \quad [items] \tag{87}$$

$$\text{Expectation Formation Time 1} = \text{Expectation Formation Time 2} = 5 \quad [days] \tag{88}$$

$$\text{Expectation Formation Time 3} = \text{Expectation Formation Time 4} = 5 \quad [days] \tag{89}$$

$$\text{Inventory Adjustment Time 1} = \text{Inventory Adjustment Time 2} = 5 \quad [days] \tag{90}$$

$$\text{Inventory Adjustment Time 3} = \text{Inventory Adjustment Time 4} = 5 \quad [days] \tag{91}$$

$$\text{Weight of Supply Line 1} = \text{Weight of Supply Line 2} = 1 \quad [dimensionless] \tag{92}$$

$$\text{Weight of Supply Line 3} = \text{Weight of Supply Line 4} = 1 \quad [dimensionless] \tag{93}$$

Remember that we assume identical inventory control structures for each echelon (see Figure 1 and equations 1-40). We also assume identical agents at different echelons (see Figure 3 and equations 54-93).

5. Heuristic 2: Shared End-Customer Demand Information

The structure and equations for heuristic 2 are similar to the structure (Figure 3) and equations (54-93) for heuristic 1. The only difference is the input variable in the expected sales equations 66, 67, and 68. In heuristic 2, *Orders 2*, *Orders 3*, and *Orders 4* are replaced by *Sales* reflecting the fact that the end-customer demand information is shared by all agents at different echelons. Remember that *Sales* is equal to *End Customer Demand* (see Figure 1 and Equation 32). The new equations are listed as follows:

$$\text{Expected Sales 1} = \mathrm{SMOOTH3}(\text{Sales}, \text{Expectation Formation Time 1}) \quad [items/day] \tag{94}$$

$$\text{Expected Sales 2} = \mathrm{SMOOTH3}(\text{Sales}, \text{Expectation Formation Time 2}) \quad [items/day] \tag{95}$$

$$\text{Expected Sales 3} = \mathrm{SMOOTH3}(\text{Sales}, \text{Expectation Formation Time 3}) \quad [items/day] \tag{96}$$

6. Heuristic 3: Further Information Sharing

The naive heuristic that completely ignores the supply line is obtained by setting *Weight of Supply Line 1*, *Weight of Supply Line 2*, *Weight of Supply Line 3*, and *Weight of Supply Line 4* equal to zero. If a decision maker uses the naive heuristic in managing inventories, he would end up with unwanted oscillations and extremely high costs. On the contrary, by setting *Weight of Supply Line 1*, *Weight of Supply Line 2*, *Weight of Supply Line 3*, and *Weight of Supply Line 4* equal to one, we assume that the decision makers at each echelon give full weight to their supply lines in determining their orders (equations 92 and 93). When a decision makers gives full weight to his supply line, this practically means that he considers the sum of his net inventory and supply line as a single stock. This systemic approach brings stability and decreases costs. Sharing the end customer demand further improves the results.

We developed heuristic 3 by using a systemic approach similar to the one that is used in determining the weight values. According to our approach, decision makers at every echelon except for the lowest consider the totality of their inventory and supply line and all the lower stage inventories and supply lines as a single stock. This heuristic would only be valid if sharing the net inventory and supply line information is possible in addition to sharing the end customer demand information. Heuristic 3 equations are the same as the heuristic 2 equations (54-61, 65, 69-93, and 94-96) except for the desired orders equations (62, 63, and 64). The new desired orders equations are given as follows:

$$\text{Desired Orders 1} = \left\{ \begin{array}{l} \text{Expected Sales 1} \\ + \text{Inventory Adjustment 1} \\ + \text{Supply Line Adjustment 1} \\ + \text{Inventory Adjustment 2} \\ + \text{Supply Line Adjustment 2} \\ + \text{Inventory Adjustment 3} \\ + \text{Supply Line Adjustment 3} \\ + \text{Inventory Adjustment 4} \\ + \text{Supply Line Adjustment 4} \end{array} \right\} \quad \left[\frac{items}{day}\right] \tag{97}$$

$$\text{Desired Orders 2} = \left\{ \begin{array}{l} \text{Expected Sales 2} \\ + \text{Inventory Adjustment 2} \\ + \text{Supply Line Adjustment 2} \\ + \text{Inventory Adjustment 3} \\ + \text{Supply Line Adjustment 3} \\ + \text{Inventory Adjustment 4} \\ + \text{Supply Line Adjustment 4} \end{array} \right\} \quad \left[\frac{items}{day}\right] \tag{98}$$

$$Desired\ Orders\ 3 = \left\{ \begin{array}{l} Expected\ Sales\ 3 \\ +\ Inventory\ Adjustment\ 3 \\ +\ Supply\ Line\ Adjustment\ 3 \\ +\ Inventory\ Adjustment\ 4 \\ +\ Supply\ Line\ Adjustment\ 4 \end{array} \right\} \qquad \left[\frac{items}{day} \right] \tag{99}$$

7. Results

We simulated the model (equations 1-53) for all the three heuristics (see Table 1) with 5 different seed values (Equation 39); seed = {1, 2, 3, 4, 5}. We preferred discrete time (DT = 1) for our simulation runs. However, the equations given in this paper would work fine with continuous time simulations too. Therefore, if one desires to run a continuous time simulation, he can do so only by giving DT a value less than 1. The length of our simulation runs is 120 days.

Table 1: Heuristic Equations

	Common Equations	Equations for Desired Orders	Equations for Expected Sales
Heuristic 1	54-61; 70-93	62-65	66-69
Heuristic 2		62-65	69; 94-96
Heuristic 3		65; 97-99	69; 94-96

The penalty values obtained from the simulation runs are given in Table 2. In order to make comparisons easier, we also normalized the average penalty values with respect to the total penalty values obtained from the three different heuristics (Table 3). According to the normalized average total penalty values, sharing the end-customer demand information (Heuristic 2) improves the performance approximately 55.5% (see the second row last column cell in Table 3). The improvement obtained from the third heuristic (the advanced heuristic suggested in this paper) is approximately 63.5% (see the third row last column cell in Table 3). The improvement obtained from the third heuristic compared to heuristic 2 is approximately 19.8% (see the sixth row last column cell in Table 3). The biggest portion of total penalty (approximately 61.2%) is generated by the uppermost echelon (stage 1 in our model) if heuristic 1 is used (see the first row first column cell in Table 3). However, if one uses heuristic 2 or 3, the biggest portion of total penalty (approximately 31.8% and 31.3%; see the fifth row fourth column and last row fourth column cells in Table 3) is generated by the lowest echelon (stage 4 in our model). Example net inventory dynamics generated by the three different heuristics for the four echelons can be seen in figures 4-7.

Table 2: Penalty values

		Penalty 1	*Penalty 2*	*Penalty 3*	*Penalty 4*	*Total Penalty*
Seed 1	**Heuristic 1**	459,898	103,229	88,748	94,471	746,347
	Heuristic 2	55,626	87,710	106,934	116,059	366,330
	Heuristic 3	49,307	69,791	83,348	91,372	293,821
Seed 2	**Heuristic 1**	421,300	111,923	79,535	86,301	699,060
	Heuristic 2	48,279	77,372	94,559	104,145	324,356
	Heuristic 3	42,046	60,252	72,597	81,893	256,789
Seed 3	**Heuristic 1**	581,197	158,066	85,228	91,386	915,879
	Heuristic 2	57,217	87,012	104,520	114,135	362,885
	Heuristic 3	51,393	69,182	81,875	90,509	292,959
Seed 4	**Heuristic 1**	464,638	146,982	88,401	90,796	790,819
	Heuristic 2	52,155	80,395	99,399	108,751	340,700
	Heuristic 3	50,210	65,992	77,617	87,320	281,140
Seed 5	**Heuristic 1**	416,177	94,795	77,945	86,457	675,375
	Heuristic 2	51,539	82,445	102,775	111,767	348,526
	Heuristic 3	45,148	63,404	77,418	86,767	272,738
Averages	**Heuristic 1**	***468,642***	***122,999***	***83,971***	***89,882***	***765,496***
	Heuristic 2	***52,963***	***82,987***	***101,637***	***110,971***	***348,559***
	Heuristic 3	***47,621***	***65,724***	***78,571***	***87,572***	***279,489***

Table 3: Normalized average penalty values

		Penalty 1	*Penalty 2*	*Penalty 3*	*Penalty 4*	*Total Penalty*
Normalized Avg. Values $\left(Value \times \frac{100}{765{,}496}\right)$	**Heuristic 1**	*61.2*	*16.1*	*11.0*	*11.7*	*100.0*
	Heuristic 2	*6.9*	*10.8*	*13.3*	*14.5*	*45.5*
	Heuristic 3	*6.2*	*8.6*	*10.3*	*11.4*	*36.5*
Normalized Avg. Values $\left(Value \times \frac{100}{348{,}559}\right)$	**Heuristic 1**	*134.5*	*35.3*	*24.1*	*25.8*	*219.6*
	Heuristic 2	*15.2*	*23.8*	*29.2*	*31.8*	*100.0*
	Heuristic 3	*13.7*	*18.9*	*22.5*	*25.1*	*80.2*
Normalized Avg. Values $\left(Value \times \frac{100}{279{,}489}\right)$	**Heuristic 1**	*167.7*	*44.0*	*30.0*	*32.2*	*273.9*
	Heuristic 2	*18.9*	*29.7*	*36.4*	*39.7*	*124.7*
	Heuristic 3	*17.0*	*23.5*	*28.1*	*31.3*	*100.0*

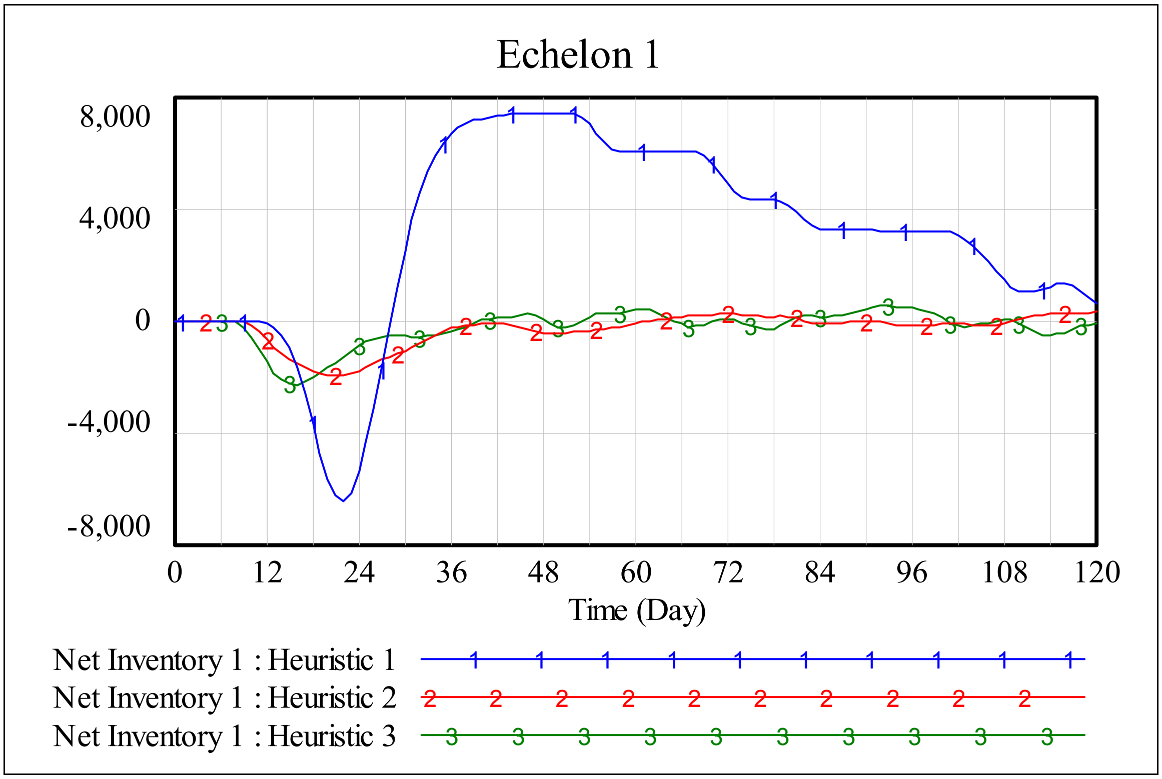

Figure 4: Dynamic behavior of *Net Inventory 1* generated by the three different heuristics

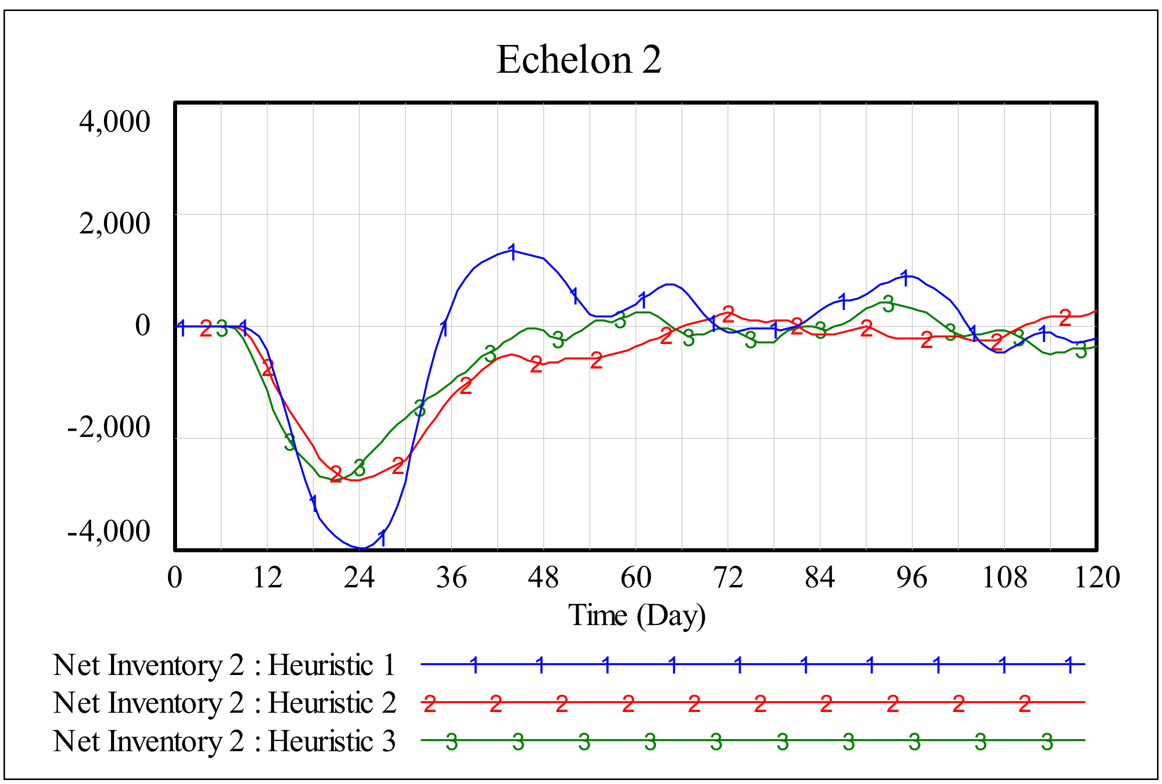

Figure 5: Dynamic behavior of *Net Inventory 2* generated by the three different heuristics

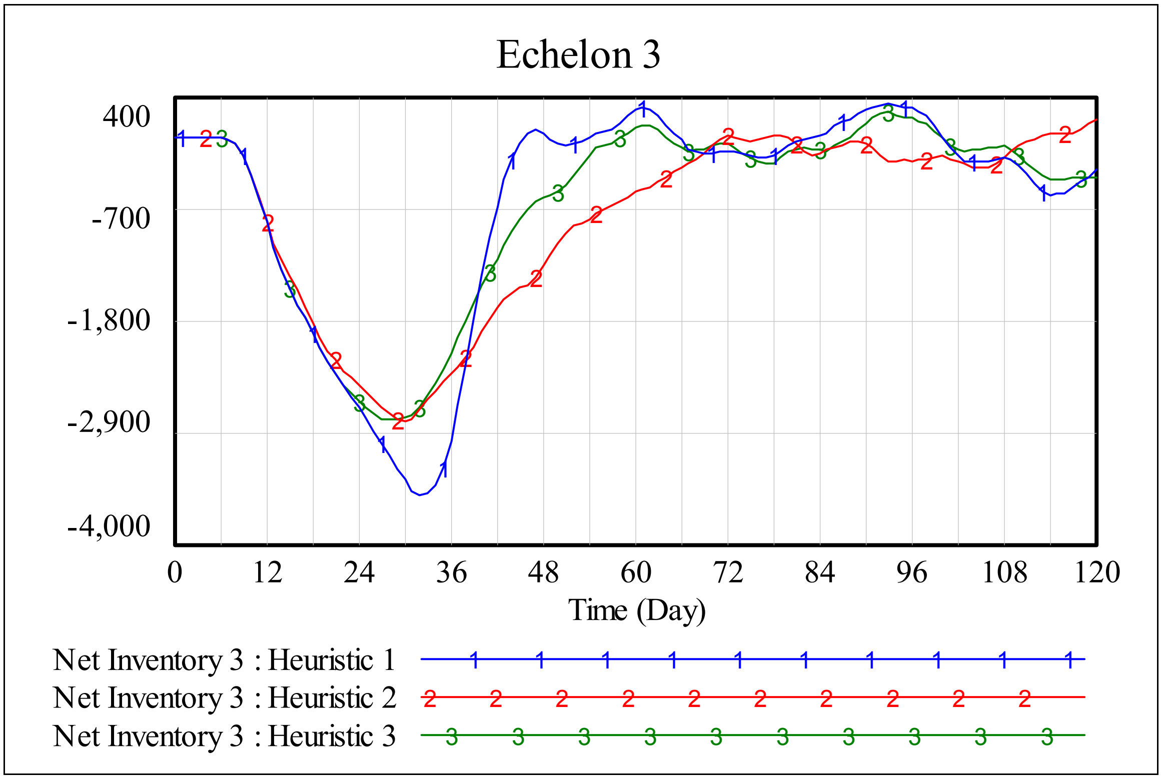

Figure 6: Dynamic behavior of *Net Inventory 3* generated by the three different heuristics

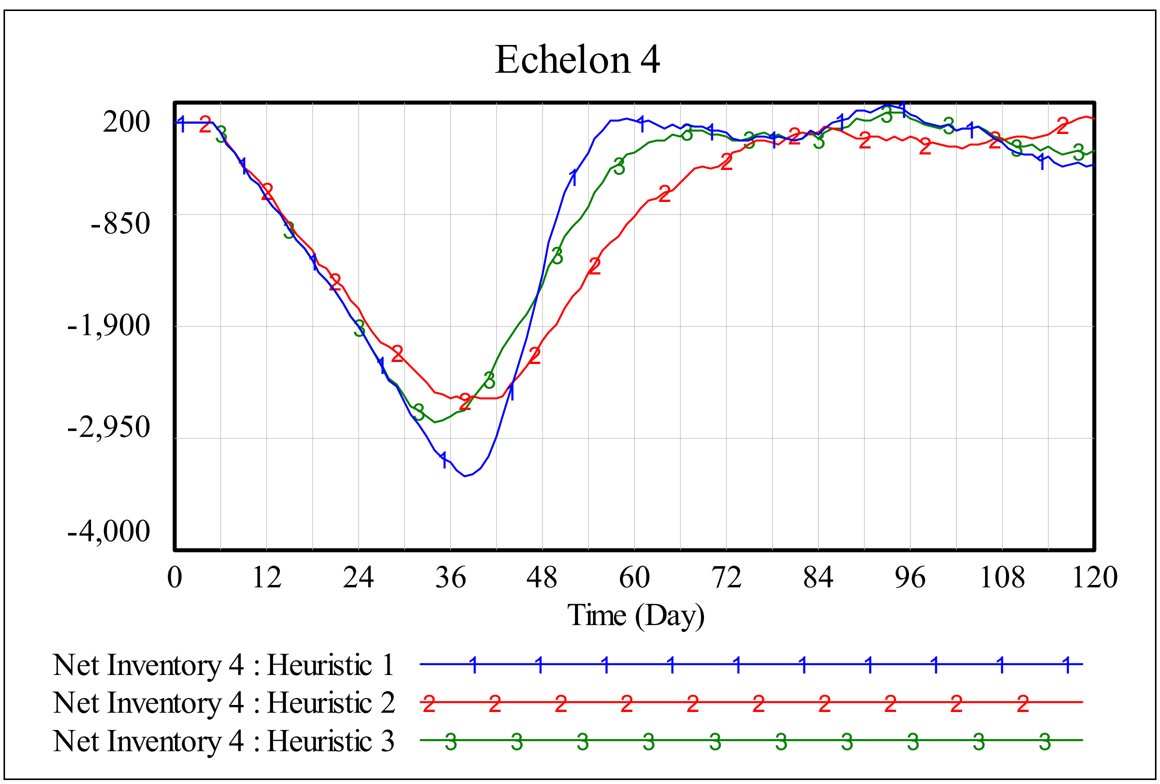

Figure 7: Dynamic behavior of *Net Inventory 4* generated by the three different heuristics

8. Conclusions and Future Research

We introduced a new and advanced inventory management heuristic for supply chains. This heuristic is based on a systemic approach that considers totality of many stocks in the order formulations; decision makers at every echelon except for the lowest consider the totality of their inventory and supply line and all the lower stage inventories and supply lines as a single stock. This heuristic would only be valid if sharing the net inventory and supply line information is possible in addition to sharing the end customer demand information. To be able to test the new heuristic, we developed a four echelon supply chain and create associated penalty formulations. To be able to compare the effectiveness of the new heuristic, we used two more heuristics. Heuristic 1 assumes no information-sharing. As a result of this assumption, the input to the expectation formation process at echelon$_i$ is the orders that it receives from its direct customer that is echelon$_{i+1}$. Sales information is the input only to the expectation formation process at echelon$_4$, which is the lowest echelon in our four-echelon supply chain model. Heuristic 2 assumes that end-customer demand information can be shared by all agents at different echelons. therefore sales information is the input to all expectation formation processes at different echelons. Heuristic 2 significantly improves the behavior and decreases associated costs. Finally, heuristic 3 assumes further information sharing and uses improved ordering formulations that consider the totality of the corresponding stage inventories and supply lines and all the lower stage inventories and supply lines as a single stock. The advanced heuristic presented in this paper further improves the behavior and associated costs.

In the continuation of this study, we plan to further test the proposed heuristic under different conditions such as different parameter values and different customer demand patterns.

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