Aggregated and Disaggregated Modeling Approaches to Multiple Agent Dynamics[1]

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Abstract: *This research deals with alternative modeling approaches to multiple agent dynamics. Models of a supply chain system are constructed to make comparisons about the capabilities of aggregated (System Dynamics) and disaggregated (Agent-Based) modeling approaches, based on a query to answer questions such as "Can aggregated, macro-level modeling capture the dynamics of micro-level, agent-based modeling? In what specific cases?" Effects of several factors, including inventory positions, prices, shadow orders, loyalty, safety stocks, and ordering policies are analyzed. It is shown that there are factors, effects of which can be captured by System Dynamics at an aggregate level; however it is also observed that System Dynamics may miss the dynamics at more detailed level resulting from the emerging heterogeneity among individual agent behaviors in these cases. There are also cases where System Dynamics cannot capture the dynamics generated by ABM, even at an aggregate level. Regarding the supply chain dynamics, it is shown that when agents try to act 'rationally', emergent system behavior may become destructive. Loyalty and reliable safety stocks are proposed as strategies against oscillations in the supply chain.*

Keywords: Agent-Based Modeling, Aggregation, Multiagent Systems, Simulation, Supply Chain, System Dynamics.

1. Introduction

Multiagent systems are systems composed of multiple interacting agents; where "agent is a system component that has autonomy in its actions and has a social ability to interact with other agents in the system through some patterns like cooperation, coordination, and negotiation" [15]. Macro and micro modeling approaches are used to simulate system-level multiagent dynamics. System Dynamics (SD) and Agent-Based (AB) modeling are two tools that are respectively used by macro and micro modeling approaches.

System Dynamics is a modeling perspective that emerged in 1950's and 1960's based on the concept of feedback theory. The feedback theory is the expression of loop structure. System Dynamics is used to model complex, nonlinear systems for which linear "cause-and-effect reasoning" is not sufficient to explain system behavior [10]. System Dynamics defines two main elements -stocks and flows- to construct the basis for this feedback loop structure. The overall behavior is characterized by the combination of positive and negative feedback loops, and stock-flow structure.

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A relatively newer modeling methodology is Agent-Based modeling. Agent-Based models are based on actions of individual agents and their interactions with other agents and their environment. The most important aspects of agent-based systems are the ability of agents to make independent decisions, and their capacity to interact with other agents according to their design objectives [15]. The aim of Agent-Based modeling is to look at the global consequences of local actions. The behavior emerges from the interactions of agents. Complexity arises from the simple rules governing the interactions of the agents [10].

The main point that makes comparison of SD and ABM approaches worthwhile is that both approaches are used in modeling complex, dynamic systems. However, there are some perception differences between two approaches. System Dynamics is based on an aggregation philosophy. SD makes an abstraction from single events and individuals; and forms a macro level modeling approach. On the other hand, Agent-Based Modeling is a micro level modeling approach; ABM focuses on the individual agents' actions. ABM defines behavior at individual level, and these local behaviors construct the overall non-deterministic behavior of the system. System Dynamics and Agent-Based modeling approaches perceive the problems from different points of view; both have advantages and disadvantages depending on the case which will be modeled. Therefore, an important contribution to the literature could be the construction of AB and SD models for the same problem set; and the comparison of characteristics of both approaches and looking for ways to combine the two approaches [10]. The AB and SD Supply Chain models constructed in the scope of this research are proposed as such a contribution to the literature.

2. Overview of Models[2]

The Supply Chain models constructed in this research are based on a three-level supply chain problem: there are customers demanding goods from the retailers, retailers demanding from the wholesalers, and finally manufacturers producing the goods and sending them downstream. There are two types of flows intrinsic to the Supply Chain: "information flow" and "material flow". Demand-based information flows upstream; and according to this information firms make several managerial decisions. According to these managerial decisions goods are produced and sent downstream through the way to the final customers. Effects of several factors are analyzed. These factors are related to the rationality level of the agents. These factors include consideration of inventory positions of the suppliers, supplier prices, shadow ordering and loyalty in the specification of the supplier of the goods and the order amounts from the selected suppliers. SD model and AB models are respectively constructed on Stella and NetLogo software packages.

2.1 Main Assumptions of the Models

The major assumptions for the models are:

- The models work in discrete-time fashion and DT is equal to 1 week.

[2] The initial structures of the models were developed by Dolunay, Kayabasi, and Soykurum (2004) in a graduation project in Industrial Engineering Department, Bogaziçi University, Istanbul. The documentation of model structure in Section 2 is based on the documentation in Dolunay, Kayabasi, and Soykurum (2004) and Barlas, and Demirel (2006).

- Only a single type of goods is considered in the models.
- A top-down hierarchical supply chain is considered, network type relations (for example between manufacturers and customers) are not allowed.
- The end-user demand is independent of the supply chain dynamics. Individual customer demand is assumed to be constant or uniformly distributed.
- FIFO principle is used in meeting the demands.
- Exponential smoothing is used by agents to forecast the demands.
- The production and transportation lead times are assumed to be constant.

2.2 Agent-Based Model Overview

In Agent-Based model there are 4 agent types –breeds, in NetLogo terminology- one for each supply chain level –customers, retailers, wholesalers and manufacturers; and extra 2 breeds are used for units that facilitate transportation –transit_manufacturer, and transit_wholesaler.

2.2.1 Customer Procedures

Customers move around in the system and give order to selected retailers by "buy" procedure. In "buy" procedure the incoming_demand of the target retailer is increased by X units amount. This is coded in the "main" procedure as follows:

```
;-------------------------------------
ask customer
[  move
   set demand X
   buy
]
;-------------------------------------
```

2.2.2 Retailer Procedures

Retailers hold information of their inventory level, incoming_demand from customers, and backlogs to be met when there is sufficient inventory.

```
;-----------------------------------
ask retailer
[  sell
   forecasting
   set incoming_demand 0
   ordering_to_wholesaler
 ]
;-----------------------------------
```

In the "sell" procedure retailers manage the interaction with the customers. In this procedure, first backlogs are controlled and met if there is sufficient inventory. After backlogs are met, the remaining inventory is used to meet the incoming_demand of that period. The excess demand is added to the backlog list, as to be met in the following period.

In the "forecasting" procedure retailers adjust their demand forecasts according to the incoming_demand of that period, using exponential smoothing.

"Ordering to wholesaler" procedure facilitates the information flow between the retailers and wholesalers. The order amount and the selection of the supplier of this order may depend on several factors such as price, inventory position, and ordering policies. The amount ordered from the selected wholesaler is added to the incoming_demand of that selected wholesaler and the wholesaler makes decisions according to this information.

2.2.3 Wholesaler Procedures

The general logic in wholesalers' procedures is similar to that of retailers, and the differences are explained below.

```
;---------------------------------------------
ask wholesaler
[  ship
   forecasting
   set incoming_demand 0
   ordering_to_manufacturer
]
;---------------------------------------------
```

Wholesalers have some additional list structures: order lists (order_list (order amount list) and id_list (id of retailers list)) and backlog lists (backlog_list and bid_list). The order lists (order_list and id_list) are updated simultaneously; and also the backlog lists.

As a second difference, wholesalers do not directly supply goods to retailers; there is an entity called transit_whole that acts as an intermediary agent between retailers and wholesalers. Transit_whole keeps track of the orders that will be transported to retailers; for this purpose three lists are used: one keeps the data of the amount that will be transported, another one keeps the data about the time when the goods are loaded on the transporter, and the other one keeps the ids of retailers that the goods will be transported to.

The goods are loaded onto transit_whole by "ship" procedure. "Ship" controls backlogs; if there is any order that is in backlog position the required amount is loaded onto the transit_whole, and inventory is decreased by an amount equal to the transported goods. And also, the related entries are deleted from backlog lists. Backlogs are met as long as there is sufficient inventory. Then, if there is sufficient inventory left, the incoming_demand of that period is met. At the end of each period the elements of the backlog lists that are not shipped and the current period's unmet demand are combined; and they form the backlog list of the next period.

2.2.4 Manufacturer Procedures

The procedures of manufacturers are similar to those of wholesalers with a fundamental difference: Manufacturers do not have any suppliers –raw material suppliers are not considered in scope of the project-, so they do not give orders to other agents; instead they give production orders inside the firm.

```
;---------------------------------
ask manufacturer
[  finish-production
   ship
   forecasting
   set incoming_demand 0
   production
]
;---------------------------------
```

Manufacturers employ production lists, where they keep track of the production amounts and the initiation times of the production. Production_placed contributes to WIP inventory. "Finish production" controls whether the production is completed; and if this is the case the procedure increases the inventory of the manufacturer.

2.3 System Dynamics Model Overview

The material and information flow structure of the Agent-Based model is preserved in the System Dynamics model. This is a three level supply chain model where there isn't any differentiation among agents. The structure is similar to that of AB model; but the observables of agents at each level are aggregated under some stocks. To give an instance, inventory_manufacturer stock keeps the cumulative inventory of all manufacturers, when compared to the Agent-Based model. Each supply chain level acts as if there is only one agent in that level.

The sequence of events is as follows: Agent observes its inventory position and gives order if necessary: demand occurs; if there is sufficient inventory on hand, shipments are dispatched; unfulfilled orders are backlogged; in transit goods arrive; and expected demand is updated. Since AB model is a discrete time model, the analysis is based on a discrete-time SD model. Figure 2.3.1 shows the stock-flow diagram of the retaliler sector of the SD model; the general structure is preserved in wholesaler and manufacturer sectors.

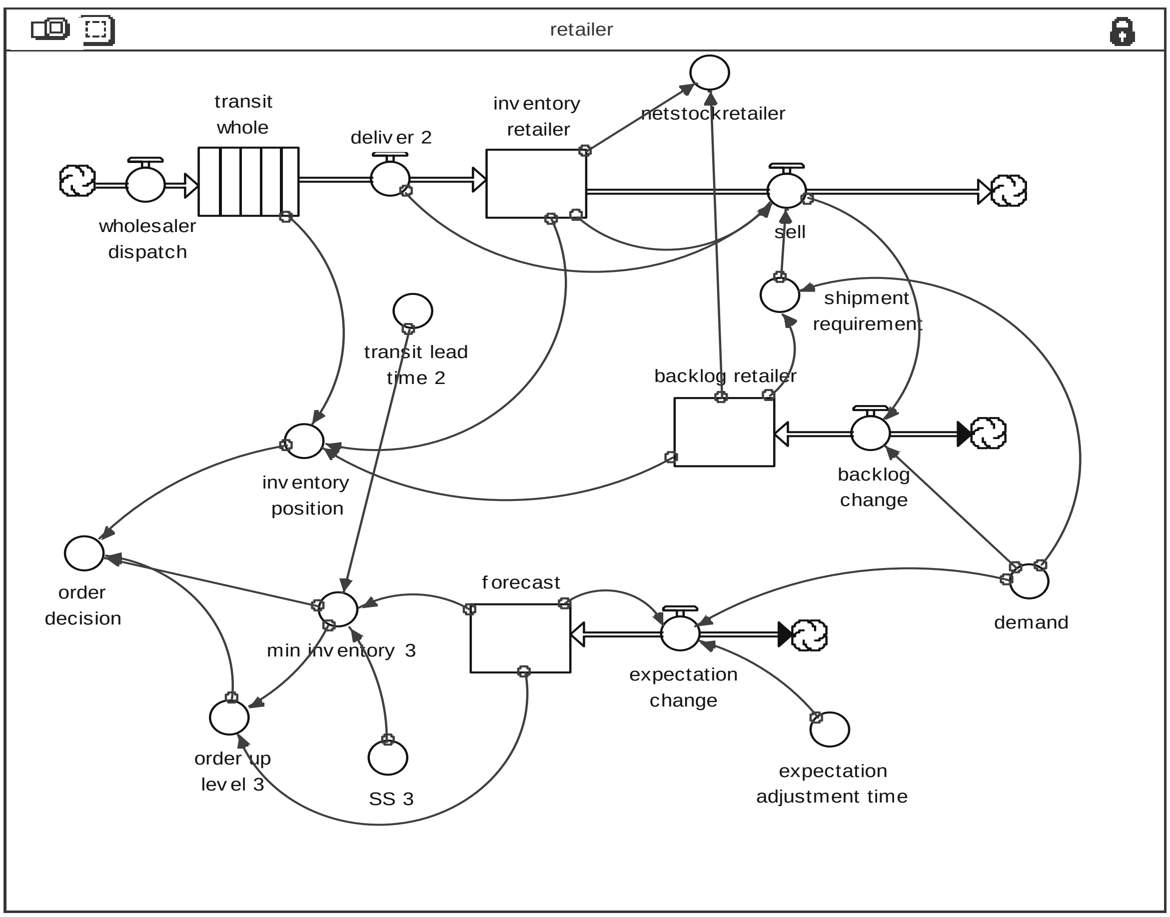

Figure 2.3.1 Supply Chain SD Model *(Retailer Level, shown as illustration)*

2.4 Ordering Policies

The following ordering policies are used. To put a note, the inventory position term is defined as: "inventory (that is physical inventory hold) *plus* order given (or production placed in the manufacturer case), which stands for the ordered but not yet received amount (that is on the supply chain) *less* backlogs to be met". [6]

(1) In the "As Needed" policy, the entity compares its forecasts with the inventory position, and if there seems to be inadequate inventory it gives order in the amount of the difference between the forecast and the inventory position. [6]

(2) When "Reorder point- Order up" policy is employed, a minimum inventory is defined. The minimum inventory is calculated by the following equation:

$$\text{min\_inventory} = \text{forecast} * \text{lead\_time} + SS$$

In which SS stands for the safety stock. Forecast is the expected sales for one period, and lead_time stands for the lead time of the upper level supplier. When the inventory position takes a value smaller than or equal to this minimum inventory level, an order is placed to increase the inventory position to the order up level. In calculating the order up level, following equation is employed:

$$\text{orderup\_level} = \text{min\_inventory} + 3 * \text{forecast} \ [6]$$

(3) In "fixed order up" policy, there is a fixed order up level and every time the inventory position falls below this level, an order equal to the amount of the difference between the order up level and the inventory position is placed. [6]

3. Verification and Validation of the Models

In order to verify the agent based model, first of all the model is run step by step using constant demand and the results of each period are compared with the hand simulation results. By this method, it is checked whether there is any inconsistency between the conceptual model and the formal model. The equations of the SD model are checked for the same verification purposes. And it was finally shown that the formal ABM and SD models are accurate representations of the conceptual models.

The validation procedure was done in order to understand whether the SD and AB models were in a one-to-one corresponding fashion. In order to conclude that differences, if there is any, in the behavior come from the fact that in one of the approaches there are multiple agents and that there are critical interaction patterns among these agents, the models must show the same behavior patterns when there is one of each agent. So, the Agent-Based model is run when there is one manufacturer, one wholesaler, one retailer and one customer. Keeping the initial values for all the variables and all the parameters same in both models, the models are tested whether they have the same structure. These tests are done under different conditions and two examples are included below in Figures 3.1-3.4. For more validation results; see Dolunay, Kayabaşı, and Soykurum (2004) and Barlas, and Demirel (2005).

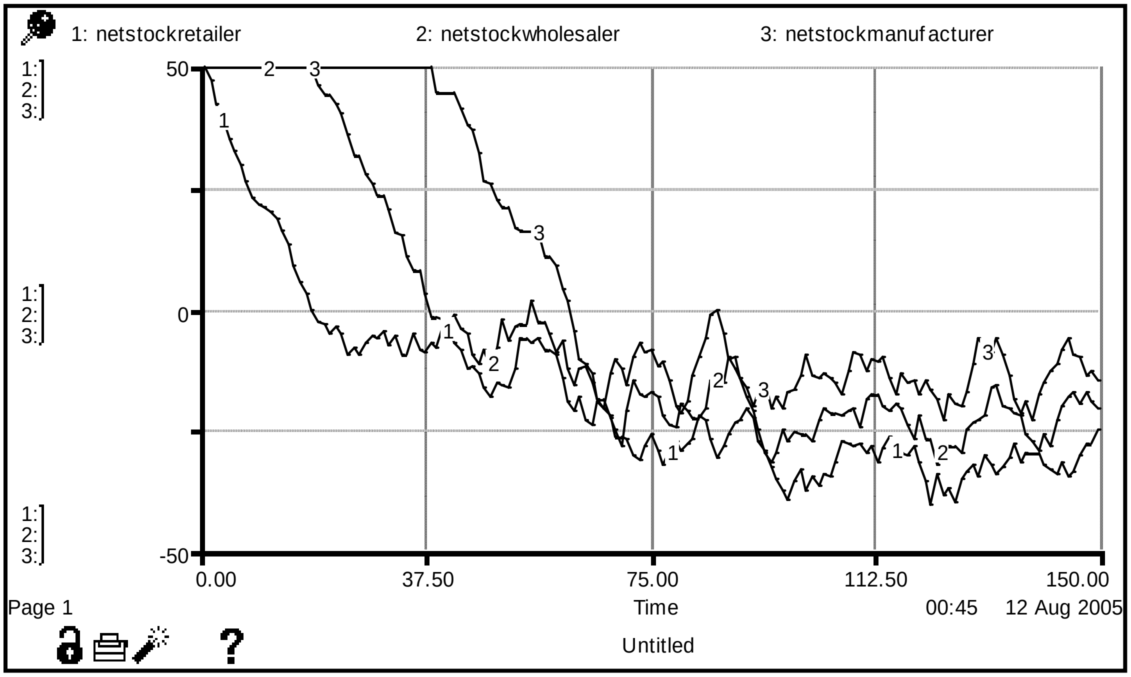

Figure 3.1 Supply Chain SD Model -Validation Output
Demand ~ Uniform (0, 5), “As Needed” Ordering Policy (O.P.),
Production Lead Time (PLT)=5, Transportation Lead Time (TLT)=3

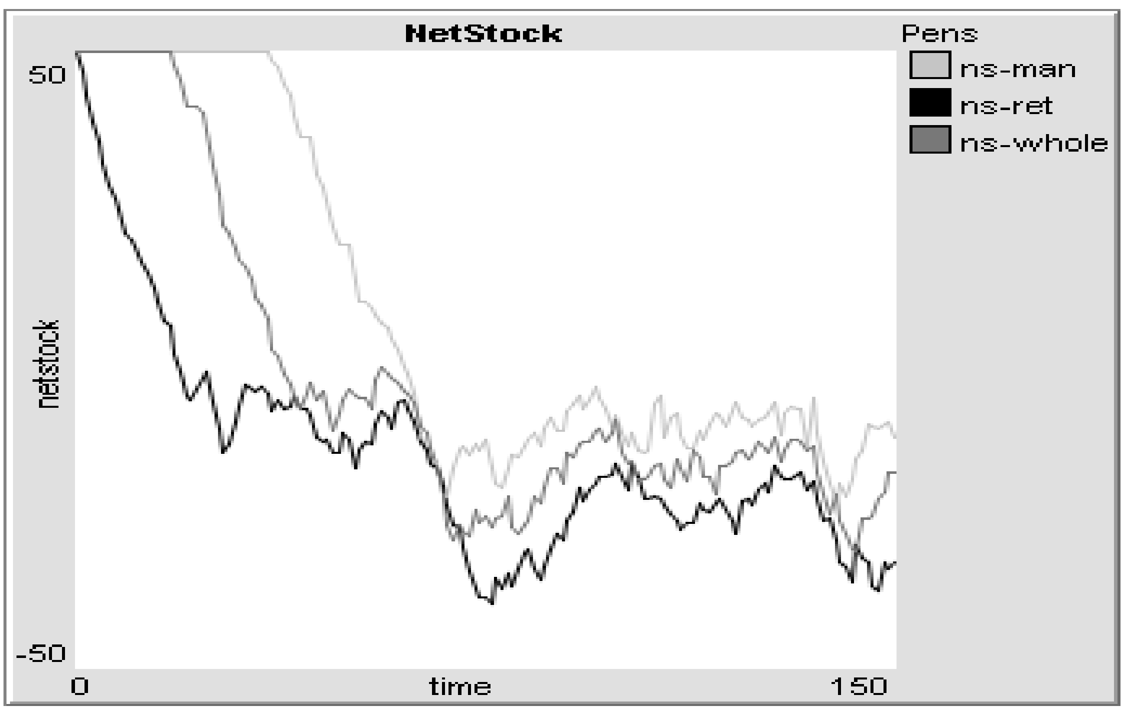

Figure 3.2 Supply Chain AB model -Validation Output
Demand ~ Uniform (0, 5), “As Needed” O.P,
PLT=5, TLT=3

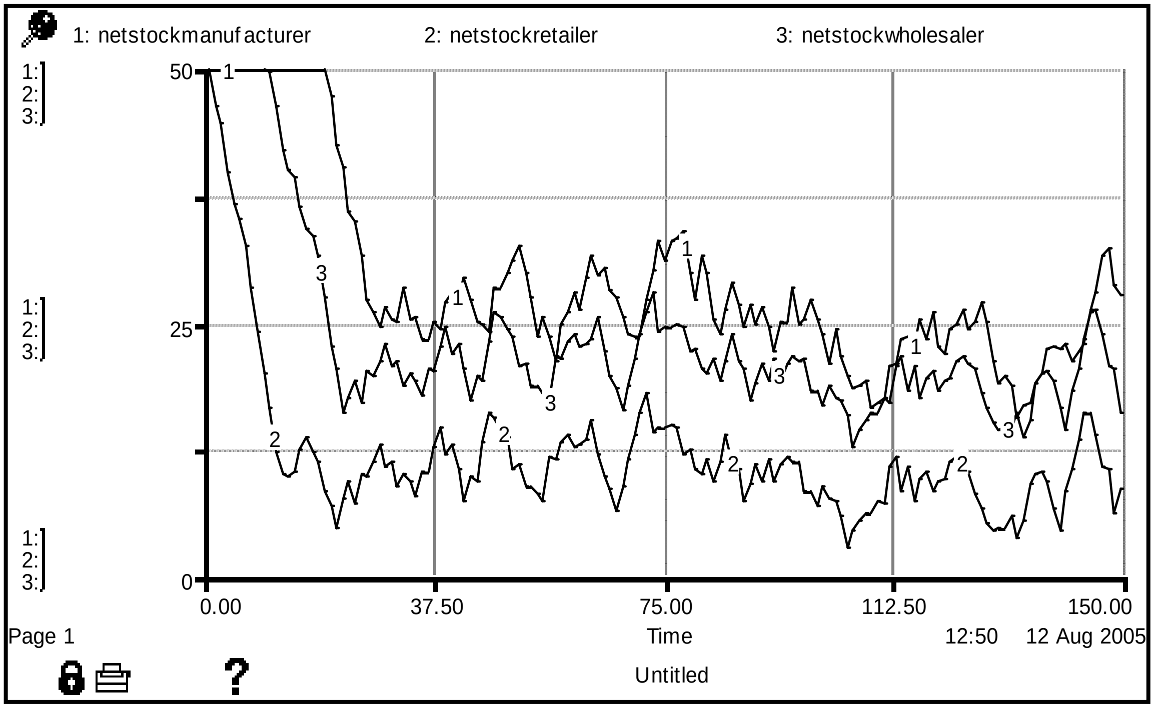

Figure 3.3 Supply Chain SD Model -Validation Output
Demand ~ Uniform (0, 5), "Fixed Order Up (FIP)" O.P,
"Manufacturer FIP"=40, "Wholesaler FIP"=30, "Retailer FIP"=20, PLT=5, TLT=3

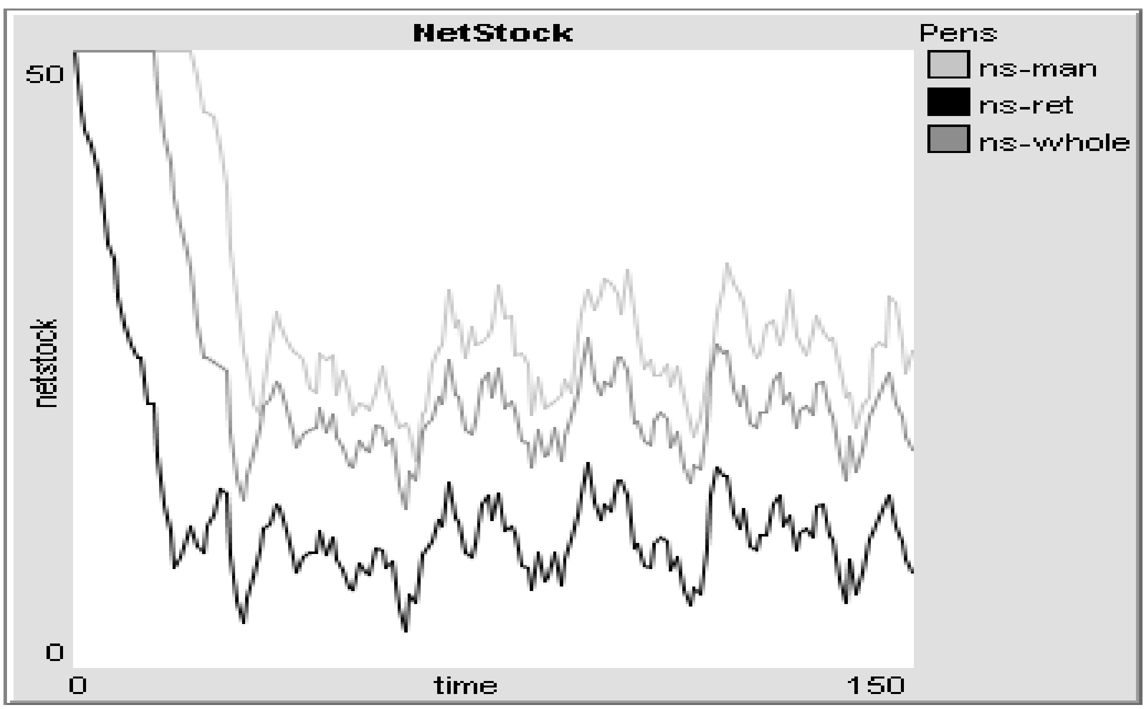

Figure 3.4 Supply Chain AB model -Validation Output
Demand ~ Uniform (0, 5), "Fixed Order Up (FIP)" O.P,
"Manufacturer FIP"=40, "Wholesaler FIP"=30, "Retailer FIP"=20, PLT=5, TLT=3

By validation procedure; it is shown that the behaviors generated by SD and AB models are very similar; the differences between the two models are negligible. They come from the fact that there is no structural difference between the two modeling approaches applied to the supply chain system.

4. Experimentation and Scenario Analysis on the Supply Chain Models

In this research, different factors that affect the ways firms behave are considered. The behavior patterns generated by SD and AB models are analyzed to compare the capabilities of the two approaches. In some cases the rationality added to the individual agents can be represented in the SD model in an aggregate manner, however in some cases it can't. When it can be added, a comparison is made regarding the behaviors generated by the two models. The extent to which the System Dynamics can capture the dynamics of the real system, which AB model resembles more, is analyzed. And another target in the research is to analyze the effects of the rationality, the decision criteria of the firms on the overall supply chain behavior.

The effects of following factors are analyzed.

Consideration of:

- Inventory Positions of the Suppliers,
- Prices of the Suppliers,
- Phantom –Shadow- Orders, and
- Loyalty

in the selection of the supplier and in the specification of order amounts.

In order to compare the results that are generated by ABM and SD models, the below parameter setting is used.

Parameter Setting 1:

- 2 manufacturers, 10 wholesalers, 20 retailers, 500 customers
- Demand ~ Uniform (0, 5) in ABM, Normal (1250,32) in SD.
- Lead time: 3 for transportation, 5 for production
- Order Policy: "Reorder Point Order Up"
- SS: 20 (for all agents)

Figure 4.1 and Figure 4.2 show the outputs of the model for random supplier selection case. In this case, agents in AB model choose their suppliers randomly from the agents in one higher step of the supply chain. SD model considers aggregated agents, thus there is no selection of the supplier.

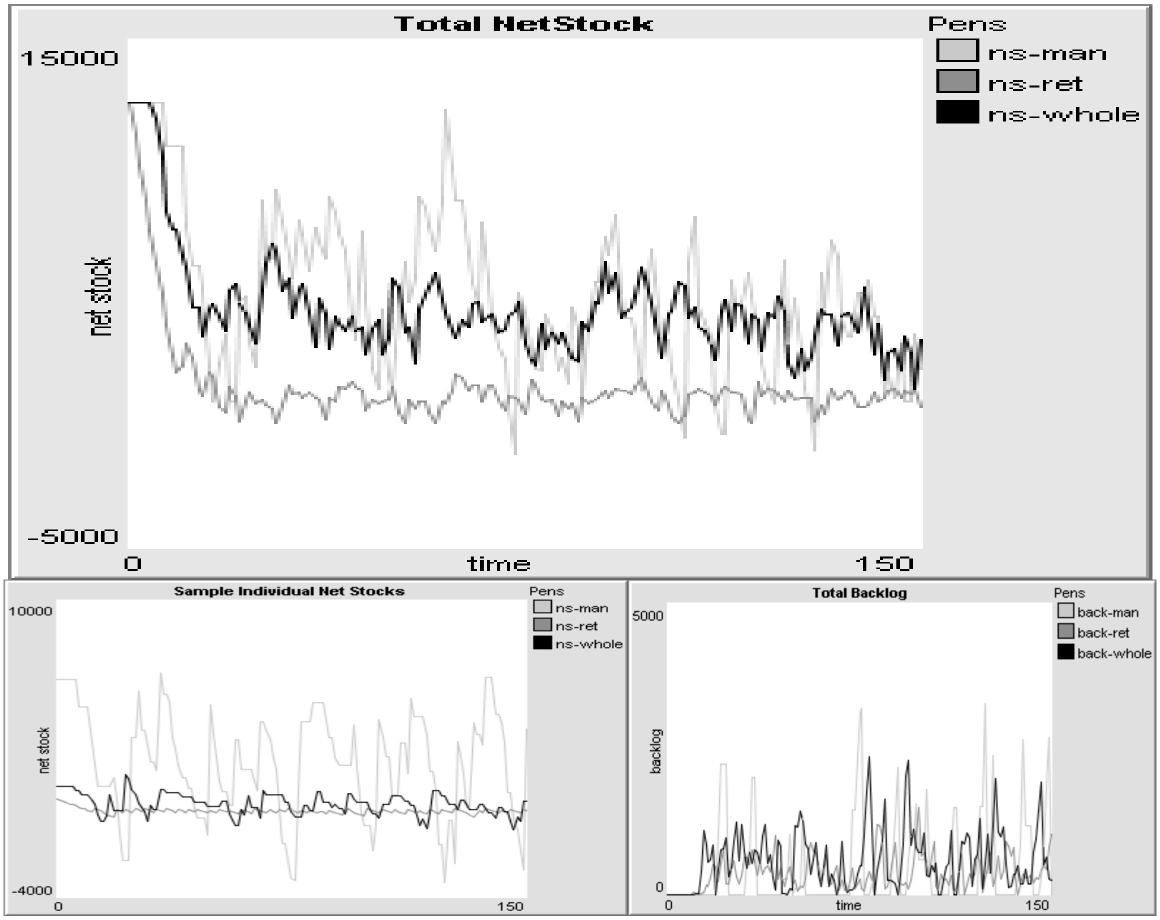

Figure 4.1 Supply Chain AB model –Parameter Setting 1
(Random Supplier Selection)

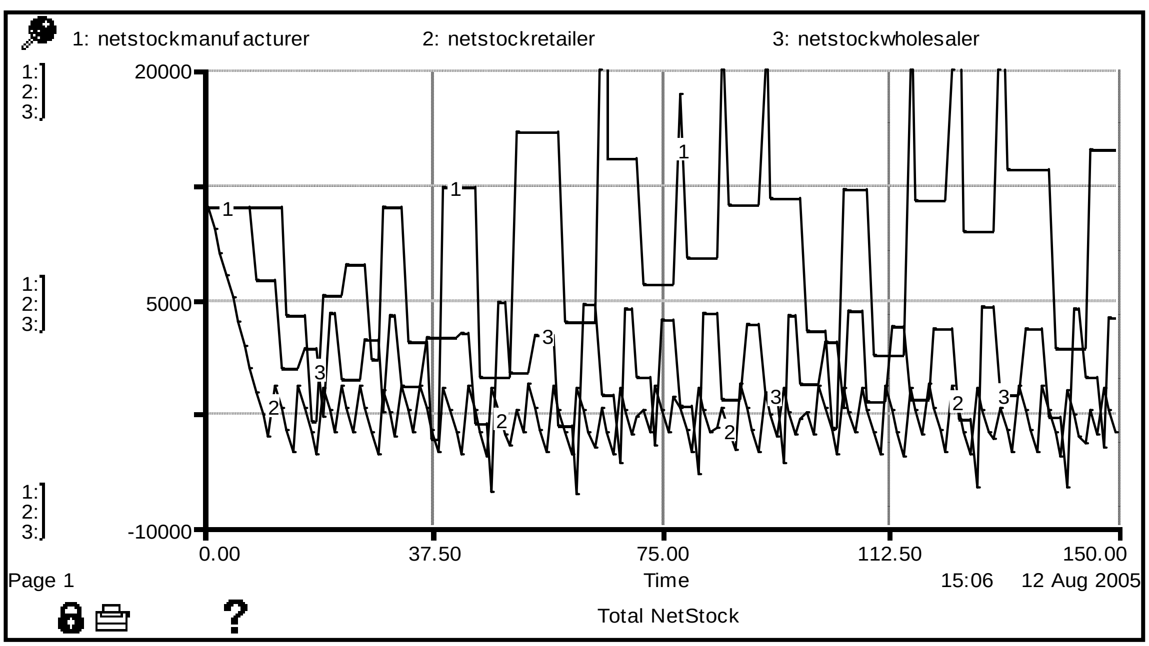

Figure 4.2 Supply Chain SD Model –Parameter Setting 1
(Random Supplier Selection)

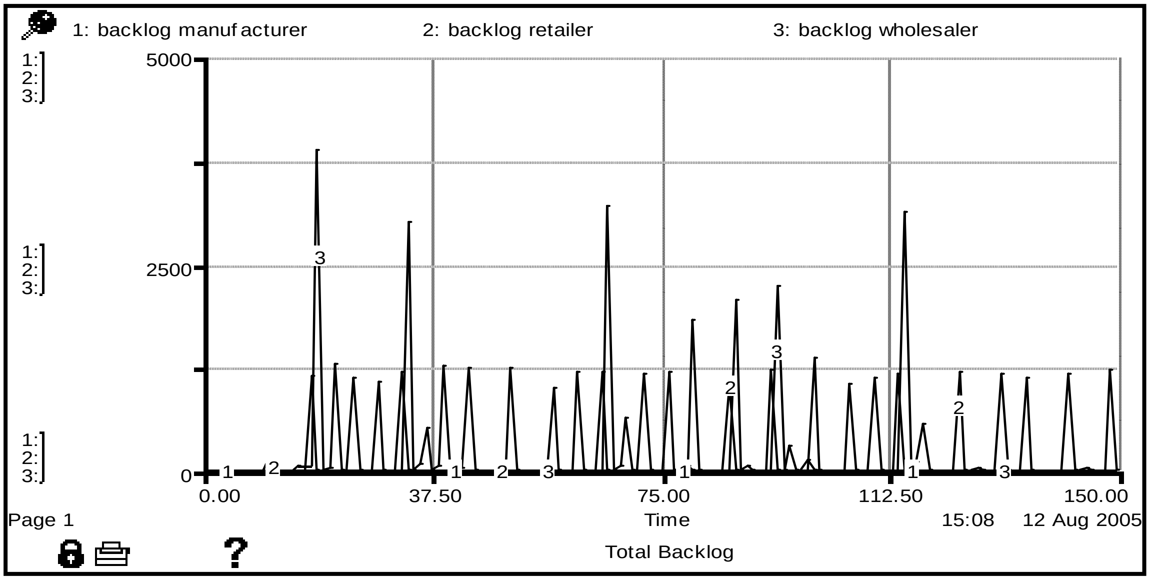

Figure 4.2 Supply Chain SD Model –Parameter Setting 1
(Random Supplier Selection) [ctd.]

SD and AB models generate similar behaviors: the fluctuations in the supply chain and the bullwhip effect are observed from both model outputs. The main structural causes of these oscillations and the bullwhip effect are the delay and feedback loops between supply chain levels. Stochasticity in demand reinforces these effects. However there are some differences between SD and AB model behaviors. The intensity of oscillations in SD model is higher, this is due to the fact there are phase lags between individual net stock positions of the agents in the AB model. For example, at a point there may be several retailers with high, and several with low inventory levels; this reduces the variation in the cumulative inventory of the retailers. In SD model the system acts as if there is a single agent; so there is not any reduction in oscillations -of the type in the AB model. It is important to note that this does not imply a structural difference between Agent-Based and System Dynamics models.

4.1 Consideration of the Supplier Inventory Positions in the Selection of the Supplier

To make agents more rational decision makers, they are made able to look for suitable suppliers by inventory position criteria. This includes looking up at the inventory levels of the suppliers and choosing one of the suppliers which can satisfy the demand.

This selection criterion is added to AB model, since there is no such distinction among aggregated individuals in SD model, this attribute can not be added to the SD model at this aggregation level. Figure 4.1.1 shows the AB model output.

When Figures 4.1 and 4.1.1 are compared, it is seen that the fluctuations in the inventory levels resulting mainly from the lead-times are further intensified by the “rationality” of agents. Looking at the sample individual net stocks graph it is seen that the oscillations in the individual inventory levels get larger at the upper levels of the Supply Chain, namely bullwhip effect is intensified.

This factor can not be added to the SD model, however it makes differences in the system behavior; therefore it is shown that SD can not catch the dynamics of this level detail.

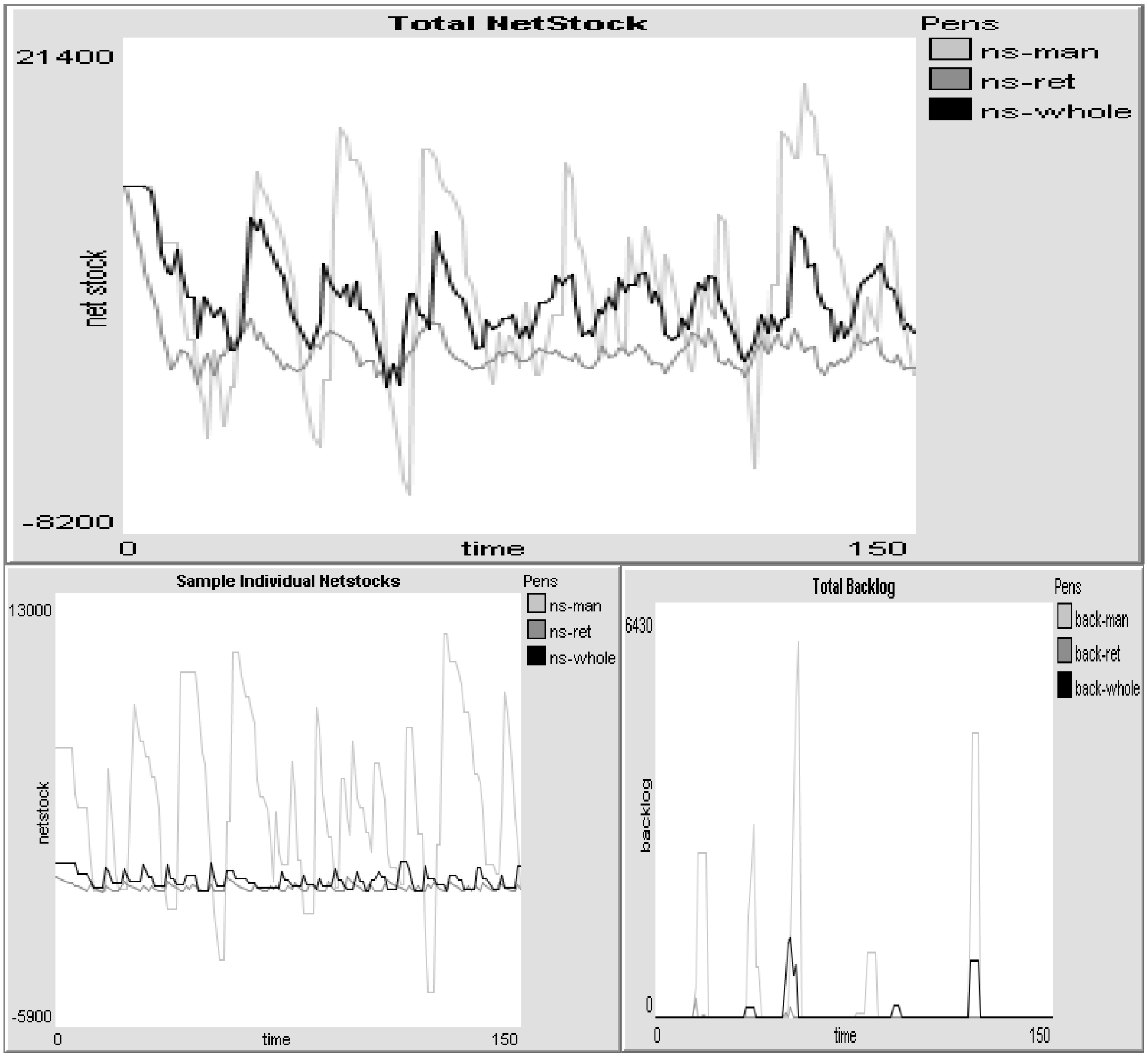

Figure 4.1.1 Supply Chain AB model –Parameter Setting 1
(Consideration of Supplier Inventory Positions in Supplier Selection)

4.2 Effects of Consideration of the Price

One of the main factors in determining the order amount and the supplier of that order is the price of the product. The effect of the price on the behavior of the agents is experimented in this research.

The effect of the price is analyzed in two steps: At first step, the order amount is not affected from the changing prices; what changes is only the supplier of the product. The second step is about changing the demand level according to the price levels. For some of the goods, the first one may be the case; and for others the second one.

4.2.1 Price as the Selection Criterion of the Supplier

Since this factor is only about the selection of the supplier and it does not affect the total demand quantity, this attribute can not be included into the SD model.

In AB model, the price is defined as a discrete function of on-hand inventory. The firms with high inventory levels determine to lower their prices to be able to squander their inventories considering the inventory holding cost; on the other hand the firms with low inventory levels put higher prices to their products to get higher revenues from the scarce products. The agents consider the prices to determine their target suppliers. It is assumed that the firms take the price as the main criterion of supplier selection.

Figure 4.2.1.1 shows the output of the AB model, when price levels are considered in selecting the suppliers.

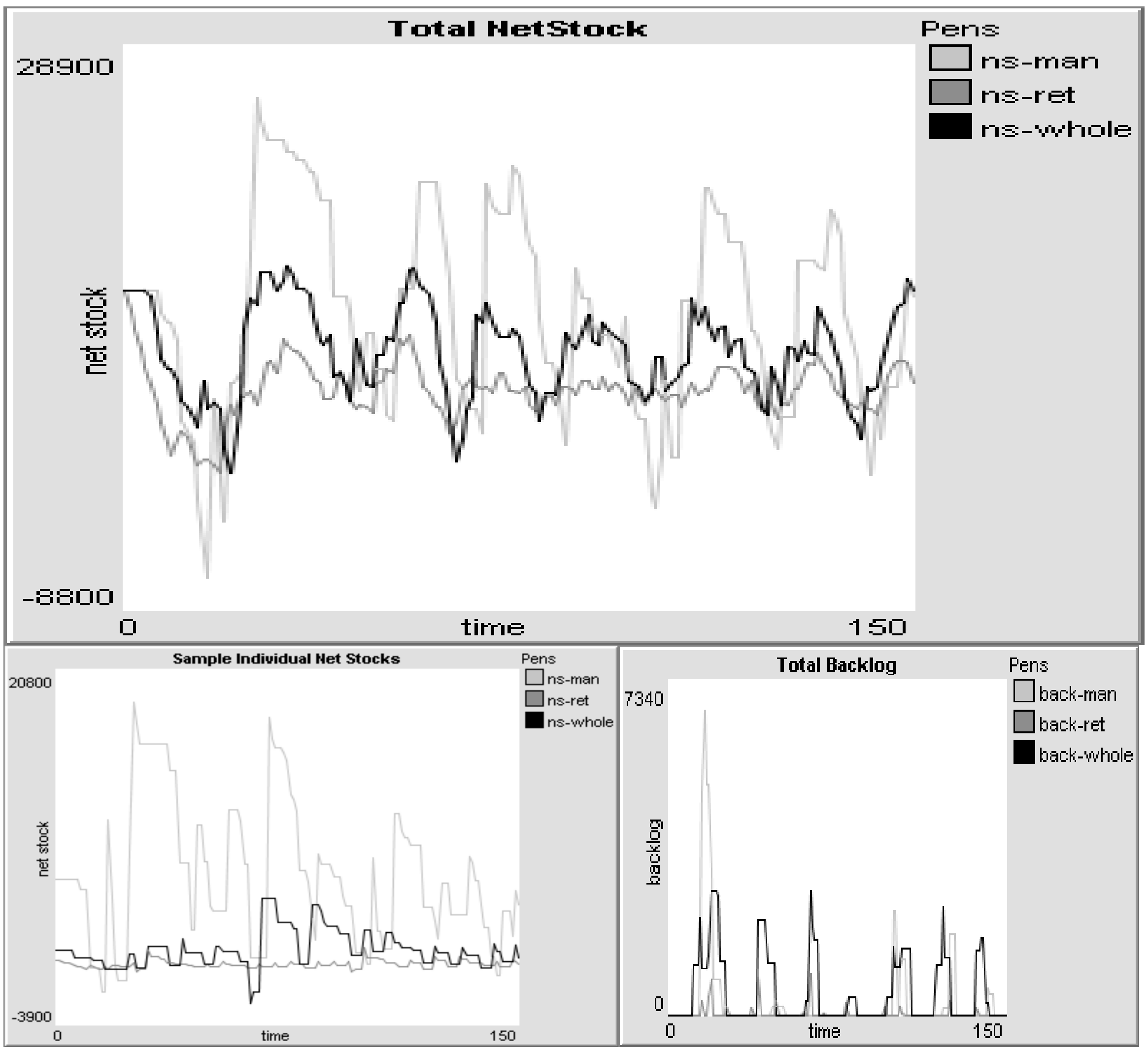

Figure 4.2.1.1 Supply Chain AB model –Parameter Setting 1
(Consideration of Price in the Supplier Selection)

As seen from the graphs the oscillations in the inventory levels are intensified by the price factor added to the lead times; and the periods of oscillations become larger. The increased autonomy of agents –reference to the heterogeneity among them- can be seen from Figure 4.2.1.2.

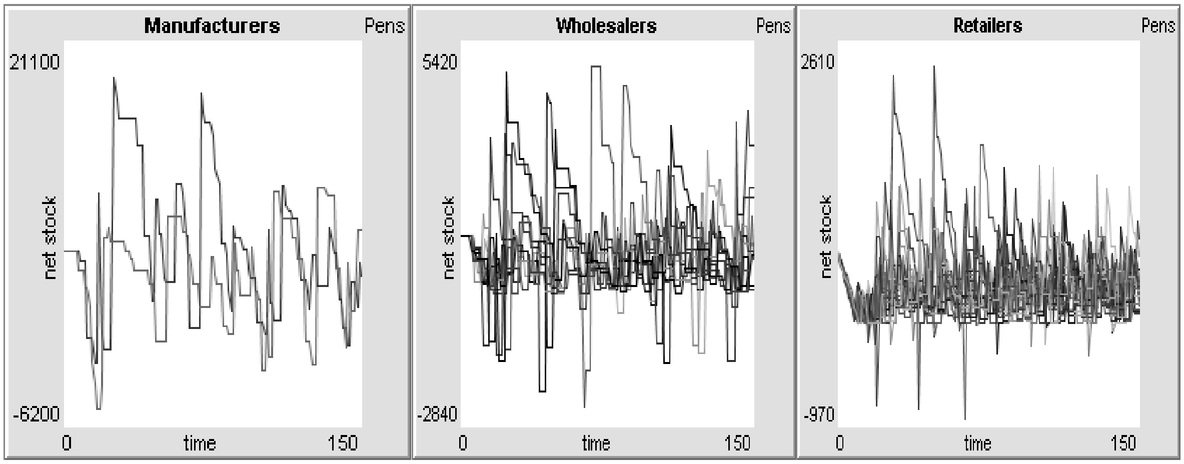

Figure 4.2.1.2 Supply Chain AB model, Individual Inventories at each level –Parameter Setting 1
(Consideration of Price in the Supplier Selection)

4.2.2 Price Also as a Determining Factor of the Order Quantity

In further analysis, it is considered that the order quantities of the agents are affected from the price. This modification can be made in SD model; but at an aggregate level. A negative feedback loop structure is defined between the average price level and the order quantity. As the price decreases, the demand from the lower chain level increases; as the demand from the lower chain level increases, the inventory level decreases; and as inventory decreases the price increases.

Figure 4.2.2.1 shows the output of the SD model with the price effect.

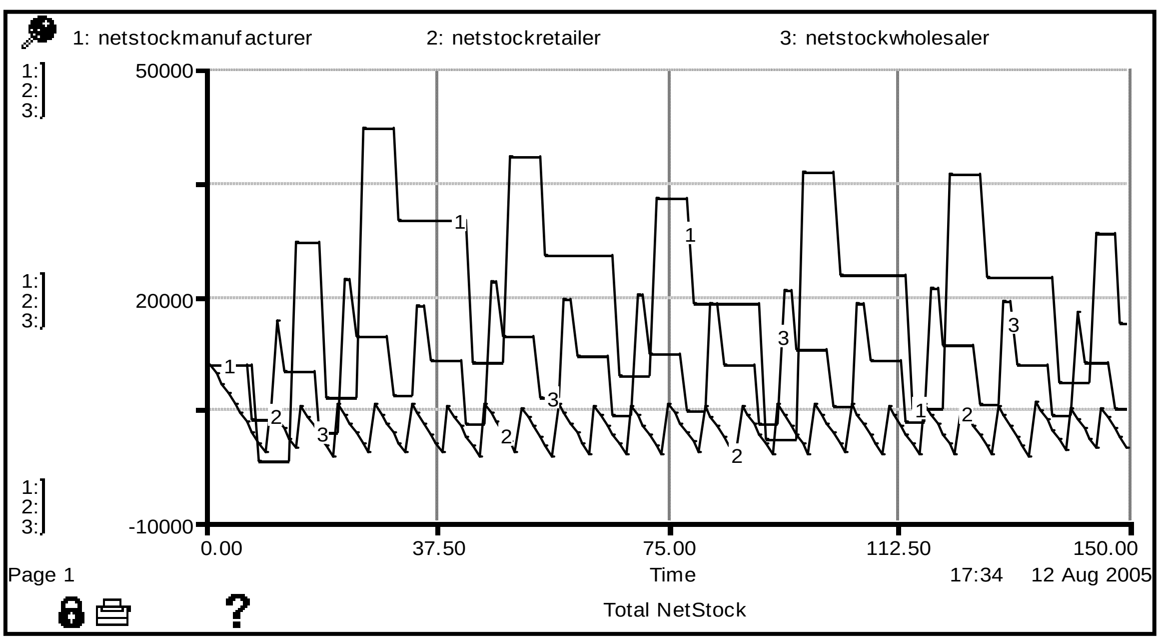

Figure 4.2.2.1 Supply Chain SD Model –Parameter Setting 1
(Order Amount Affected by Price)

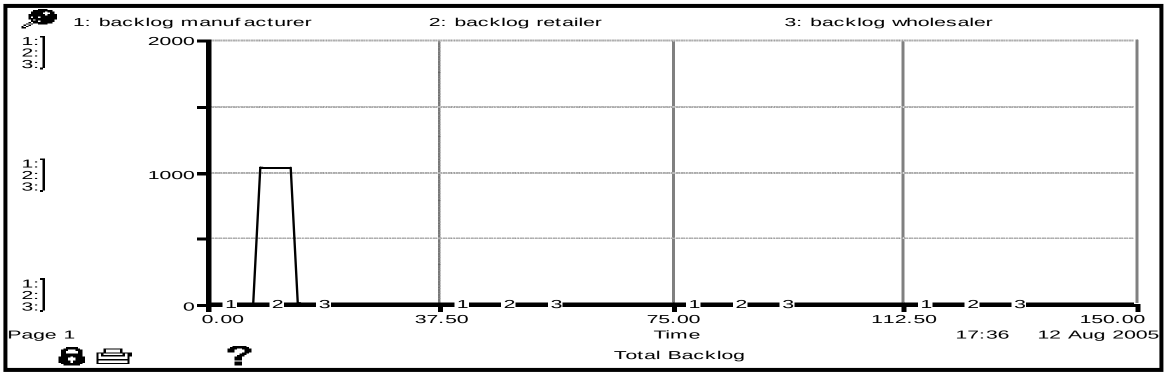

Figure 4.2.2.1 Supply Chain SD Model –Parameter Setting 1
(Order Amount Affected by Price)[ctd.]

As can be seen from Figure 4.2.2 and Figure 4.2.2.1, the behavior of the SD model with and without price factor are similar but the intensity of oscillations are bigger in the one with price factor. It is also important to note that the intensity of oscillations increase in the direction from retailers to manufacturers, namely the bullwhip effect.

There are two mechanisms that cause oscillations in the Supply Chain; first one is the delay due to the lead times and bullwhip effect, and the other one is the changing price levels. But there is a point SD model can not capture: the autonomy of agents at the same level of the chain. Figures 4.2.2.2 and 4.2.2.3 show the ABM generated behavior with the same decision rule. The periodicity in the SD model is more blurred in the ABM case; this is due to the differences among individual inventory levels. The increased autonomy of agents, reference to the heterogeneity among them, can be seen from Figure 4.2.2.3.

Both ABM and SD models reveal the destructive effect of price on the firms. The firms are acting in a way they think as rational; but the emergent system behavior gives harm to all of the agents.

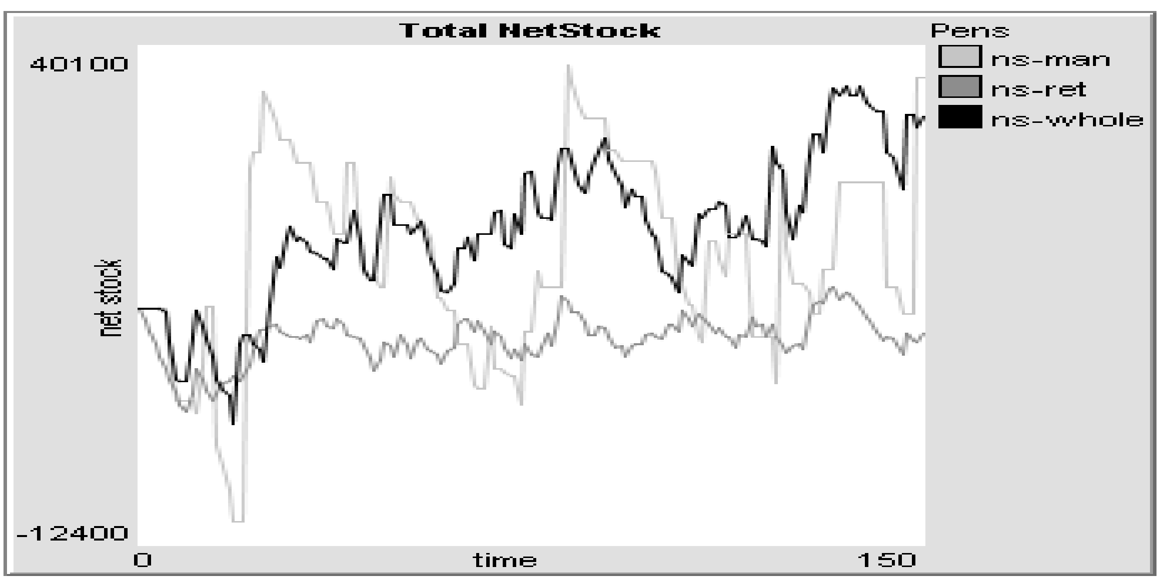

Figure 4.2.2.2 Supply Chain AB model –Parameter Setting 1
(Order Amount Affected by Price)

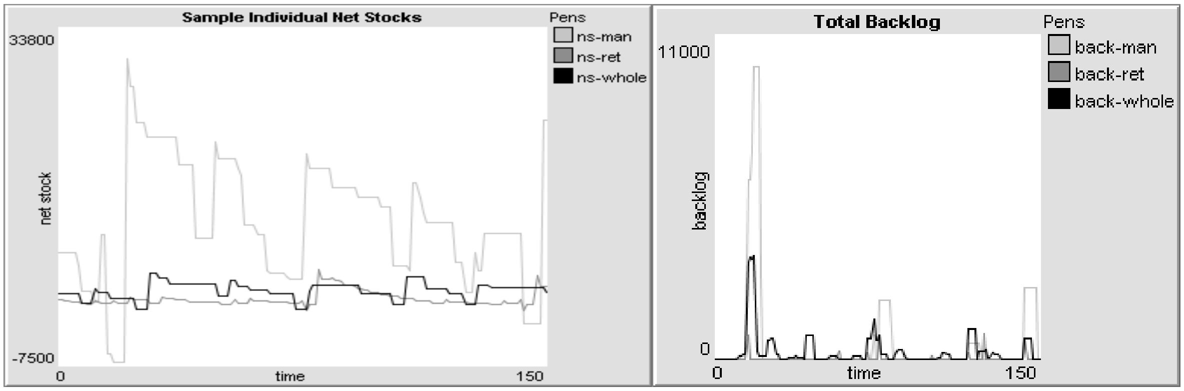

Figure 4.2.2.2 Supply Chain AB model –Parameter Setting 1
(Order Amount Affected by Price)[ctd.]

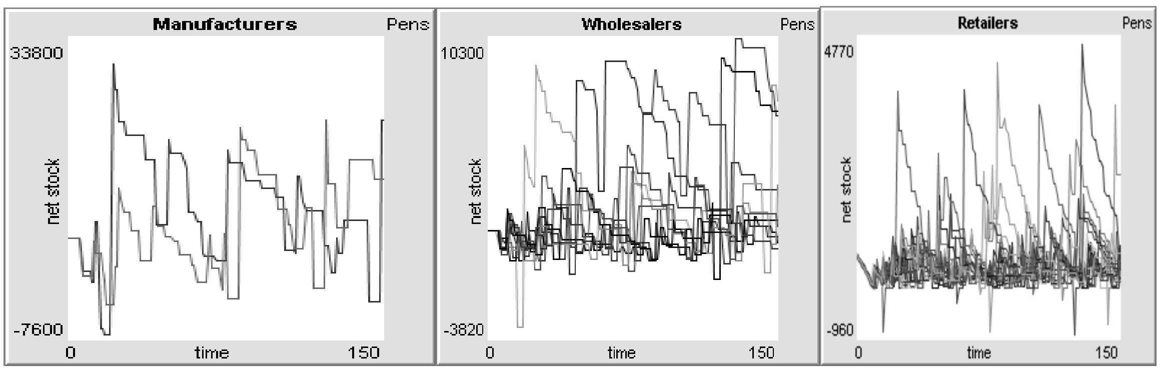

Figure 4.2.2.3 Supply Chain AB model Individual Inventories at each level –Parameter Setting 1
(Order Amount Affected by Price)

4.3 Effects of Consideration of the Loyalty in the Selection of the Supplier

Another factor that shapes behavior of the Supply Chain is the loyalty among the enterprises. The loyalty may be defined as a function of several factors, and in the scope of this research it is defined as a function of the price of the supplier and the length of the time interval the firms engage in the relationship. Loyalty may also be defined as a function of service time, shadow orders, etc.

This factor can only be formulated in ABM; since there are no distinctions among individuals in SD aggregation.

The purpose is to answer the following question: "Can loyalty be a factor that diminishes fluctuations in the supply chain?"

In AB model, each customer is assigned a random retailer, each retailer a random wholesaler, and each wholesaler a random manufacturer. The firms can tolerate their suppliers' prices to some extent depending on the history of their relationship and if they decide that the price is at a level that can not be tolerated, they switch to the supplier with the minimum price. Prices of agents are defined in the same way as before –as a function of inventory. Figure 4.3.1 shows the output of the AB model for the "Loyalty" case.

When behaviors are analyzed it is seen that loyalty brings stability to the system at sustainable inventory levels, the fluctuations are reduced. This comparison implies that in a market open to fluctuations due to the price changes, demand uncertainties and production/transportation lead-time delays; the most efficient policy –among the alternatives investigated- is to combine trust along the Supply Chain with the rationality of individual agents. In other words, when each firm is loyal to its supplier and each customer keeps its rationality in the sense that “if the price levels are too high, an agent switches to another supplier”, the best for the all occurs.

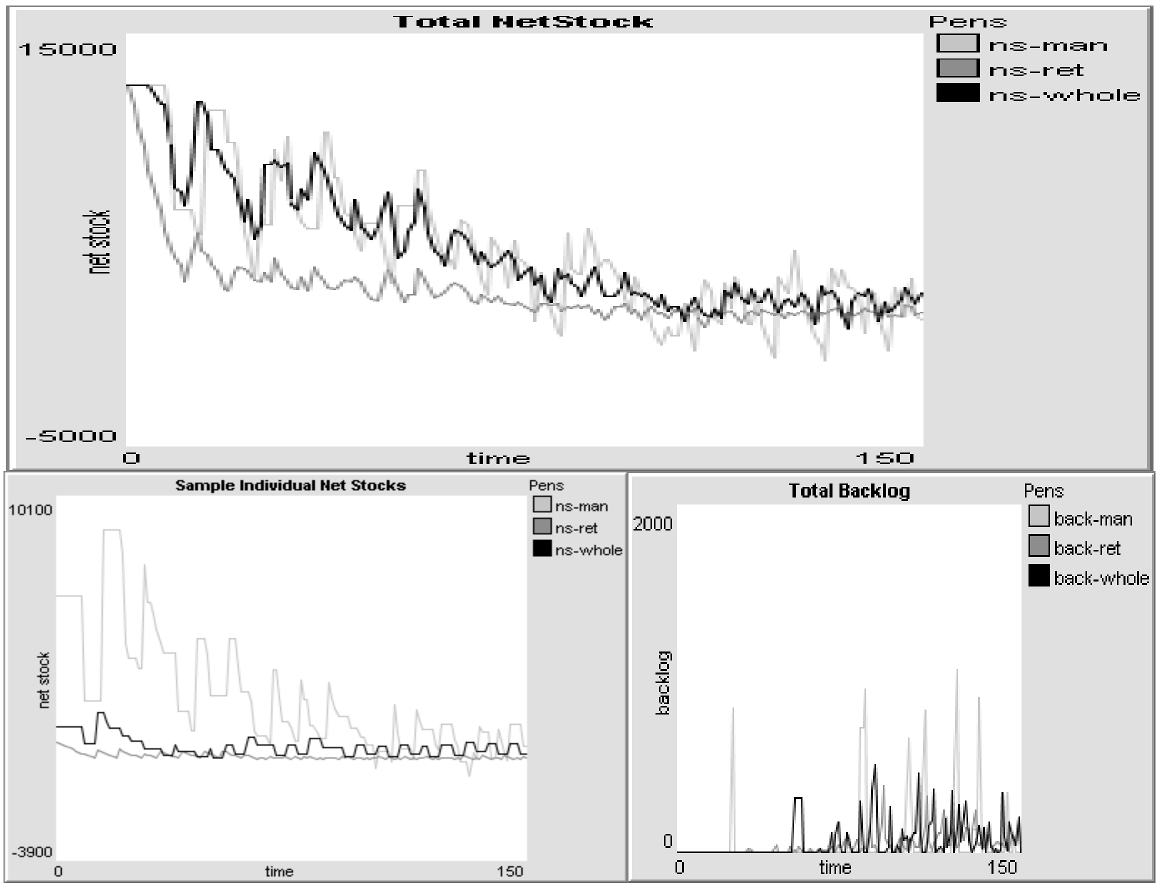

Figure 4.3.1 Supply Chain AB model –Parameter Setting 1
(Consideration of Loyalty in the Supplier Selection)

4.4 Effects of Shadow Orders

The firms may consider giving shadow –phantom- orders when the delivery times of the products exceed tolerable levels. When the supply is scarce –that is the reason of the high delivery times-, there is a competition among the firms to gather the supplied goods and each firm will show its demand more than its original need. This is an observed attitude of firms, especially in sectors where the customers can cancel their orders in any time of production or even during the delivery process. [12] Since there is significant delay in the system and the suppliers can not perceive the actual demand levels; shadow ordering phenomenon intensifies the fluctuations and the bullwhip effect in the supply chain. Shadow ordering is formulated in both SD and AB models. Shadow orders are defined as actions of only customers and retailers; wholesalers do not give shadow orders.

In AB model, an agent looks at its maximum delay time for the orders it has given, and if this is over a threshold value; it considers giving orders to two different suppliers. This is added to the SD model at an aggregate level. The phantom order giving decision is given by looking at the expected average delay time. Figure 4.4.1 shows the AB model output with shadow orders effect. Compared to Figure 4.1, it can be seen that the average inventory levels of retailers, wholesalers and manufacturers are higher resulting from the effects of shadow orders. Figure 4.4.2 shows the SD model output with shadow orders effect. General conclusions are similar to those of AB model.

It is shown that the SD model can capture the dynamics generated by phantom orders at an aggregate level. However, again, when the behavior characteristics are compared, some differences are observed. In SD model, the inventory levels fluctuate almost in a periodic pattern, especially at lower levels of the chain; but this periodic pattern is more blurred in the AB model. The amplitudes and periods of oscillations are different for ABM and SD models. SD model captures the system behavior at an aggregate level, however it can not capture the dynamics generated by the autonomy of the agents since SD can not handle each agent separately. The increase in rationality, and therefore in the heterogeneity among the individual agents is the main cause of this attribute. The increased heterogeneity among individuals can be seen from Figure 4.4.3.

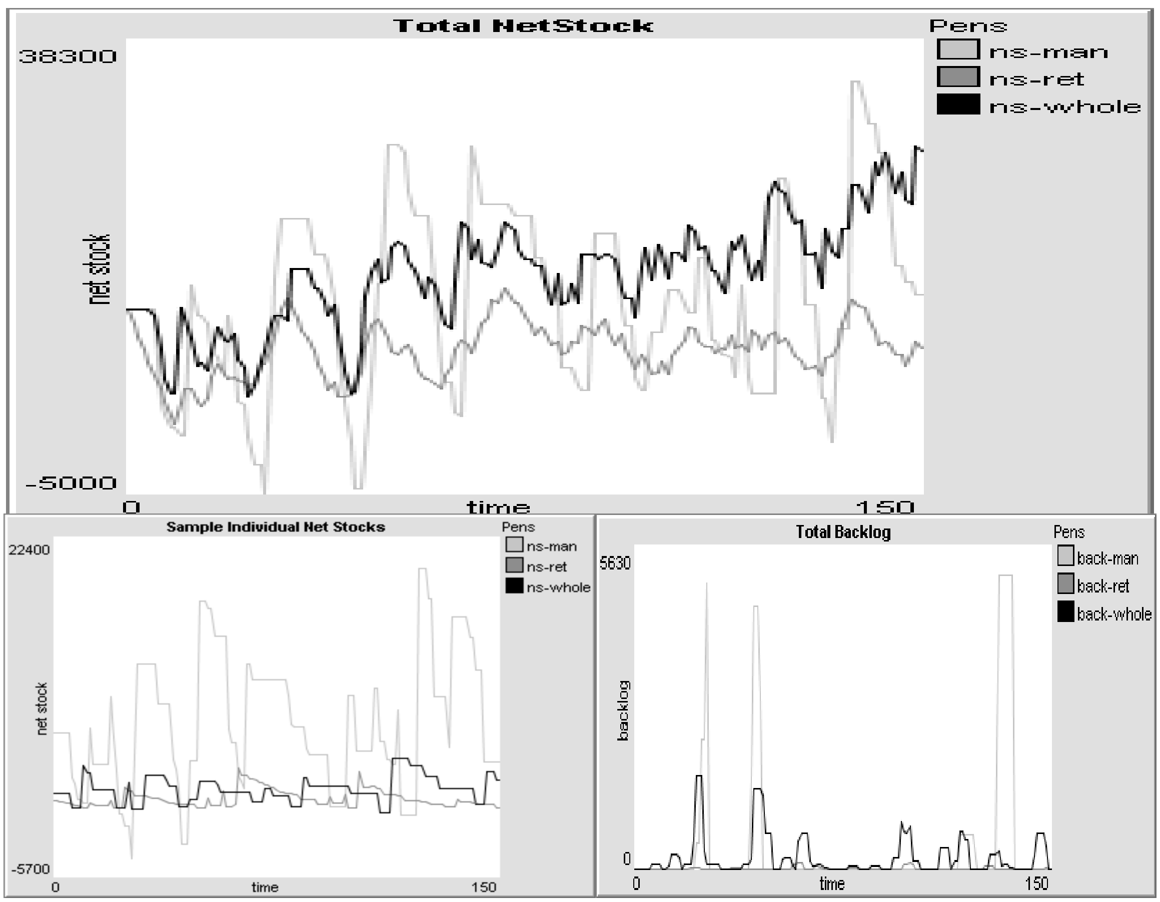

Figure 4.4.1 Supply Chain AB model –Parameter Setting 1
(Order Amount Affected by Price & Shadow Orders)

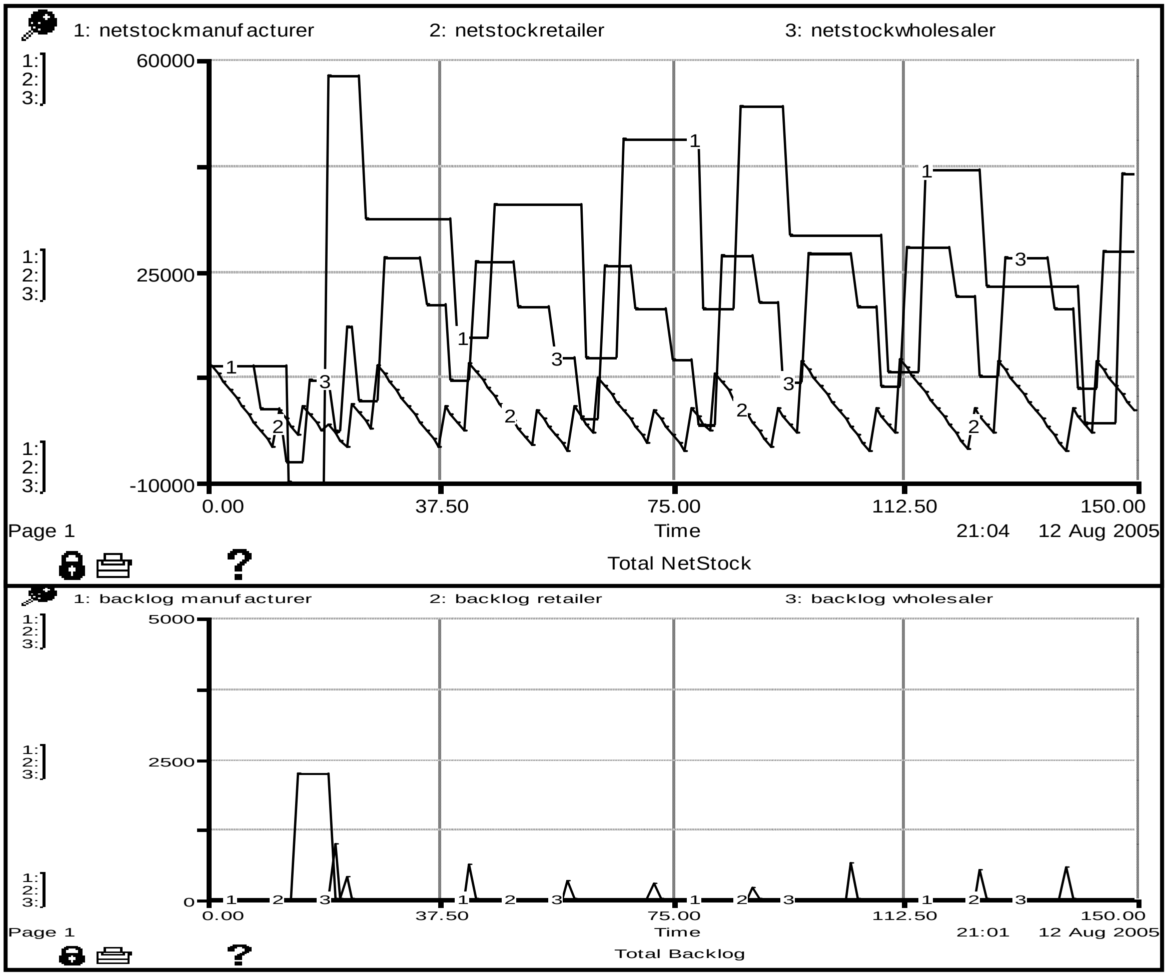

Figure 4.4.2 Supply Chain SD Model –Parameter Setting 1
(Order Amount Affected by Price & Shadow Orders)

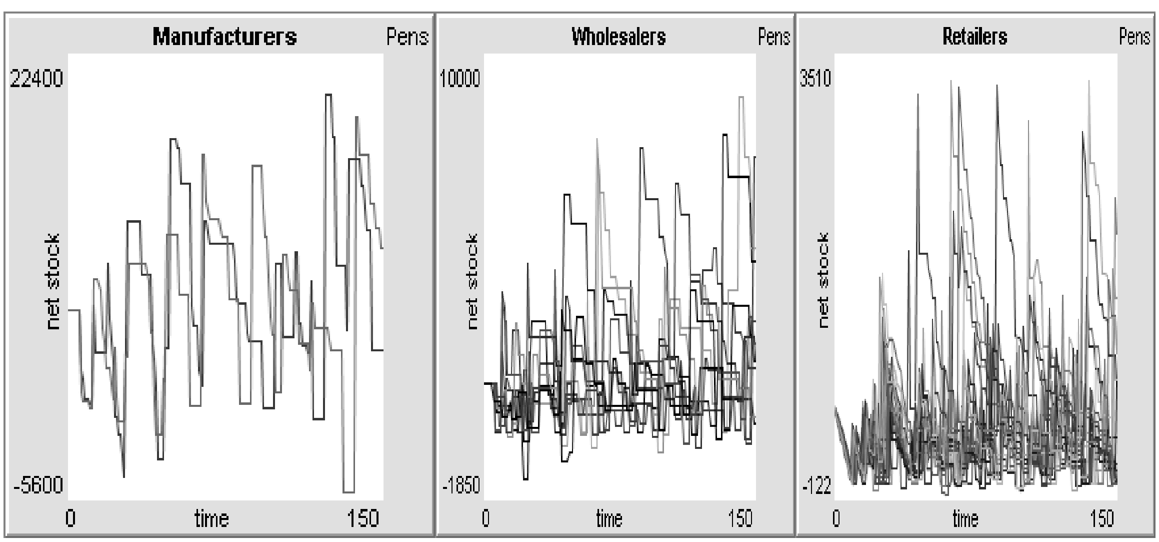

Figure 4.4.3 Supply Chain AB model Individual Inventories at each level –Parameter Setting1
(Order Amount Affected by Price & Shadow Orders)

4.5 Effects of Safety Stocks

An important factor in supply chain dynamics is the specification of safety stocks. To overcome backlogs, safety stocks should be considered; however safety stocks cause an increase in inventory holding costs. Thus there is a trade-off between inventory holding cost and backlog cost.

When the outputs generated in sections 4.1-4.4 are analyzed; it is seen that backlogs occur in the system, especially at the beginning of the simulations. To overcome backlogs, it is decided to assign higher SS values to the agents at higher levels of the supply chain.[3] The Figures 4.5.1-4.5.9 show the related outputs of the models. When the Figures 4.5.1-4.5.9 are compared with the corresponding graphs in sections 4.1-4.4; it is seen that the backlogs are mostly obviated and the fluctuations are not intensified by the effect of higher safety stock levels. So it is an important point for agents –firms- to select appropriate safety stock values that will obviate the backlogs and will keep the inventory holding costs at a profitable level. In further research, heuristics to find safety stock values that minimize the totality of inventory holding costs and backorder costs may be investigated.

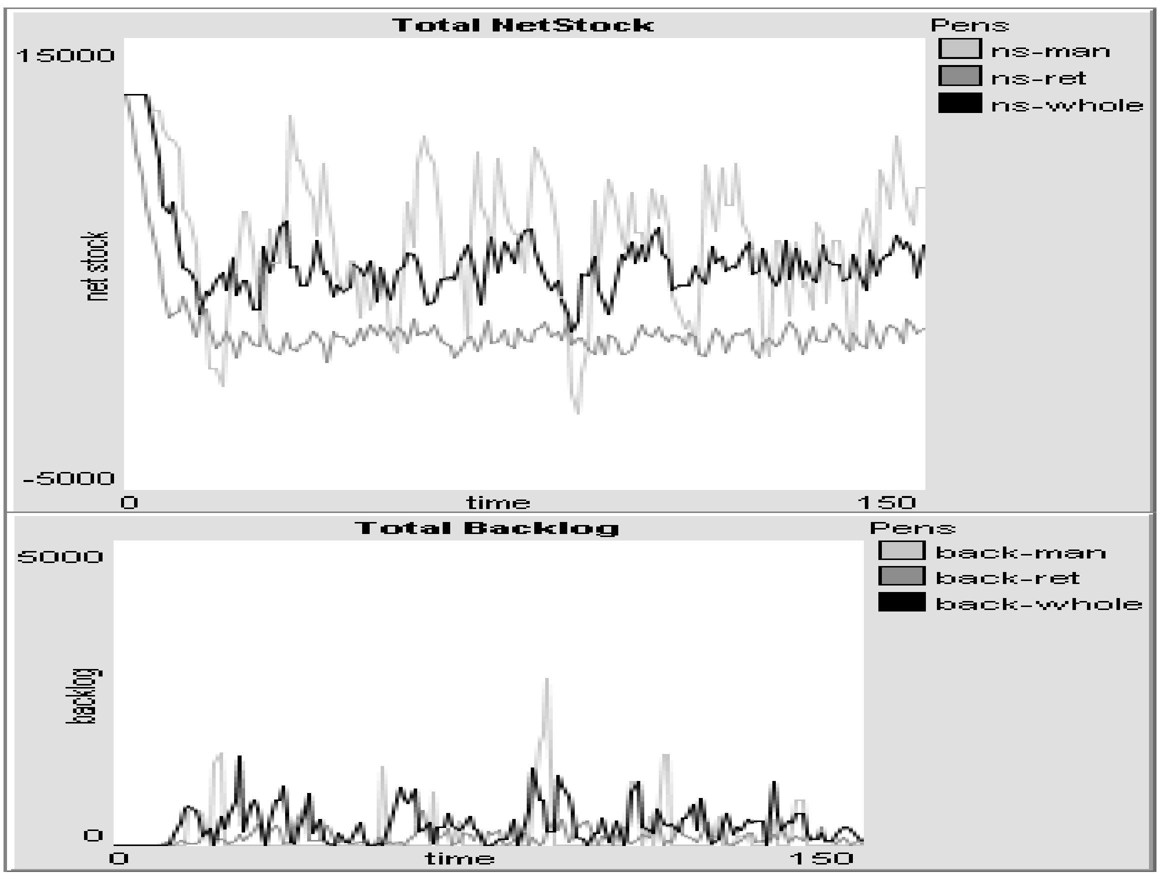

Figure 4.5.1 Supply Chain AB model –Parameter Setting 2
(Random Supplier Selection)

[3] Parameter Setting 2 is used for this purpose. Parameter Setting2 is the same as Parameter Setting1, except the SS values. In Parameter Setting2; SS(retailers) = 50, SS(wholesalers) = 100, and SS(manufacturers) = 1000.

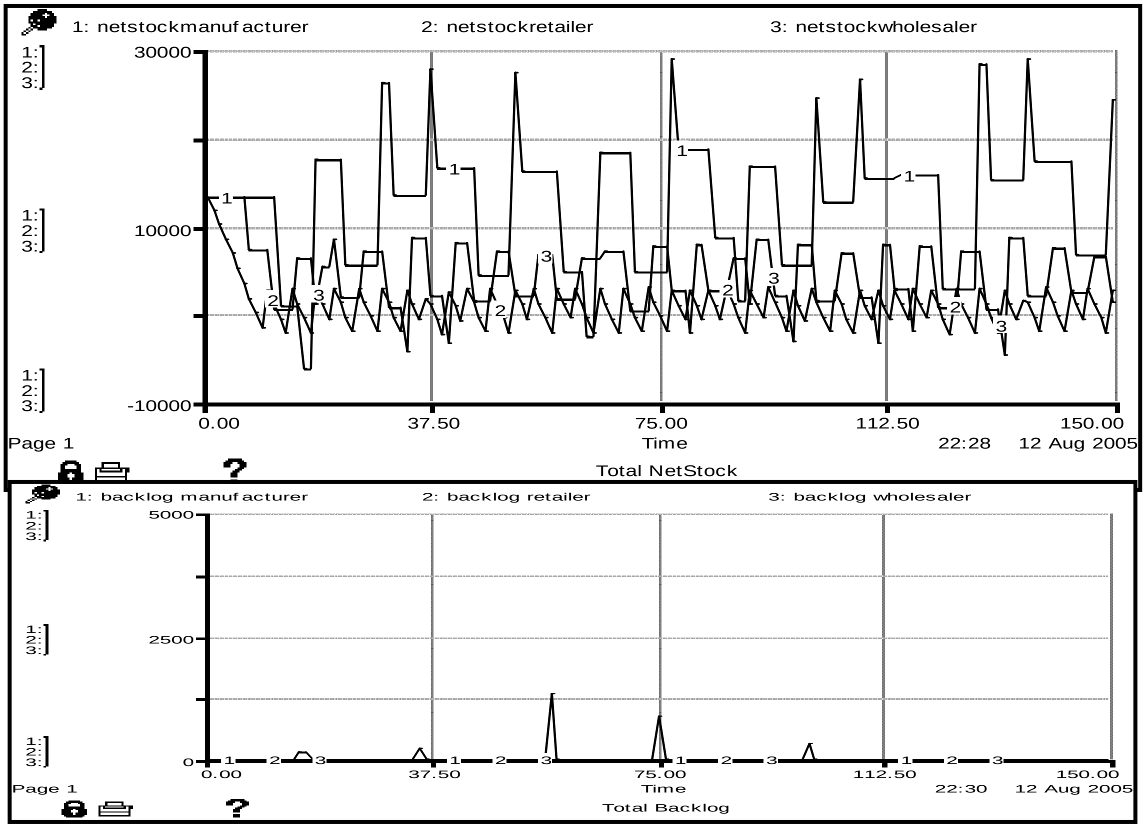

Figure 4.5.2 Supply Chain SD Model –Parameter Setting 2 *(Random Supplier Selection)*

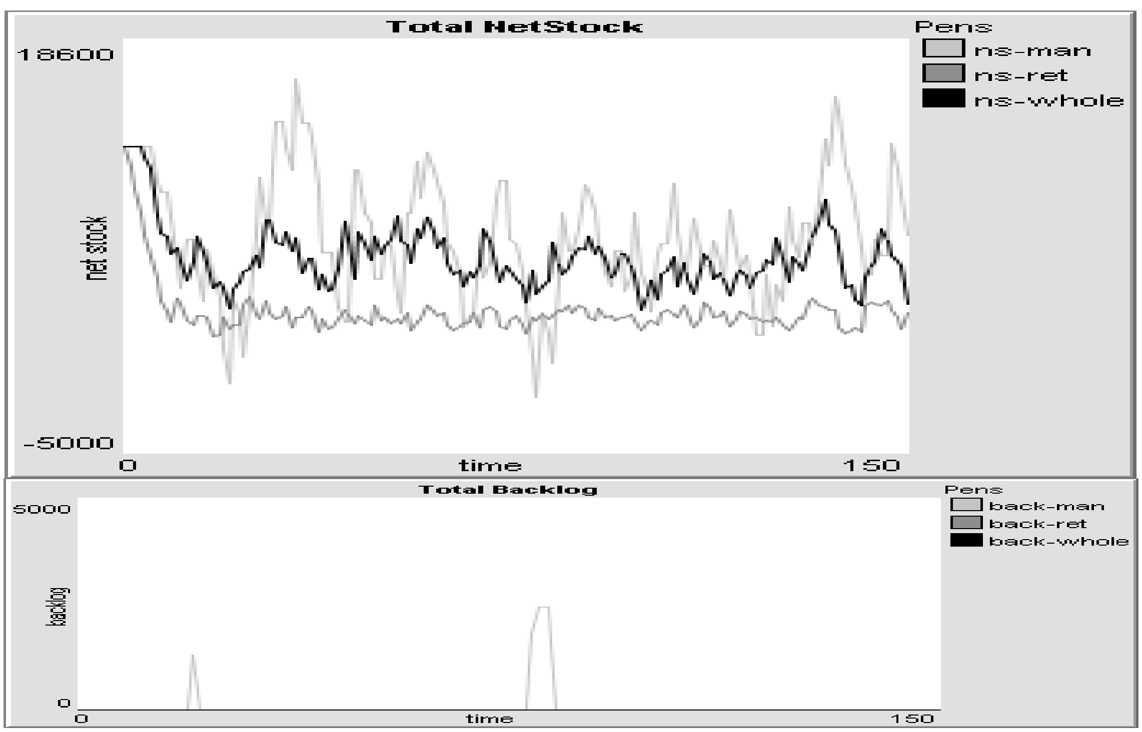

Figure 4.5.3 Supply Chain AB model –Parameter Setting 2
(Consideration of Supplier Inventory Positions in Supplier Selection)

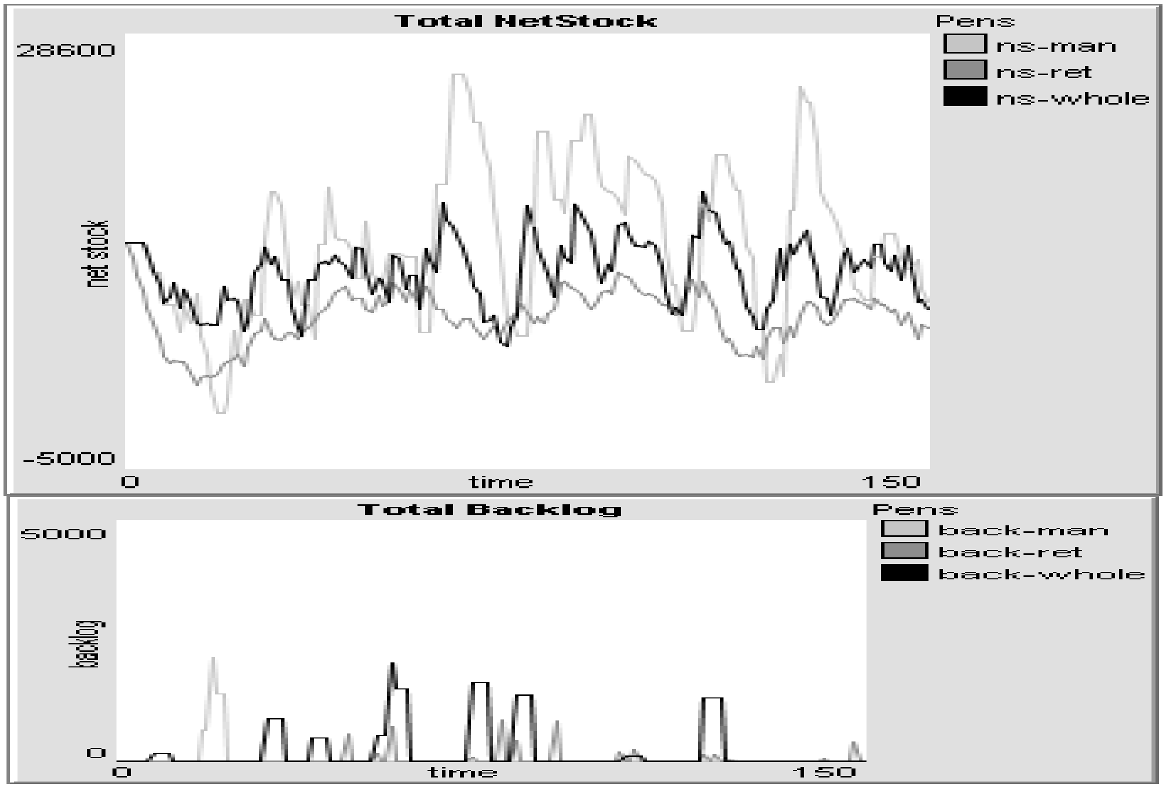

Figure 4.5.4 Supply Chain AB model –Parameter Setting 2
(Consideration of Price in Supplier Selection)

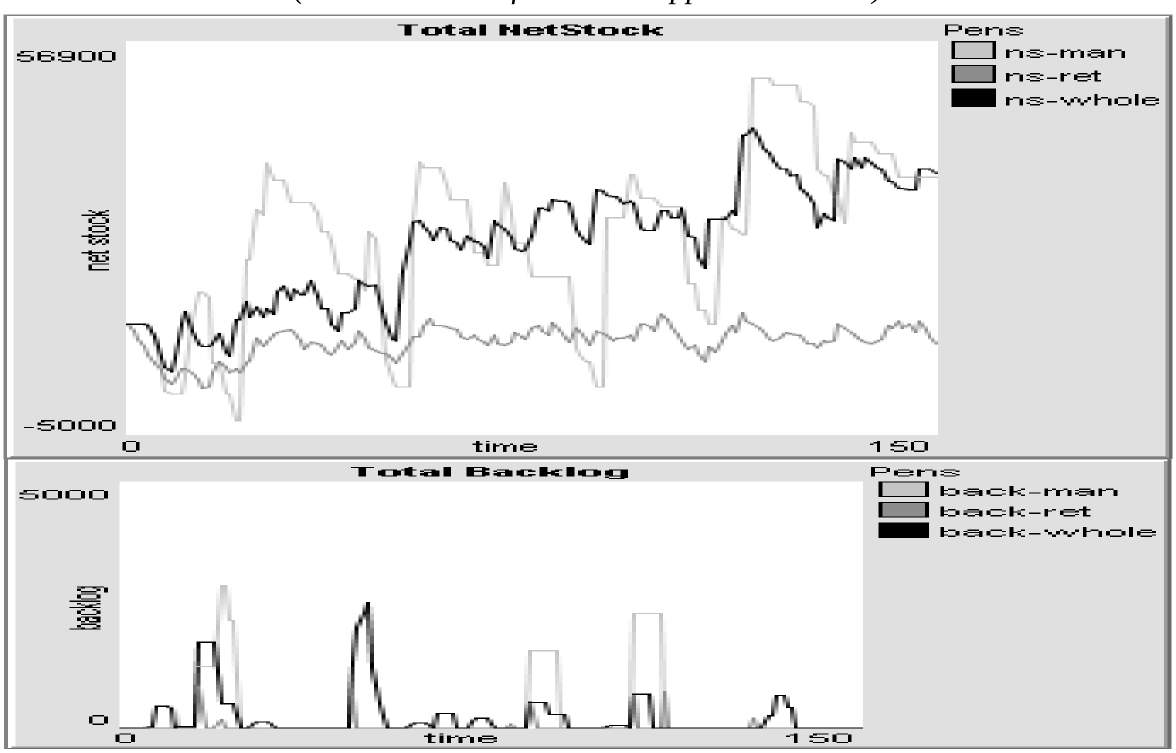

Figure 4.5.5 Supply Chain AB model –Parameter Setting 2
(Order Amount Affected by Price)

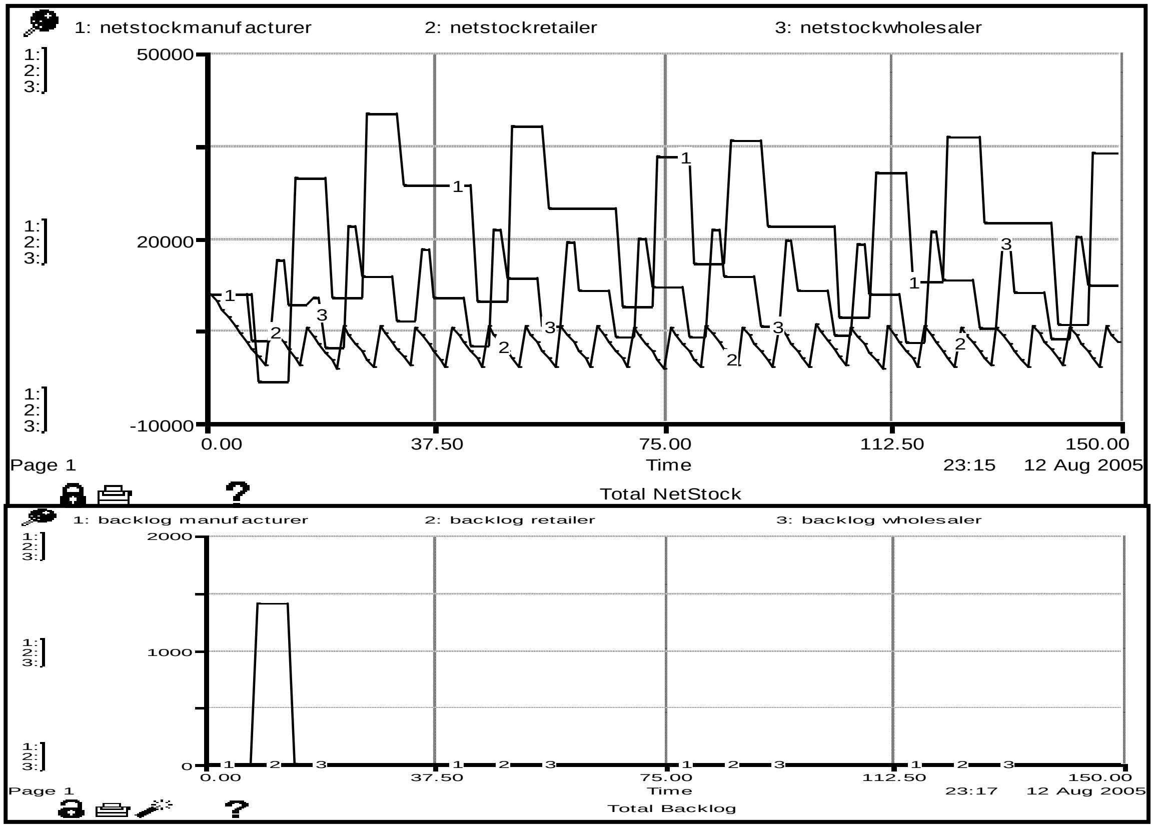

Figure 4.5.6 Supply Chain SD Model –Parameter Setting 2
(Order Amount Affected by Price)

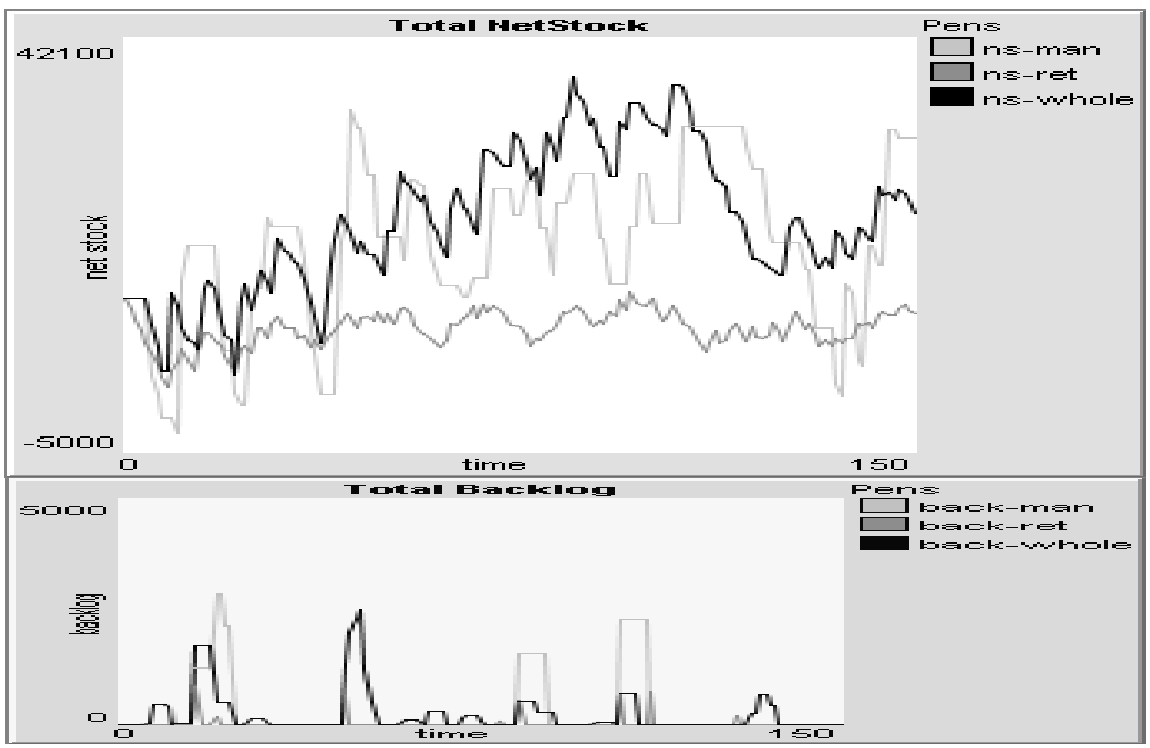

Figure 4.5.7 Supply Chain AB model –Parameter Setting 2
(Order Amount Affected by Price & Shadow Orders)

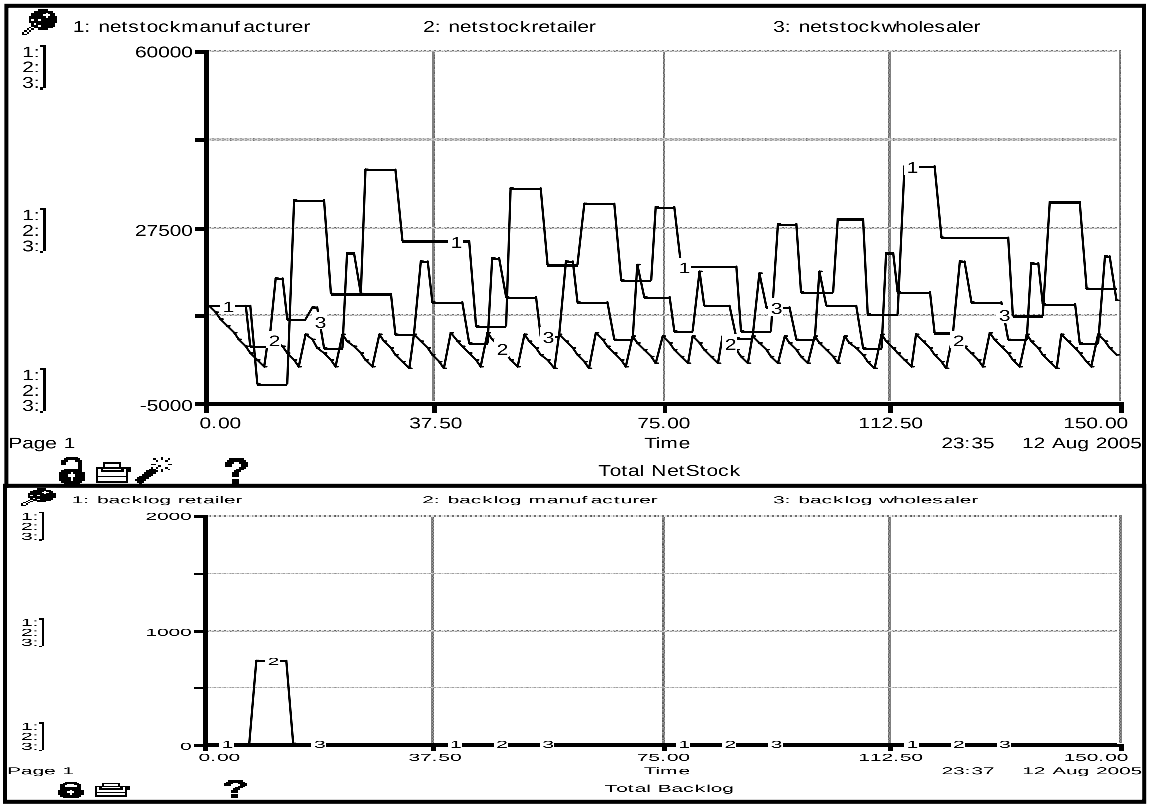

Figure 4.5.8 Supply Chain SD Model –Parameter Setting 2
(Order Amount Affected by Price & Shadow Orders)

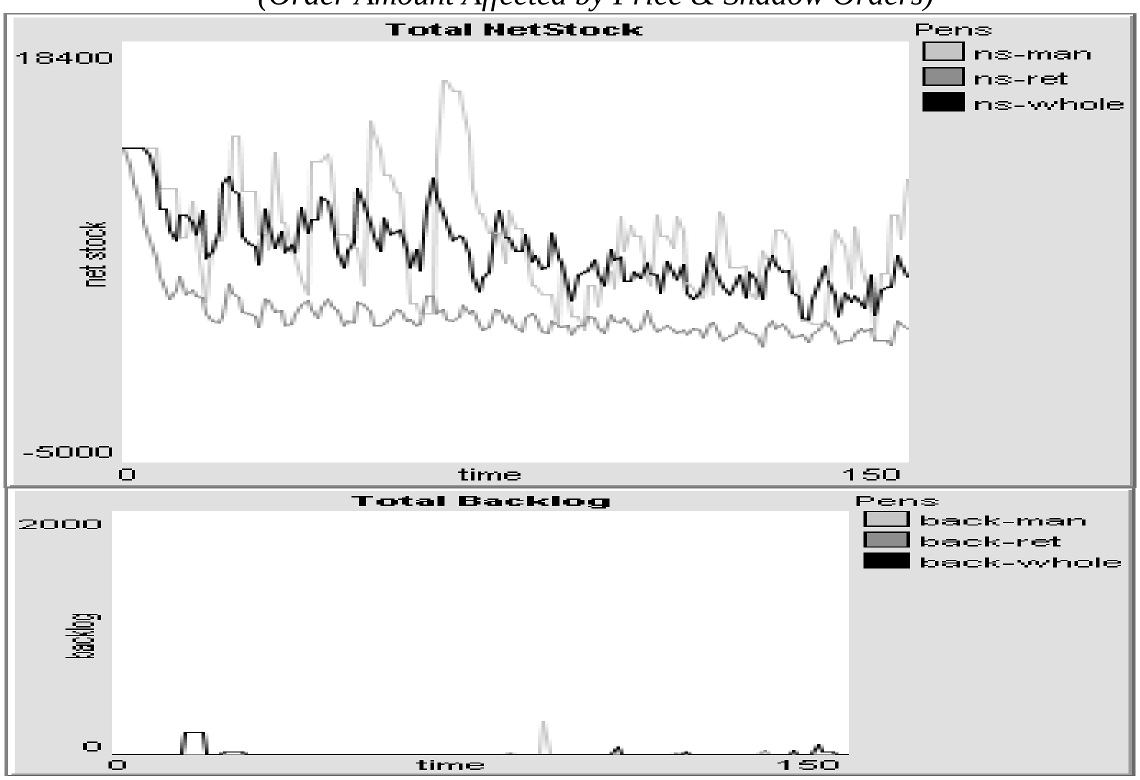

Figure 4.5.9 Supply Chain AB model –Parameter Setting 2
(Loyalty)

4.6 "Fixed Order Up" Policy vs. "Reorder Point Order Up" Policy

Another factor that affects the oscillations in the supply chain is the ordering policies. The question investigated in this research is "Does 'fixed order up policy' reduce the fluctuations in the system?"[4] Figures 4.6.1-4.6.9 show the related outputs of the models. It is apparent from Figures 4.6.1-4.6.6 that the fixed order up policy almost fully removes the oscillations in the system. Even if the price mechanism is active, the oscillations are not exaggerated. Shadow orders can't become dominant because there is no extra delay in the system depending on the backlogs. Since this ordering policy requires giving orders at each period –more often than Reorder Point Order Up policy-, the situation implies ordering cost-inventory cost trade off. It may not be profitable to give orders each period considering this trade-off. In further research, a system with real cost values may be considered and an analysis based on this tradeoff may be utilized.

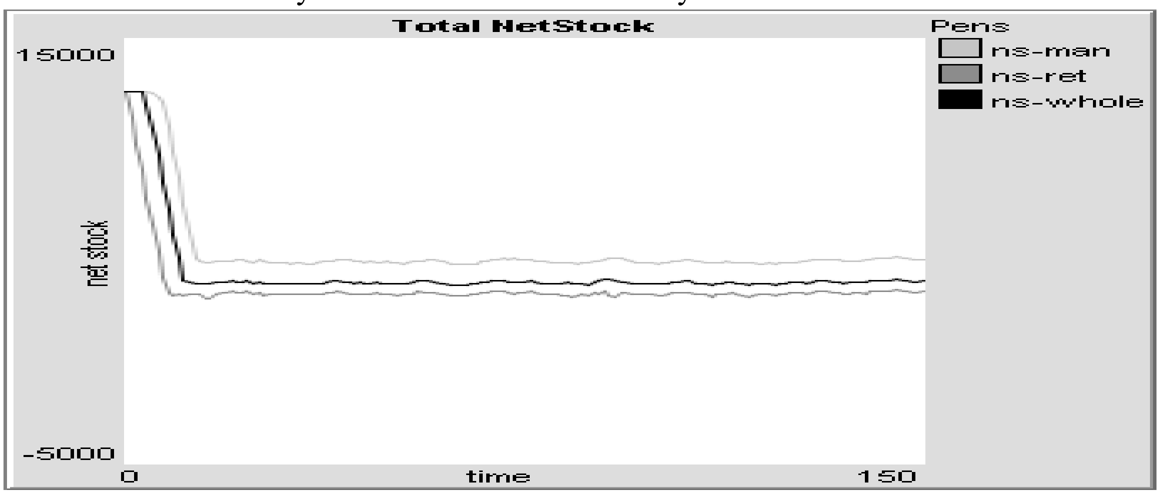

Figure 4.6.1 Supply Chain AB model –Parameter Setting 3
(Random Supplier Selection)

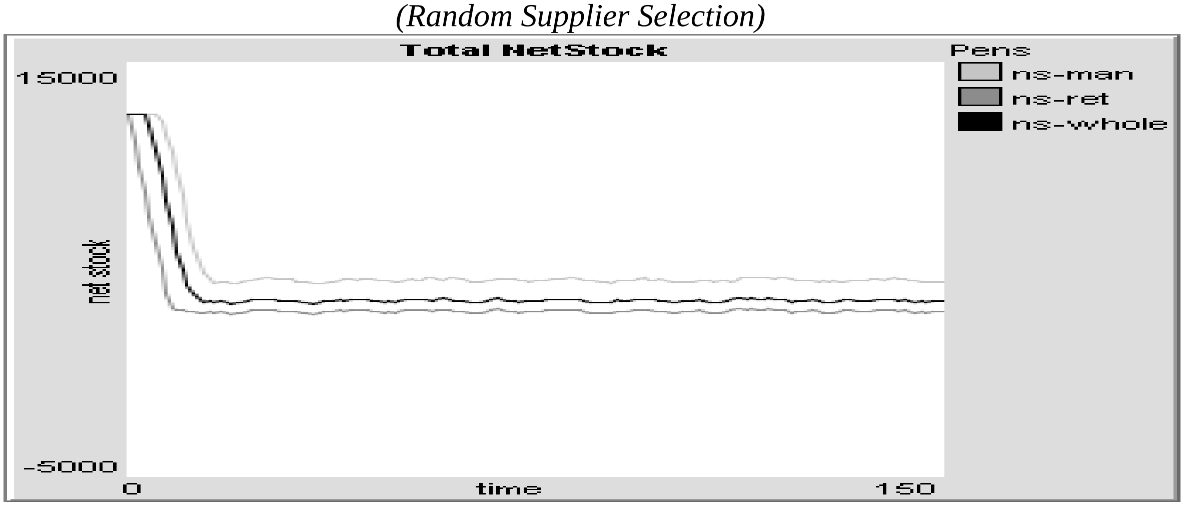

Figure 4.6.2 Supply Chain AB model –Parameter Setting 3
(Consideration of Inventory Positions in Supplier Selection)

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[4] Parameter Setting 3 is used for this purpose. Parameter Setting3 is the same as Parameter Setting2, except "Order Up Level" values. In Parameter Setting3; Order Up Level (retailers) = 400, Order Up Level (wholesalers) = 850, and Order Up Level (manufacturers) = 6000.

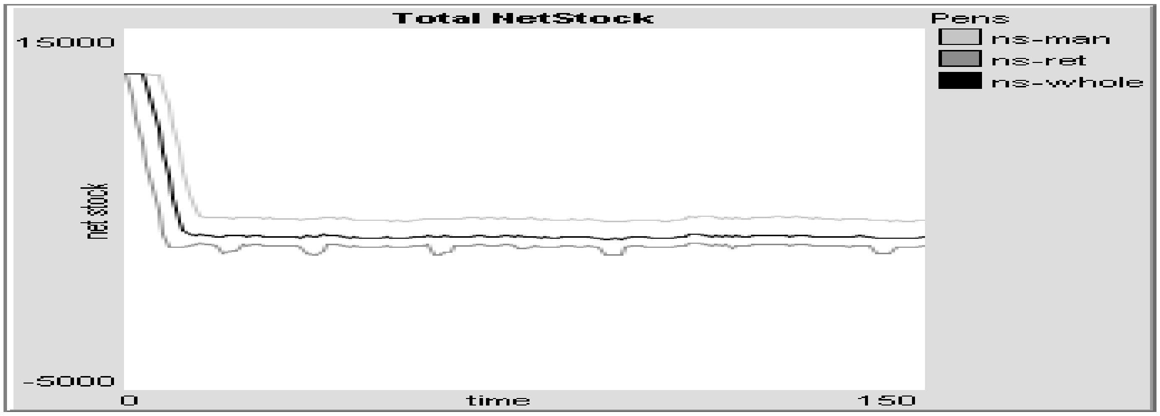

Figure 4.6.3 Supply Chain AB model –Parameter Setting 3 *(Consideration of Price in Supplier Selection*)

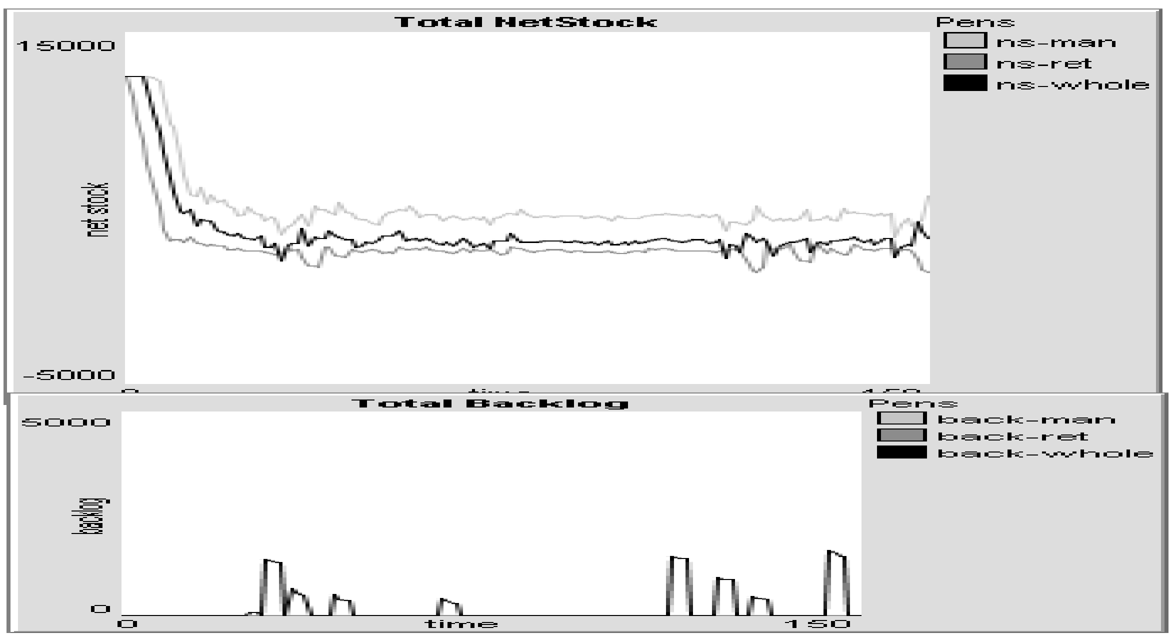

Figure 4.6.4 Supply Chain AB model –Parameter Setting 3
(Order Amount Affected by Price)

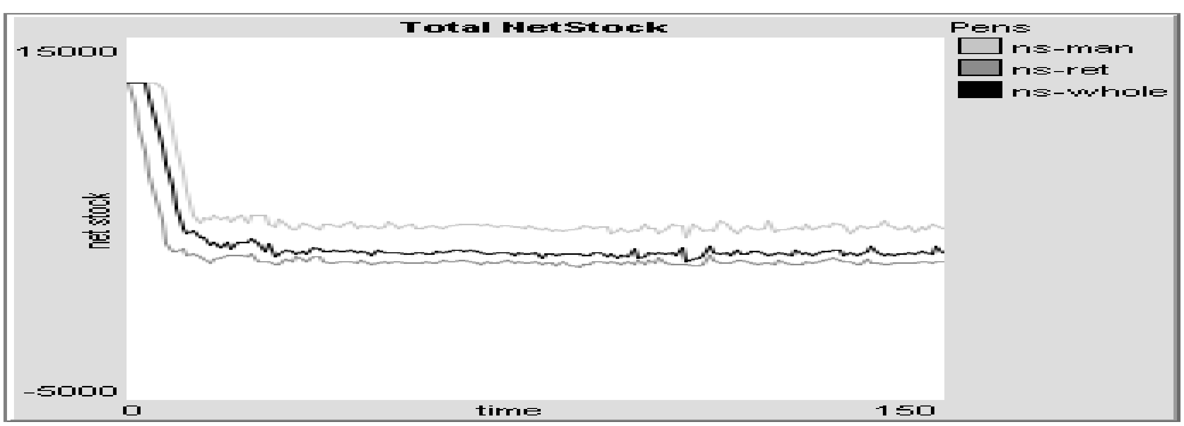

Figure 4.6.5 Supply Chain AB model –Parameter Setting 3
(*Order Amount Affected by Price & Shadow Orders*)

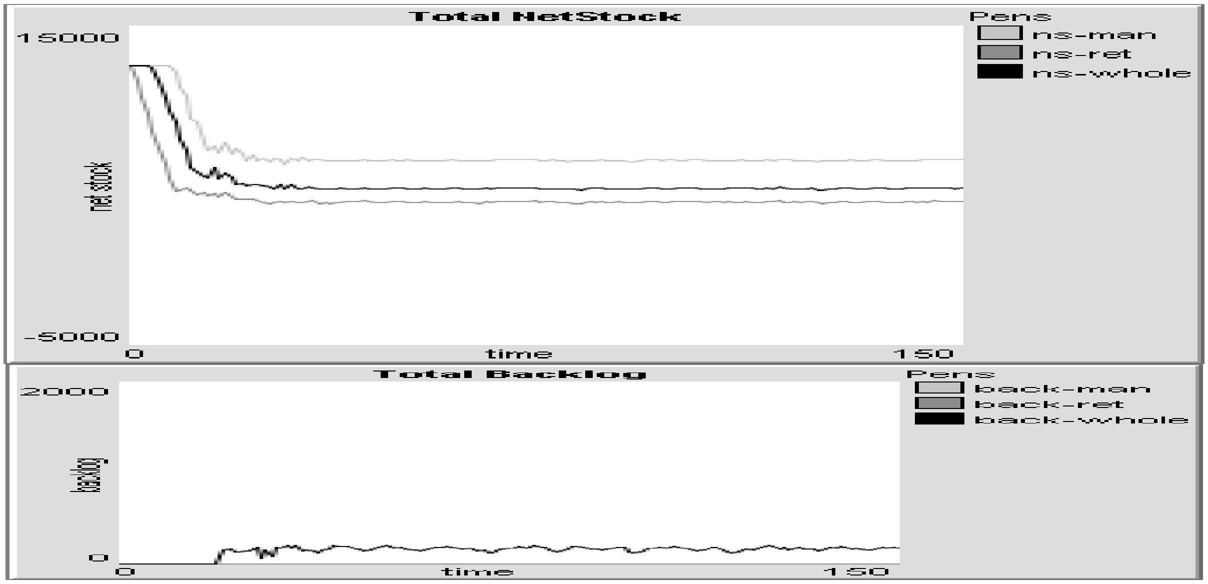

Figure 4.6.6 Supply Chain AB model –Parameter Setting 3(*Loyalty)*

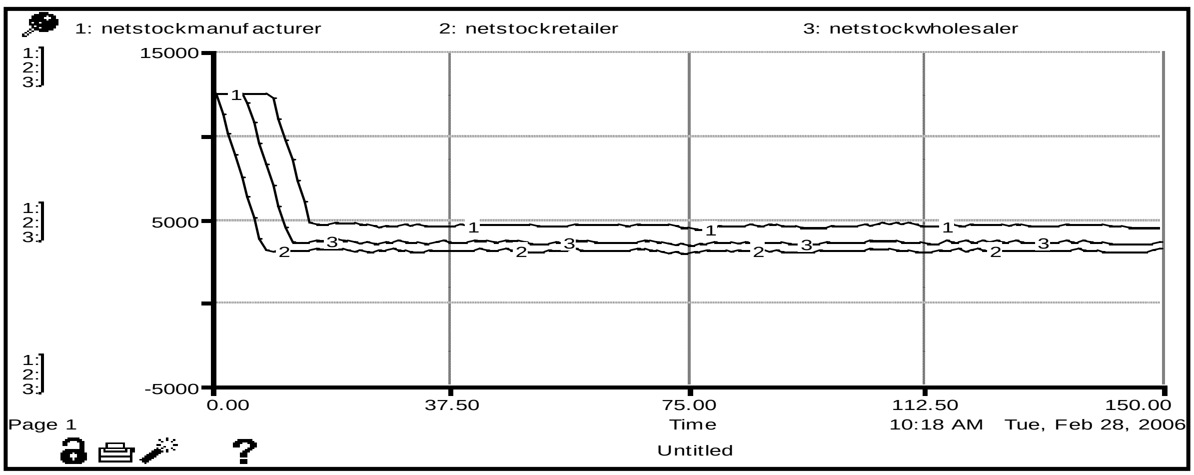

Figure 4.6.7 Supply Chain SD Model –Parameter Setting 3*(Random Supplier Selection)*

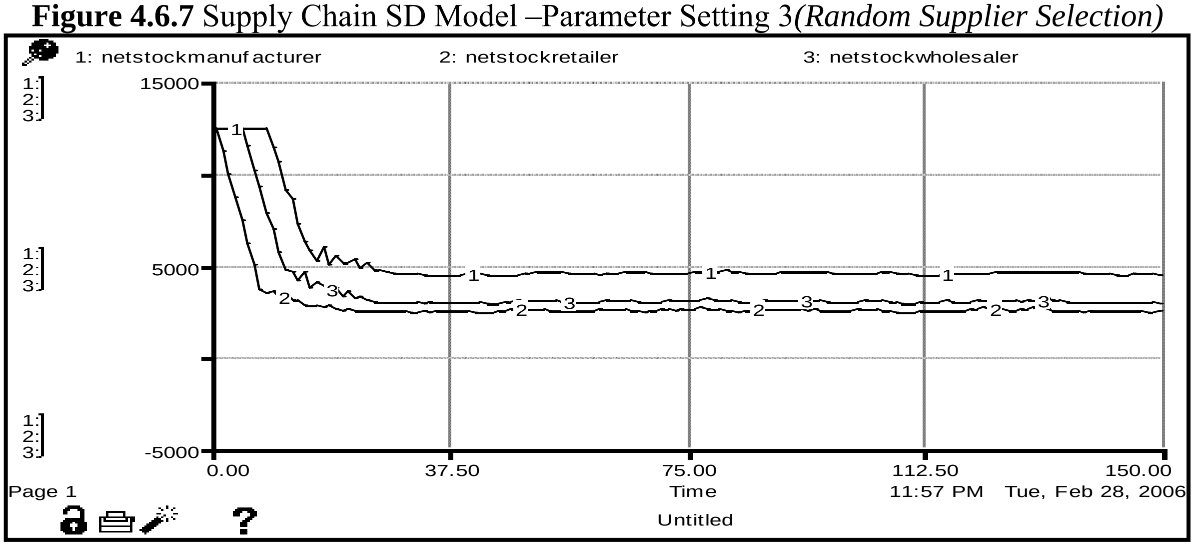

Figure 4.6.8 Supply Chain SD Model –Parameter Setting 3

(Order Amount Affected by Price)

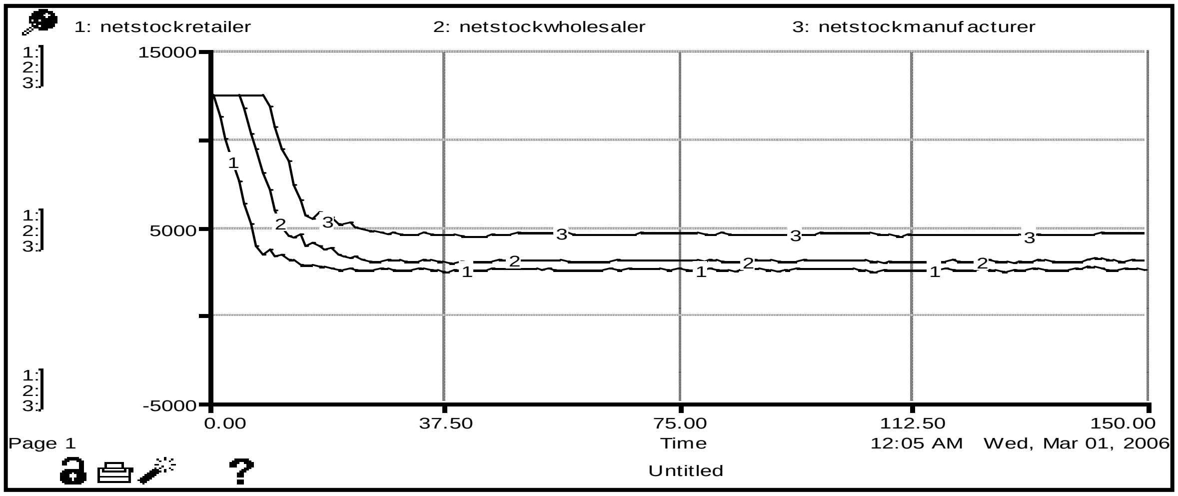

Figure 4.6.9 Supply Chain SD Model –Parameter Setting 3
(*Order Amount Affected by Price & Shadow Orders*)

Table 4.1 shows the general conclusions inferred from the analysis of the supply chain model.

(Table 4.1) Summary of Experiments with the Supply Chain Model

FACTOR	SD&ABM COMPARISON	SUPPLY CHAIN DYNAMICS
Consideration of Supplier Inventory Positions in Supplier Selection	It can not be defined in SD model, thus SD can not capture the dynamics.	Agents act in a 'rational' way individually; but overall system behavior leads to increased oscillations in inventory.
Consideration of Price in Supplier Selection	It can not be defined in SD model, thus SD can not capture the dynamics.	Agents act in 'rational' way individually; but overall system behavior leads to increased oscillations in inventory.
Order Amount Affected by Price	SD captures at an aggregate level, but misses the heterogeneity among individuals. Near periodic patterns in SD, more blurred patterns in ABM.	Agents act in a 'rational' way individually; but overall system behavior leads to increased oscillations in inventory.
Effect of Shadow Orders	SD captures at an aggregate level, but misses the heterogeneity among individuals. Near periodic patterns in SD –especially at retailers and wholesalers levels, more blurred patterns in ABM.	Agents act in a 'rational' way individually; but overall system behavior leads to increased oscillations in inventory.
Consideration of Loyalty in Supplier Selection	It can not be defined in SD model, thus SD can not capture the dynamics.	Significantly decreases oscillations in inventory levels.
Effect of Safety Stock	Consideration of different safety stock values does not cause a systematic difference between SD and ABM behaviors.	Choosing appropriate SS values prevents backlogs.
Fixed Order Up Policy vs. Reorder Point Up Policy	SD and AB models generate similar behaviors.	Fixed Order Up policy decreases oscillations, but increases ordering cost.

5. Conclusions & Further Research

In this research, the aim is to investigate the capabilities of macro and micro level modeling approaches on multi-agent systems. The analysis is based on a supply chain model. Effects of several factors including consideration of supplier inventory positions, supplier prices, shadow orders, loyalty in supplier selection and order amount determination, and also effects of ordering policies and safety stocks are analyzed. General implications regarding the comparison of aggregated (SD) and disaggregated (AB) modeling approaches are made; and also supply chain dynamics are analyzed using the models.

Based on the analysis of the supply chain models, it is shown that there are factors that can not be defined by macro modeling approach at an aggregate level. These include the cases where there is a change only in the qualitative interaction logic of the agents -in the sense that one agent selects another to interact with, based on some decision criterion; however the quantitative decision is not affected from this criterion. Such an example is the consideration of the price in the selection of the supplier- the supplier is selected by looking at the price level, but the order amount requested from the supplier is not affected from this decision. System Dynamics can not capture this detail dynamics, because there is no distinction among individual agents in the SD model. Therefore, there may be factors which significantly affect the supply chain behavior, but can not be captured by the SD model even at an aggregate level. These are cases where the rationality and autonomy of the agents, and the heteregoneity and interaction patterns among the individuals significantly affect the emergent system behavior. Due to the fact that macro modeling approach does not differentiate among individuals, aggregated modeling can not capture the dynamics generated by these factors, which can be well-represented in the micro modeling environment.

For the factors that can be defined on the SD model, macro modeling approach may capture the generated dynamics at an aggregate level; however it may miss the heterogeneity among the individual agents emerging from the increase in rationality of agents. Such an example is the shadow orders case. Shadow ordering phenomenon can be included into the SD model at an aggregate level, by feedback loop structure. However when the behaviors generated by aggregated and disaggregated models are analyzed, it is seen that although System Dynamics can capture the general dynamics –the increase in amplitudes and periods of oscillations-, it can not capture the dynamics resulting from the heterogeneity among the agents. While near periodic patterns are observed in SD output –especially at retailers and wholesalers levels-, more blurred patterns are observed in ABM output. Thus differences occur between the emergent ABM behavior and aggregated SD behavior. These are cases where the rationality and autonomy of the agents, and the heteregoneity and interaction patterns among the individuals significantly affect the emergent system behavior. Due to the fact that macro modeling approach does not differentiate among individuals, macro modeling approach can capture the dynamics generated by these factors only at an aggregate level.

Regarding the supply chain dynamics, the fluctuations in the supply chain and the bullwhip effect are observed. The main sources of the fluctuations are explained to be the dynamic, nonlinear and feedback nature of the supply chain. It is shown that in such an environment, coupled with significant delays in the system, when agents try to act 'rationally' –in terms of price modifications, shadow orders, etc.- the emergent system behavior may become destructive for the whole. Loyalty in the supply chain is proposed as an alternative to overcome the destructive effects of oscillations in the supply chain. The ordering policies and safety stock levels are also observed to be important factors that affect the system behavior.

Effects of time-aggregation (discrete vs. continuous time macro models, effects of different ordering periods for different levels of the supply chain, etc.), analysis of customer selection dynamics (priority based queue disciplines, etc.), analysis of alternative loyalty and price formulations, construction of a network type supply chain, application of the model to a real life supply chain, and alternative aggregation formulations to capture micro modeling dynamics in macro model may be considered in further research.

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