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ALTERNATIVE MODELING APPROACHES TO MULTIPLE AGENT MODELING

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Alternative Modeling Approaches to Multiple Agent Modeling

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This research deals with alternative modeling approaches to multiple agent modeling. Models of a supply chain system are constructed to make a comparison about the capabilities of macro (System Dynamics) and micro (Agent-Based) modeling approaches based on a query to find answers to questions, such as "Can aggregated, macro-level modeling capture the dynamics of the micro-level agent based modeling? In what specific cases?" Effects of several factors including inventory positions, price, shadow orders, loyalty and ordering policies are analyzed from this perspective. It is concluded that there are factors, effects of which can be captured by the System Dynamics model at an aggregate level; but it is observed that System Dynamics may miss the heterogeneity among the individual agents related to their autonomy in decision making –effect of shadow ordering is an example of this case. On the other hand there are cases where System Dynamics can not capture the dynamics of the ABM model even at an aggregate level –effect consideration of the inventory positions in selection of supplier is an example of this case. Regarding the supply chain dynamics, it is concluded that more the agents think they are acting rationally more destructive the emergent system behavior becomes. Loyalty in the supply chain and consideration of reliable safety stocks are proposed to be cautions against the oscillations in the supply chain.

Keywords: System Dynamics, Agent-Based Modeling, simulation, multiagent systems, supply chain.

1. Introduction

Multi-agent systems are systems composed of multiple interacting agents; and "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. The two commonly used modeling approaches used to simulate multi-agent systems, where there are multiple agents engaging in different relationship patterns with other agents, are: System Dynamics Modeling (SD) and Agent-Based Modeling (ABM).

System Dynamics is a modeling perspective that emerged in 1960's based on the concept of feedback theory. The feedback theory is the expression of loop structure, or in other words circular causality [10]. System Dynamics is used to model complex, nonlinear systems where the simple "cause-and-effect reasoning" is not sufficient in explaining the system behavior. 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.

A relatively new emerging modeling methodology is Agent-Based modeling. Agent-Based models are based on the actions of individual agents and their interactions with other agents. The most important aspects of agent-based systems are the ability of agents to make important decisions themselves, and their capacity to interact with other agents according to their design objectives. The aim of Agent-Based modeling is to look at the global consequences of local actions; the system behavior emerges from the interactions of agents. Complexity arises from the interaction of individuals.

The main point that makes comparison of SD and ABM approaches meaningful is that both two are used in modeling complex, dynamic systems. But there are differences in their perceptions of the problem. The most basic difference in the perceptions of the two modeling approaches is their focus level on the problem. System Dynamics is based on an aggregation philosophy. SD makes an abstraction from single events and individuals; and forms a macro level modeling approach. SD is interested in defining the relationships among aggregated system variables. On the other hand, Agent-Based Modeling is a micro level modeling approach. Contrary to the implications of System Dynamics Modeling, 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 [8]. 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. So an important contribution to this literature is the construction of ABM 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 ABM and SD Supply Chain models constructed in the scope of this research are thought as such a contribution to the literature.

2. Overview of Models

The Supply Chain models constructed in this research project are based on a 3 level supply chain problem: there are customers demanding goods from the retailers, retailers demand from the wholesalers, and finally there are manufacturers producing the goods and sending them downstream. In this sense 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 give several managerial decisions which are analyzed in the course of this project. According to these managerial decisions goods are produced and sent downstream through the way to the final customers. Effects of several factors on behaviors of models are analyzed. These factors are related to the autonomy and rationality of the agents. These factors include consideration of inventory positions, price levels, shadow ordering and loyalty in the specification of the supplier of the goods among the enterprises in the higher level of the chain and the order amounts from the selected suppliers.

SD model is constructed using Stella software and ABM model by NetLogo software.

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.
- 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 finished goods 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 stated at the beginning of the simulation and constant throughout the whole process; there isn't any insufficiency related to scheduling, material availability, capacity problems or machine breakdowns.
- The prices are defined as functions of inventory positions.
- In the Agent-Based model, shadow order is defined as a function of maximum delay time at the upper supply chain level.
- In the System Dynamics model, shadow order is defined as a function of average delay time at the upper supply chain level.
- The loyalty is defined as a function of the price of the supplier and the length of the time interval the firms engage in the relationship.

2.2 Agent-Based Model Overview

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

2.2.1 Customers Procedures:

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

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

2.2.2 Retailers 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 administer the interaction with the customers. In this procedure, first backlogs are controlled and met if there is sufficient inventory. After the backlogs are met, the remaining inventory is then used to meet the incoming_demand of that period. The excess demand is added to the backlog list to be met in the next period.

In the "forecasting" procedure retailers adjust their 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 depend on several factors, such as price, and ordering policies. The ordered amount from the selected wholesaler is added to the incoming_demand of that wholesaler and the wholesaler makes decisions according to this information.

2.2.3 Wholesalers 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). These order lists are parallel in the sense that the index of the order in order_list is the same as the index of retailer in id_list. They are updated simultaneously. Backlog lists work in a similar fashion to store the data about unmet orders and the related retailers.

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 keeps the data about the time when the goods are loaded on the transporter, and the other keeps the id's of retailers that the goods will be transported to.

The goods are loaded onto transit_whole by "ship" procedure. Ship, firstly controls the backlogs; if there is any order that is in backlog position –namely if the backlog list is not empty- the required amount is loaded onto the transit_whole, and inventory is decreased an amount equal to the transported goods. And also, the related entries are deleted from backlog lists. This loop continues until the whole backlogs are supplied as long as the on-hand inventory is greater than zero. Then, if there is sufficient inventory left, the incoming_demand of that period is met. Shipments are made due to the FIFO principle. At the end of each period the elements of the backlog lists that are not shipped and the current period's unmet demands are combined; and they form the backlog list of the next period.

The remaining logic and procedures are similar to those of retailers.

2.2.4 Manufacturers 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-, 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 beginning times of the production. Production_placed contributes to WIP inventory. "Finish production" controls whether the production time has passed since the production was placed; and if this is the case the procedure increases the inventory of the manufacturer.

2.3 System Dynamics Model Overview

This is a three level supply chain model where there is no differentiation among agents. The structure is similar to that of ABM 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 same material and information flow structure of the Agent-Based model is preserved in the System Dynamics model.

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; expected demand is updated. Since ABM model is a discrete time model, the analysis is based on the discrete SD model where “DT = 1”.

Figure 2.3.1, Figure 2.3.2, and Figure 2.3.3 show the stock-flow diagrams of the supply chain SD model.

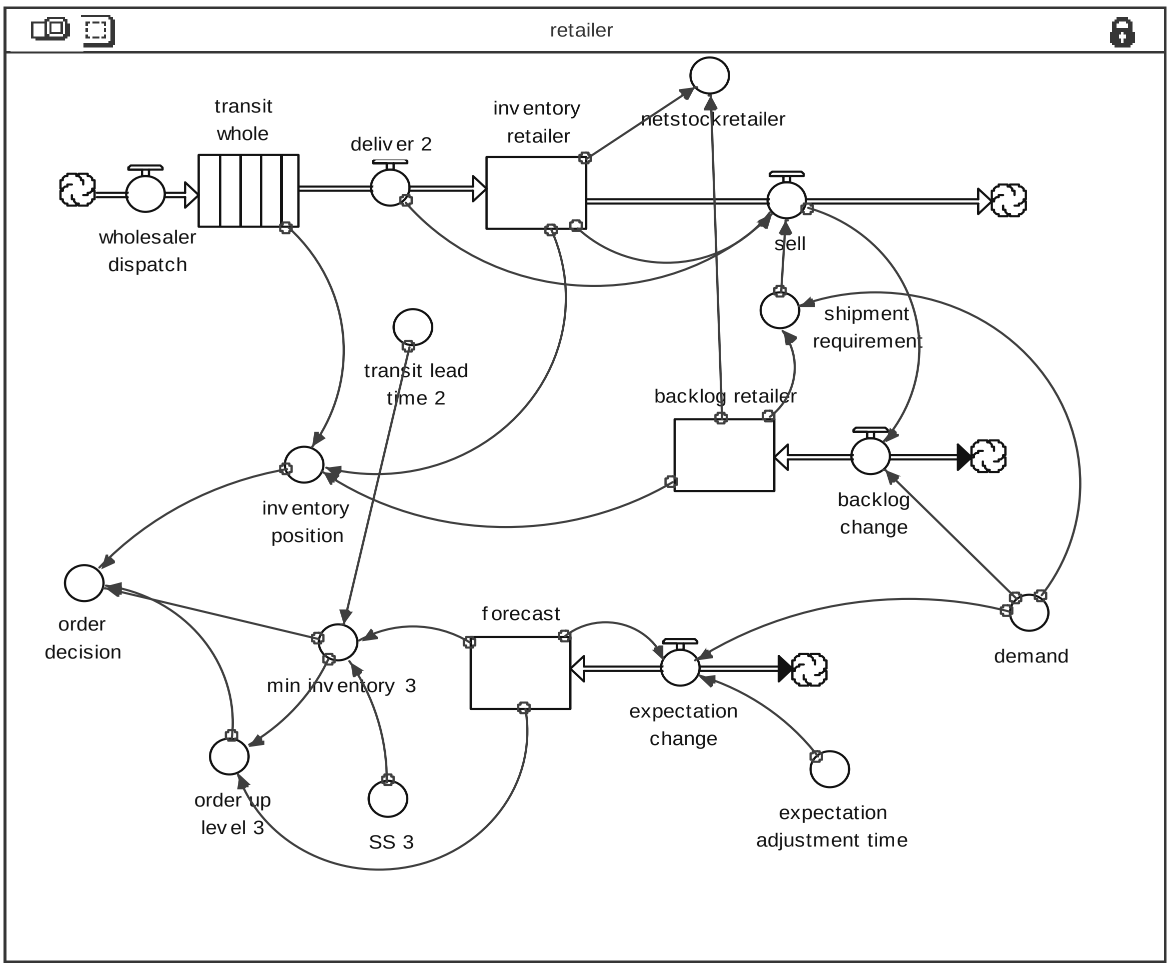

Figure 2.3.1 *Supply Chain SD Model -Retailer Level*

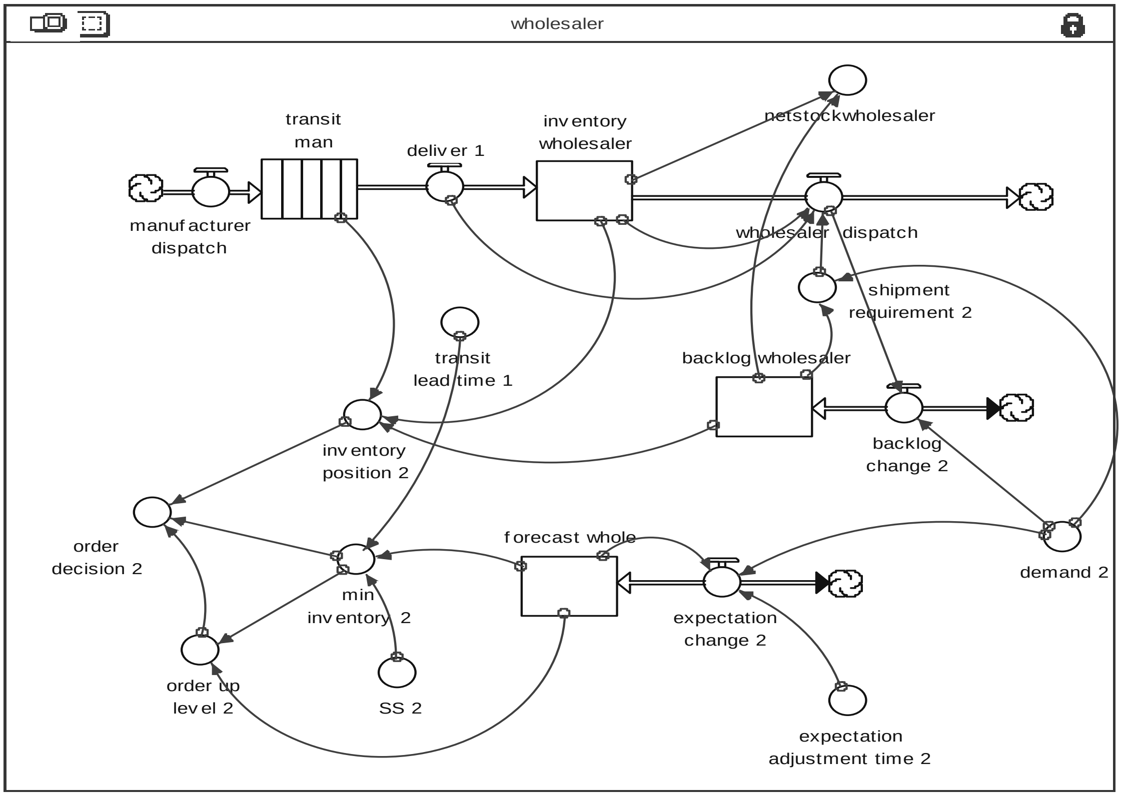

Figure 2.3.2 *Supply Chain SD Model -Wholesaler Level-*

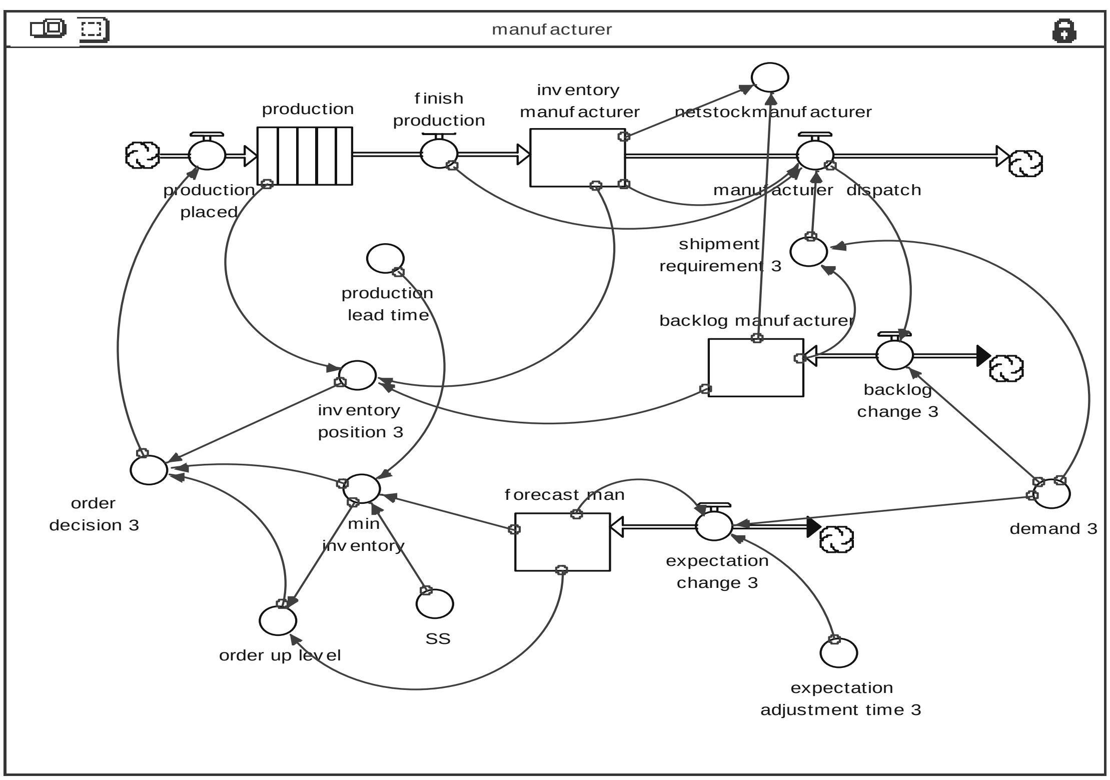

Figure 2.3.3 *Supply Chain SD Model -Manufacturer Level-*

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 amounts (that is on the supply chain) *less* backlogs to be met".

(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 difference between the forecast and the inventory position.

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

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

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 order up level. In calculating the order up level following equation is employed:

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

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

(4) In "inflated lead time order up" policy, the logic is the same as "fixed order up" policy but every time a different order up level is calculated via the equation below:

$$\text{orderup\_level} = \text{forecast} * (\text{lead\_time} + 1) + \text{SS}$$

3. Validation of the Models

In order to verify the agent based model, first of all 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 concluded that the formal ABM and SD models are consistent with the conceptual models.

The validation procedure was done in a process to understand whether the SD and ABM models were in a one-to-one corresponding fashion. In order to conclude that the difference, if there is any, in the behavior comes from the facts 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 if they have the same structure. These tests are run under different conditions and two examples are included below in Figures 3.1-3.4.

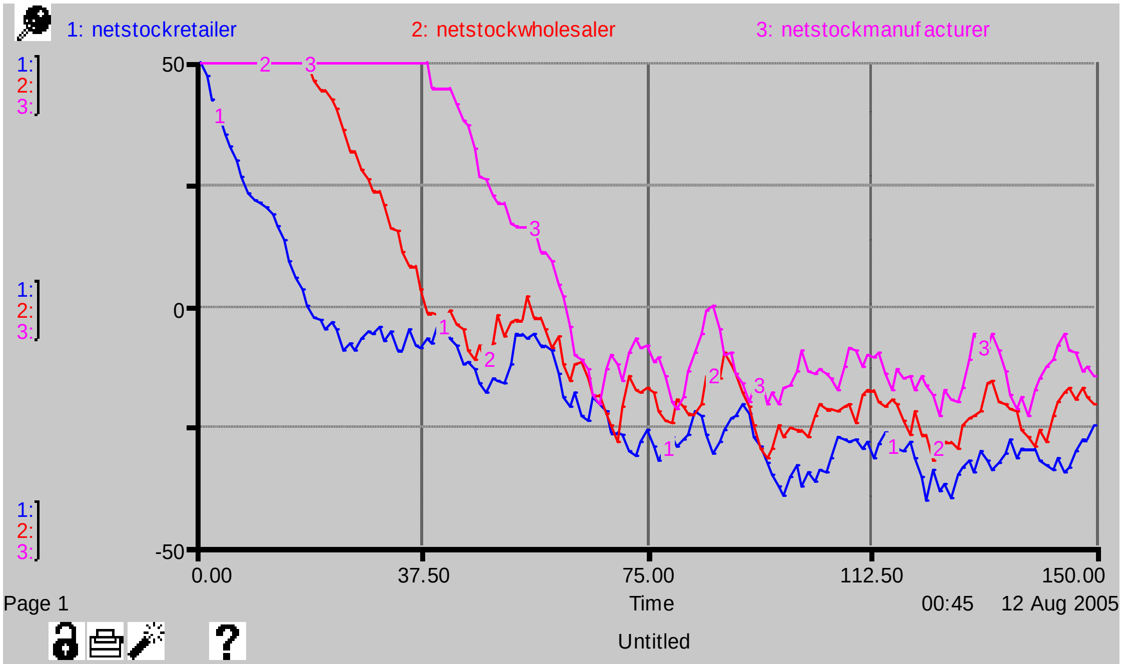

Figure 3.1 Supply Chain SD Model -Validation Output
Demand ~ Uniform (0, 5), "As Needed" |Ordering Policy (O.P.), Production Lead Time (PLT)=5, Transportation Lead Time (TLT)=3

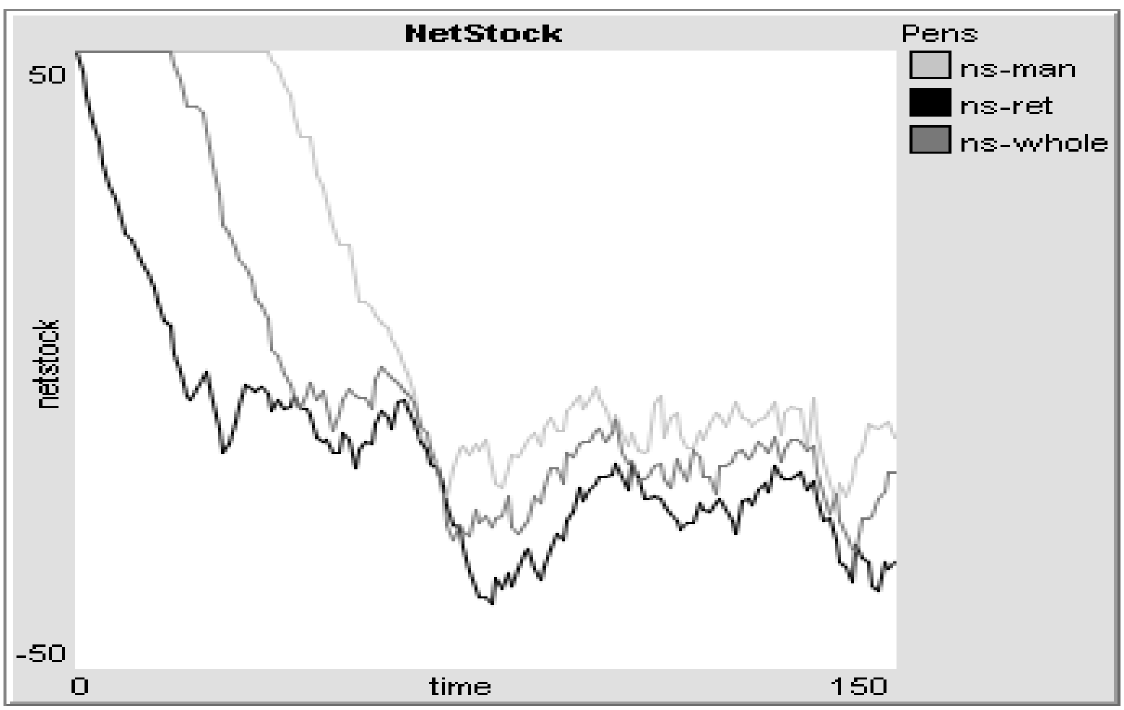

Figure 3.2 Supply Chain ABM Model -Validation Output
Demand ~ Uniform (0, 5), "As Needed" O.P, PLT=5, TLT=3

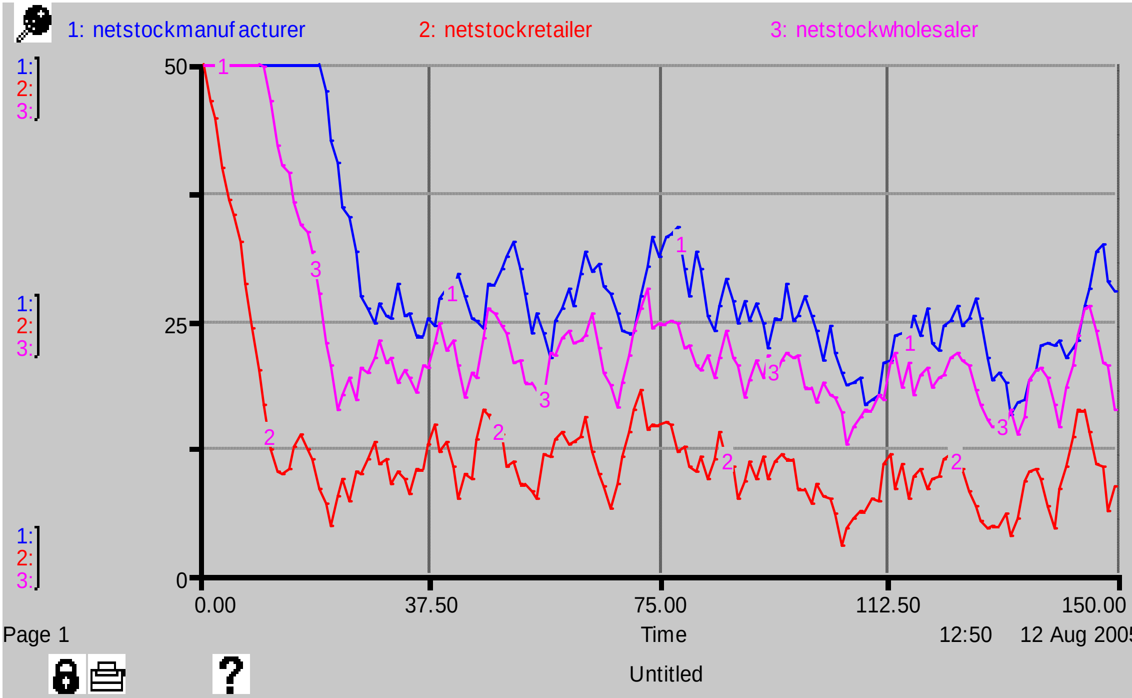

Figure 3.3 Supply Chain SD Model -Validation Output
Demand ~ Uniform (0, 5), "Fixed Order Up (FIP)" O.P,
"Manufacturer FIP"=40, "Wholesaler FIP"=30, "Retailer FIP"=20, PLT=5, TLT=3

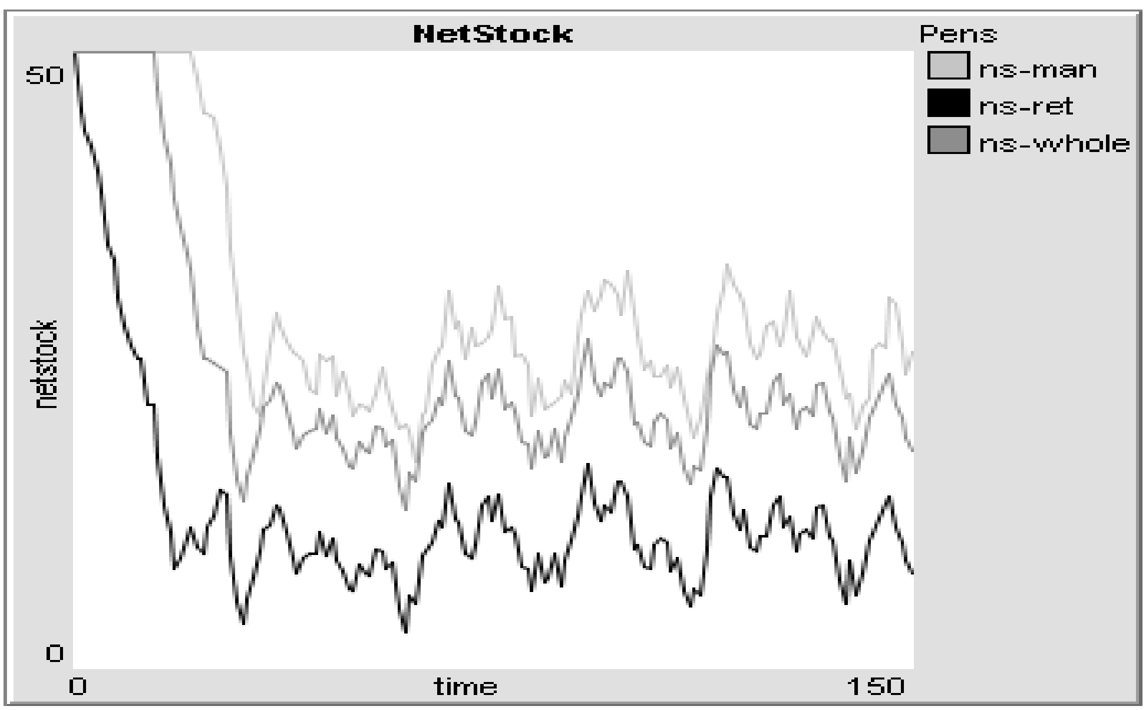

Figure 3.4 Supply Chain ABM Model -Validation Output
Demand ~ Uniform (0, 5), "Fixed Order Up (FIP)" O.P,
"Manufacturer FIP"=40, "Wholesaler FIP"=30, "Retailer FIP"=20, PLT=5, TLT=3

As seen from Figure 3.1&Figure 3.2, and Figure 3.3&Figure 3.4; the net stock levels generated by SD and ABM models are very similar; the differences between the two models are negligible.

Another validation test that is applied on validation of the models is "extreme condition tests". The considered extreme condition is "demand=0". The flows in the models stop; Figure 3.5 and Figure 3.6 show the related outputs.

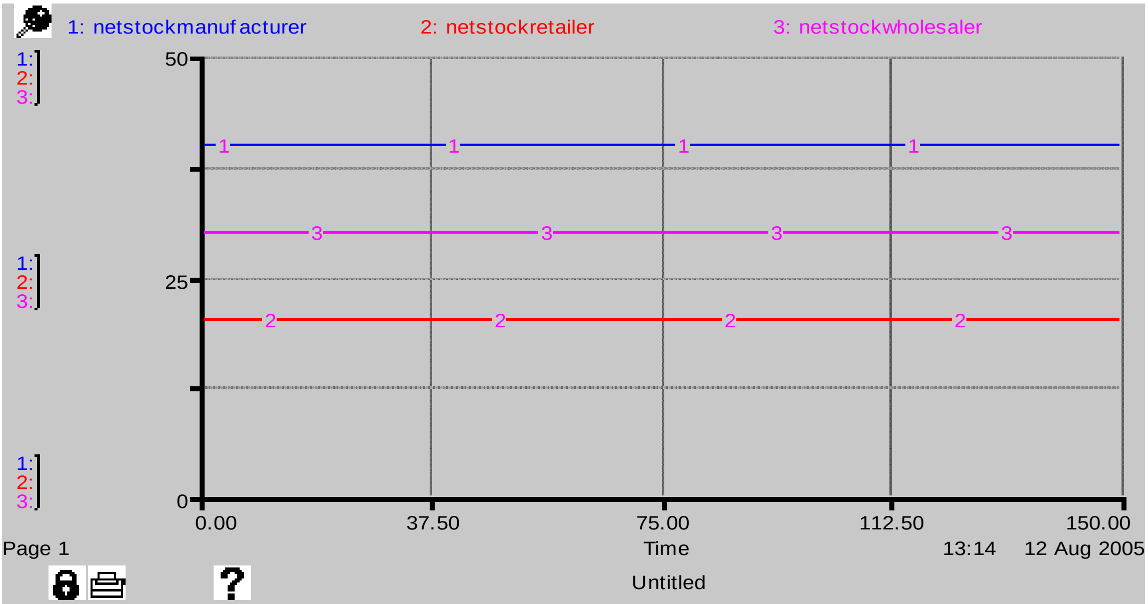

Figure 3.5 Supply Chain SD Model -Validation Output
Demand = 0, "As Needed" O.P, PLT=5, TLT=3

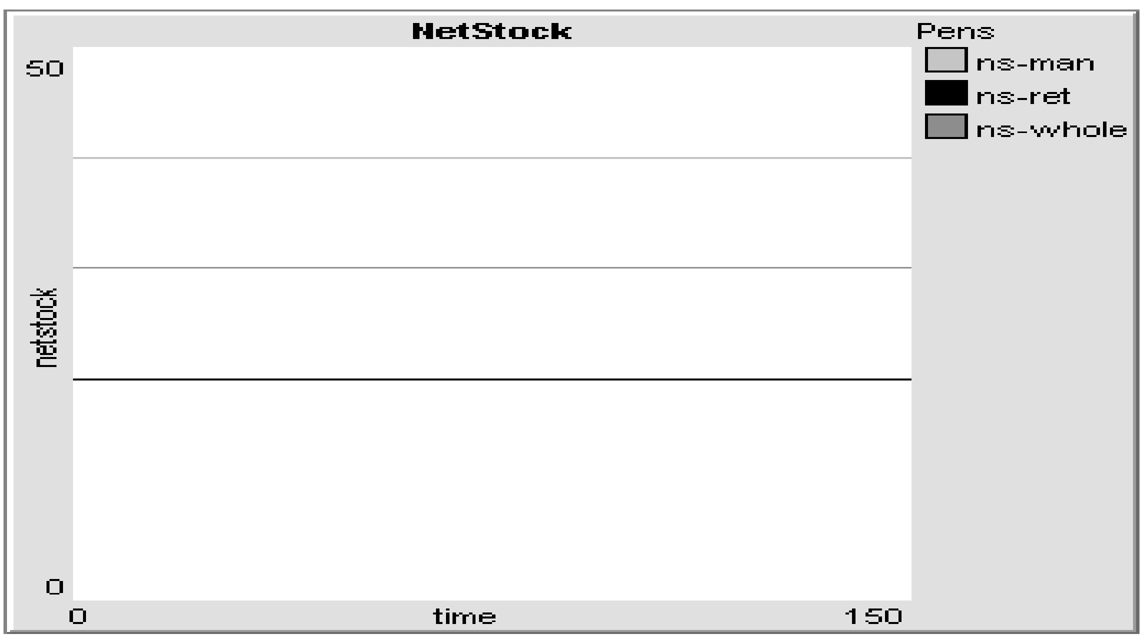

Figure 3.6 Supply Chain ABM Model -Validation Output
Demand = 0, "As Needed" O.P, PLT=5, TLT=3

These validation tests imply 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

What is tried to be done in this research is to add different structures to the system that will affect the ways firms in the model behave and then to compare the behavior patterns generated by SD and ABM models.

In some cases the autonomy added to the individual agents can be aggregated to the SD model but in some cases not. When it can be added, a comparison is made about the results generated by the two modeling methodologies; but there are cases where the SD model can not capture the dynamics generated by ABM model. This analysis is a comparison of macro and micro modeling approaches to find answers to questions, such as "Can aggregated, macro-level modeling capture the dynamics of the micro-level agent based modeling? In what specific cases?" The extent to which the SD model can capture the dynamics of the real system which ABM model resemble more will be analyzed. And another target in the research is to analyze the effects of firms' decisions on the overall supply chain behavior.

The effects of following factors are analyzed.

<u>Consideration of:</u>

- Inventory Positions,
- Price,
- Phantom –Shadow- Orders, and
- Loyalty

In the selection of the supplier –supplier of the finished good in one higher level of the supply chain; retailer for customer, etc.- and in the specification of order amounts.

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

<u>Parameter Setting 1:</u>

- 2 manufacturers, 10 wholesalers, 20 retailers, 500 customers
- Demand ~ Uniform (0, 5)
- 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 ABM model choose their suppliers randomly -without any criteria- among the agents in the one higher step of the supply chain. SD model considers aggregated agents, thus there is not a selection of the supplier; order amounts are decided and these amounts are dispatched from the higher steps to lower steps of the chain.

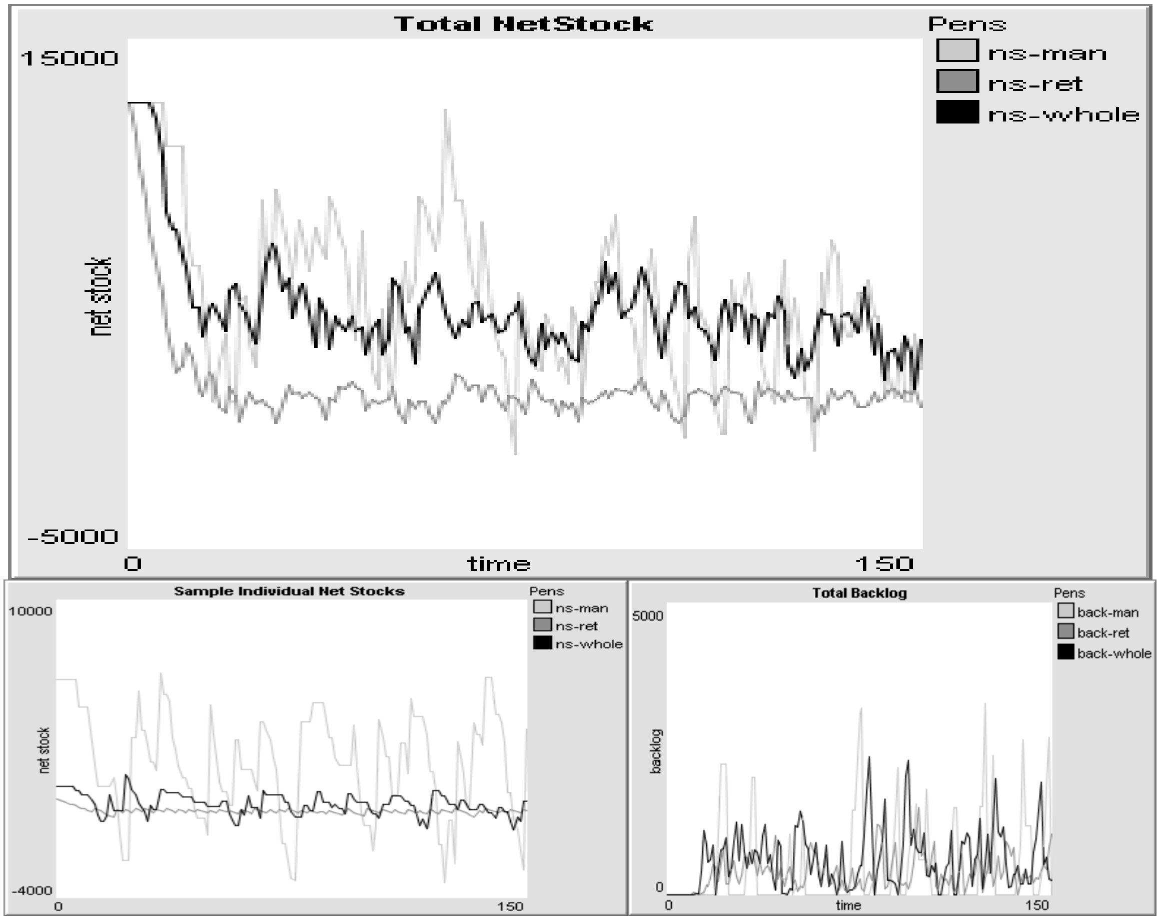

Figure 4.1 Supply Chain ABM Model –Parameter Setting 1
(Random Supplier Selection)

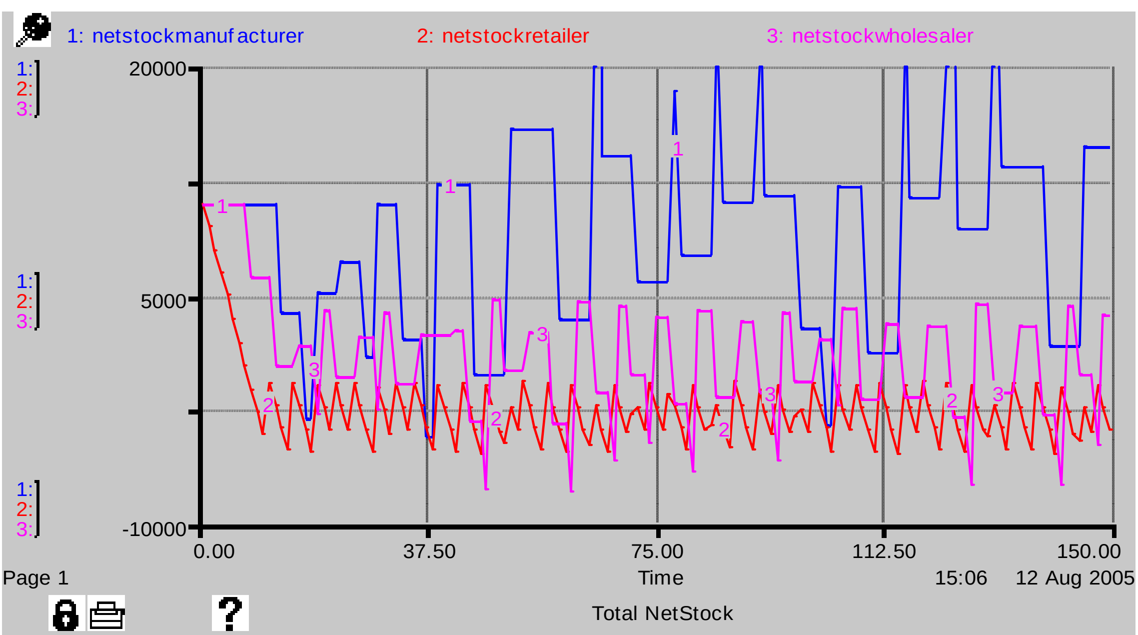

Figure 4.2 Supply Chain SD Model –Parameter Setting 1
(Random Supplier Selection)

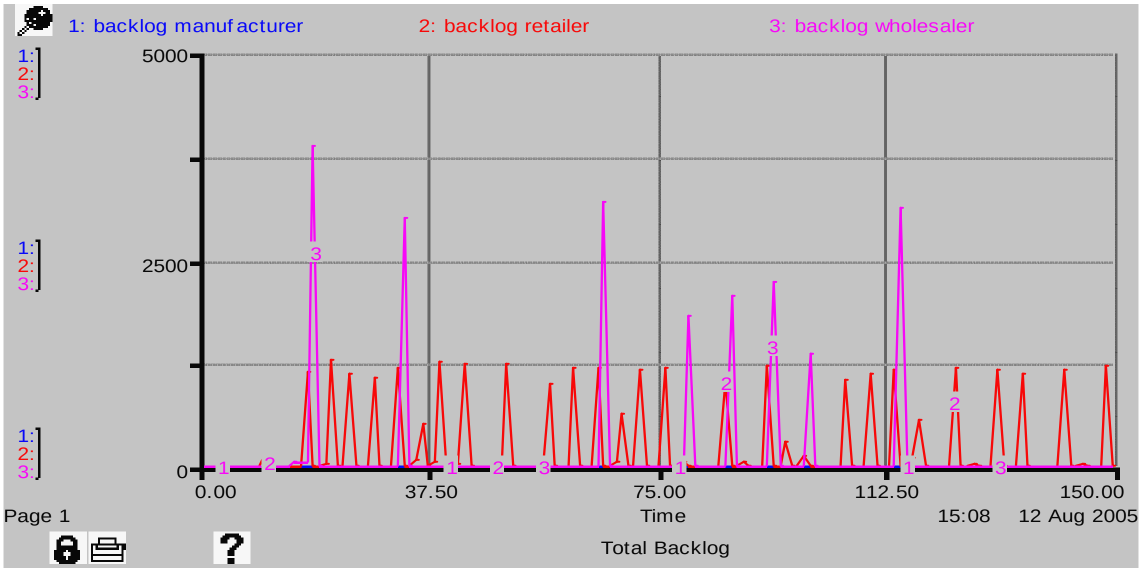

Figure 4.2 Supply Chain SD Model –Parameter Setting 1
(Random Supplier Selection), [ctd.]

To compare the results generated by SD and ABM models, they generate similar behaviors; but the degree of oscillations in SD model are relatively higher resulting from the fact there are phase lags between the patterns of net stock positions of the agents in ABM model. In SD model the system acts as if there is a single agent; so there is not any reduction of the type in ABM model in oscillations. It is important to note that this does not imply a structural difference between Agent-Based and System Dynamics models.

4.1 Consideration of Inventory Position in the Selection of the Supplier

To make agents more intelligent, more rational decision makers, they are made able to look for the suitable suppliers by inventory position criteria. This includes a look up in the inventory level (also considering new coming demands at the same time interval) and choosing one of the retailers which can satisfy the demand. For this a list of retailers is created and a search over this list is done until coming up with a satisfactory retailer. If there is no such one, one is randomly selected.

This selection criterion is added to ABM 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 ABM model output.

When Figures 4.1 and 4.1.1 are compared, it is seen that the oscillations 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.

The demands of the customers are prone to be collected around the retailers with high inventory levels. These retailers will give out their inventory; but -since their forecasts increase- they give bigger order amounts to the wholesalers and these forecasts will be collected around wholesalers with high levels of inventory and this goes like that to the level of manufacturers. This decision process of agents causes boom and busts in the inventory levels of retailers, wholesalers and manufacturers. Since the number of manufacturers is 2, the number of wholesalers is 10 and the number of retailers is 20; the oscillation is most significant in the upper levels of the Supply Chain. This factor can not be added to the SD model, but that makes difference in the system behavior; so it is concluded that SD can not catch the dynamics of this level detail.

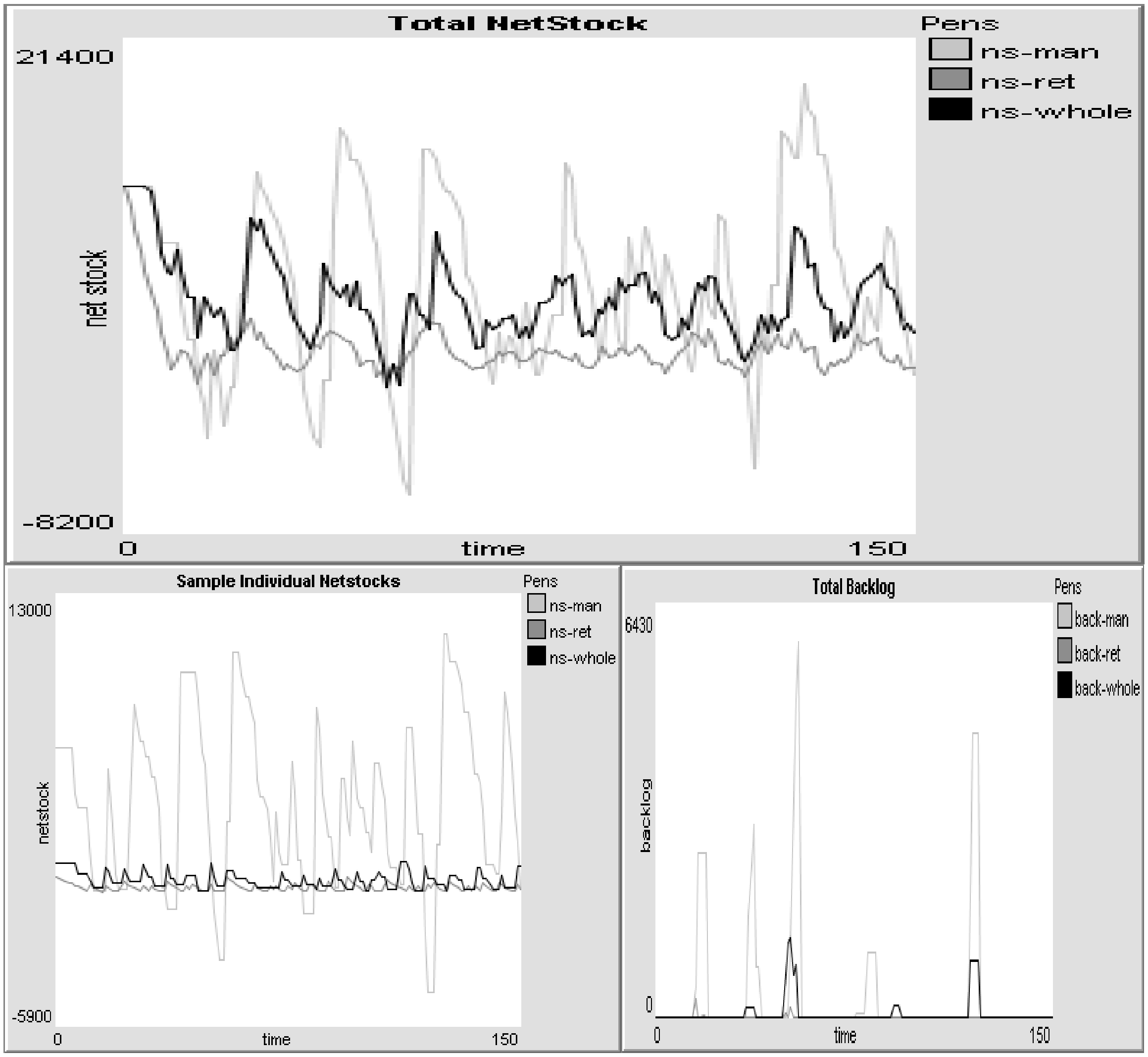

Figure 4.1.1 Supply Chain ABM Model –Parameter Setting 1
(Consideration of Inventory Positions in Supplier Selection)

4.2 Consideration of Price in Supplier Selection

One of the main factors in determining the order amount and the supplier of this 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 at two steps: At first step, the order amount is not affected by 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.

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 ABM model, the price is defined as a discrete –table- 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 puts higher prices to their products to get a higher revenue 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 ABM model, when price levels are considered in selecting the suppliers.

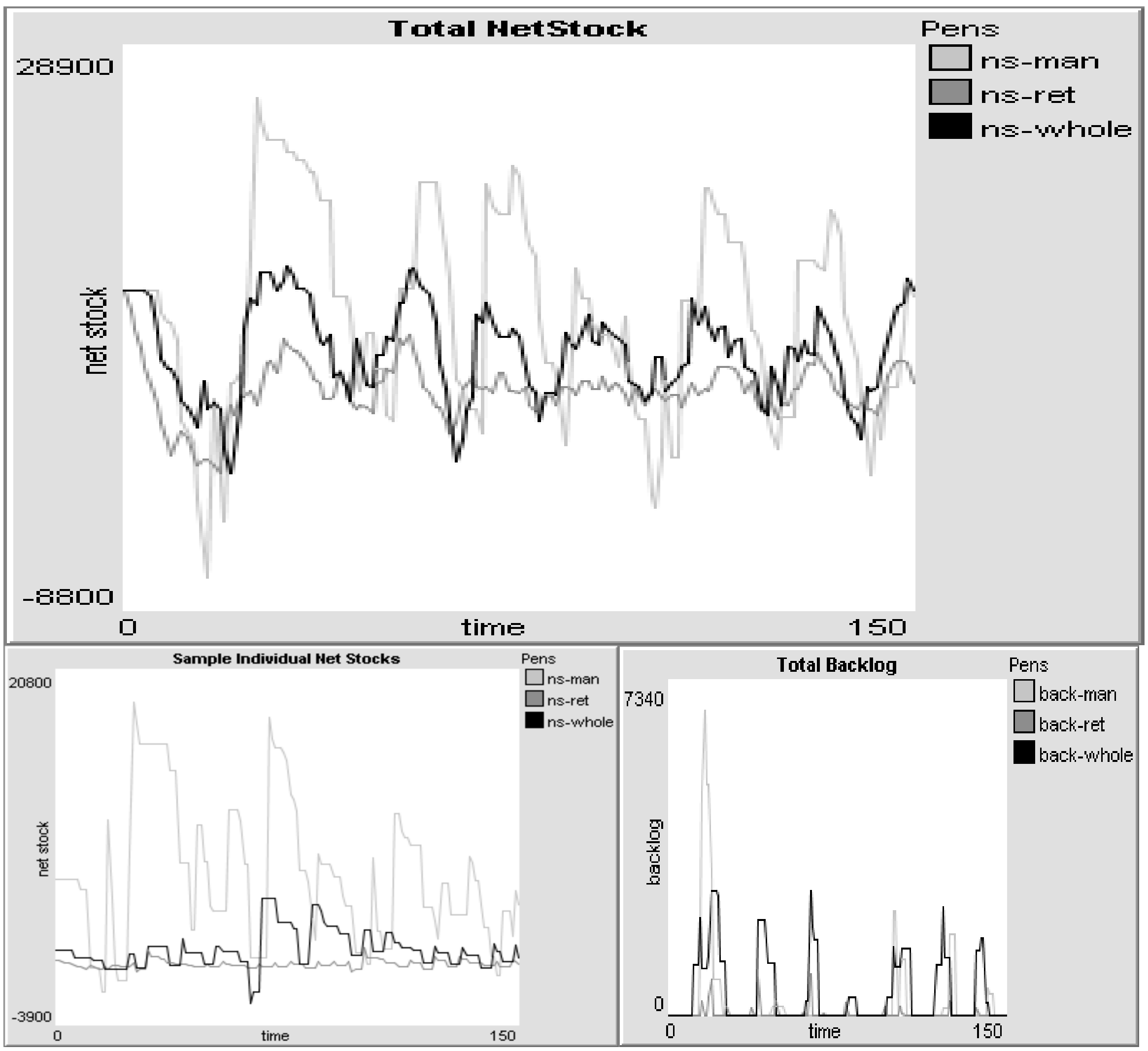

Figure 4.2.1.1 Supply Chain ABM Model –Parameter Setting 1
(Price as the Selection Criterion of the Supplier)

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.

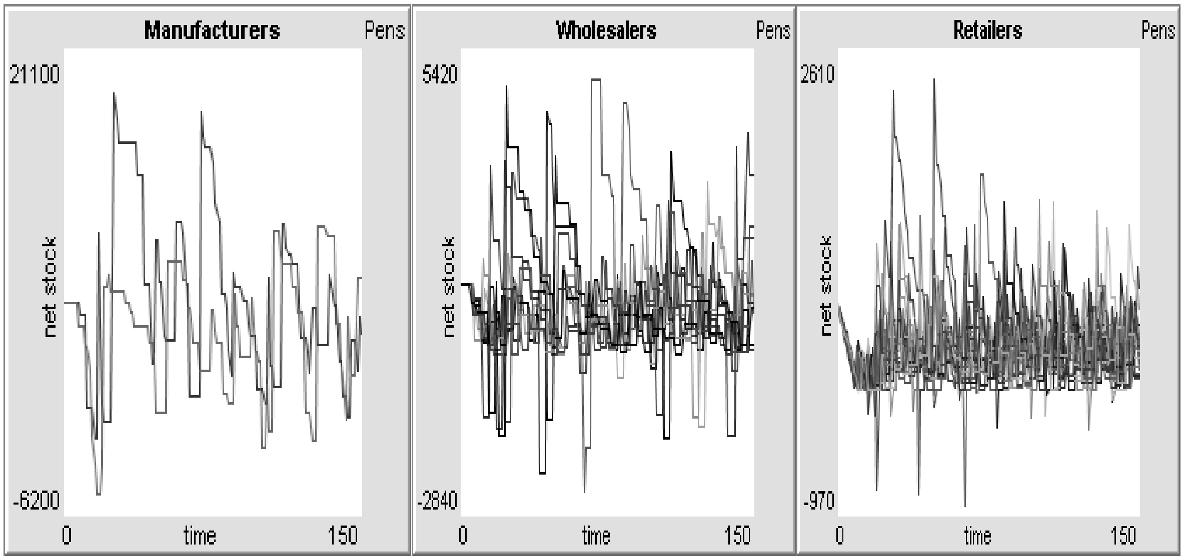

Figure 4.2.1.2 Supply Chain ABM Model, Individual Inventories at each level –Parameter Setting 1 *(Price as the Selection Criterion of the Supplier)*

4.2.2 Price as Also a Determining Factor of the Order Quantity

In further analysis, it is considered that the order quantities of the agents will be affected by price. They can look at the average price level or the min. of prices at the upper level of the supply chain.

This modification can be made in SD model; but at an aggregate level. A 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 and as the price increases, the demand from the lower chain level decreases. The inventory level specifies the price, and the inventory level is decreased by the incoming demand.

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

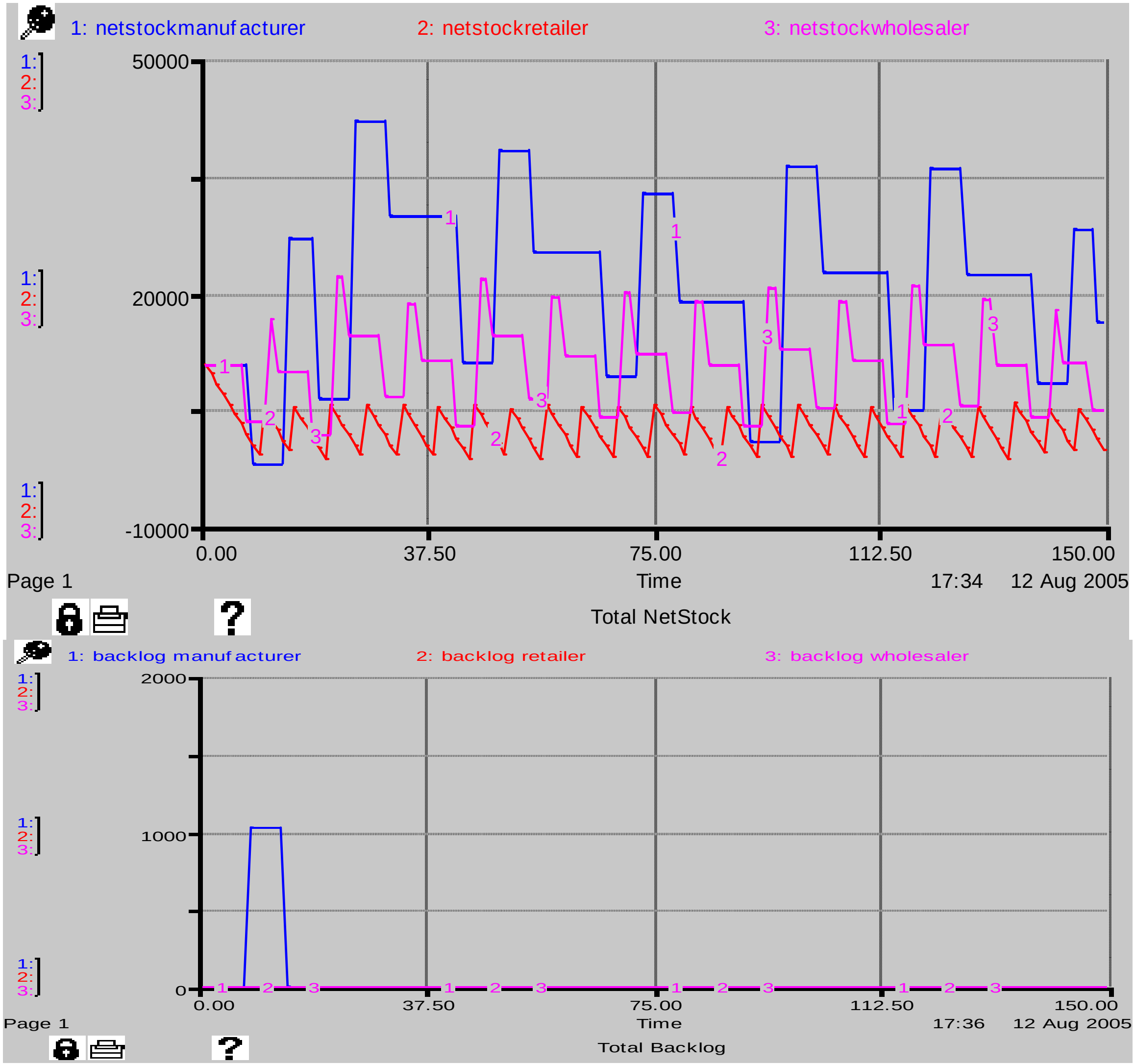

Figure 4.2.2.1 Supply Chain SD Model –Parameter Setting 1
(Order Amount Affected by Price)

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 oscillations are bigger in the one with the price factor. It is also important to note that oscillations increase in the direction from retailers to manufacturers.

There are two mechanisms that cause oscillations in the Supply Chain, first one is the delay due to the lead times 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 rules. The oscillations increase in ABM model and the periodicity in the SD model is more blurred in the ABM case. The increased autonomy of agents, 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 very rational; but the emergent system behavior gives harm to everybody.

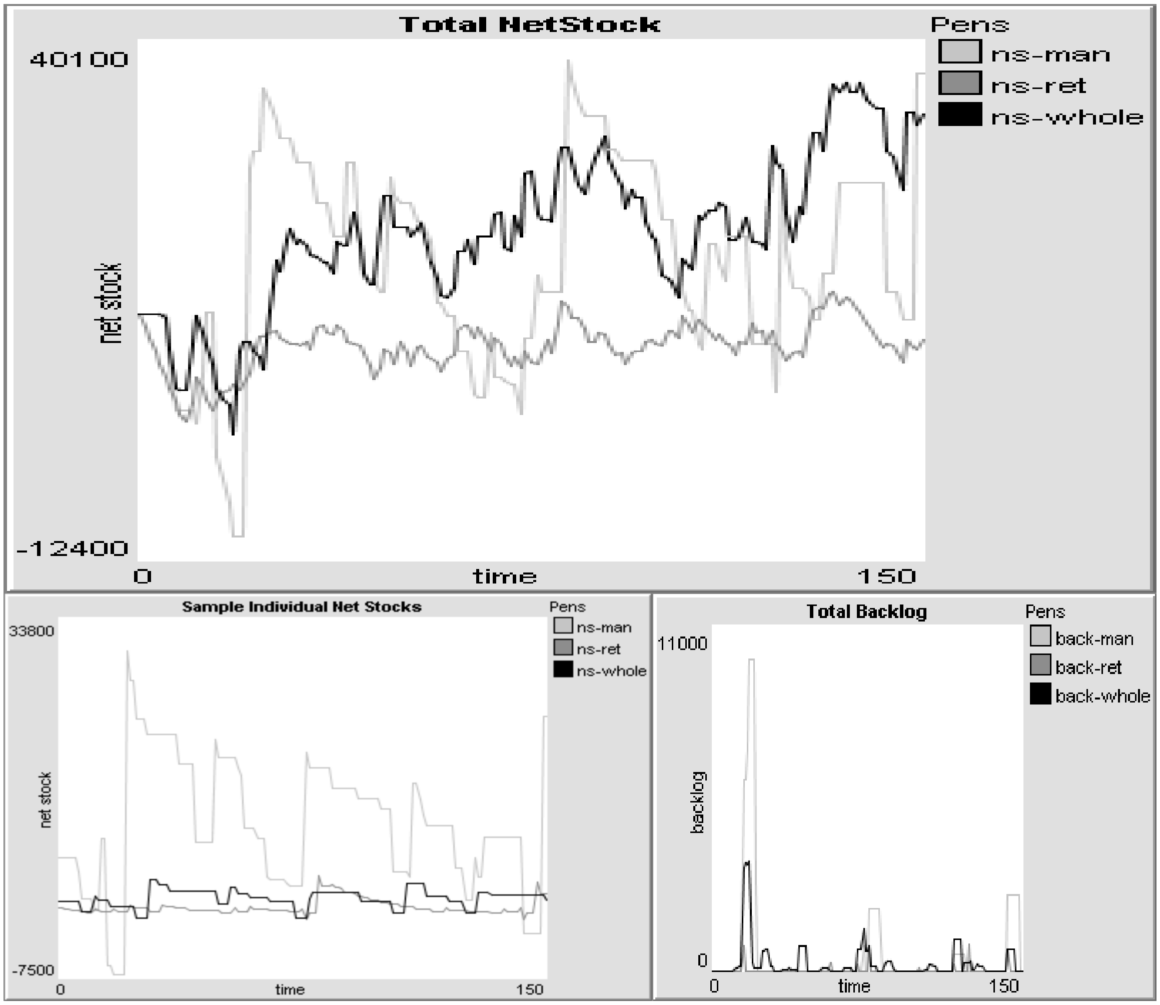

Figure 4.2.2.2 Supply Chain ABM Model –Parameter Setting 1
(Order Amount Affected by Price)

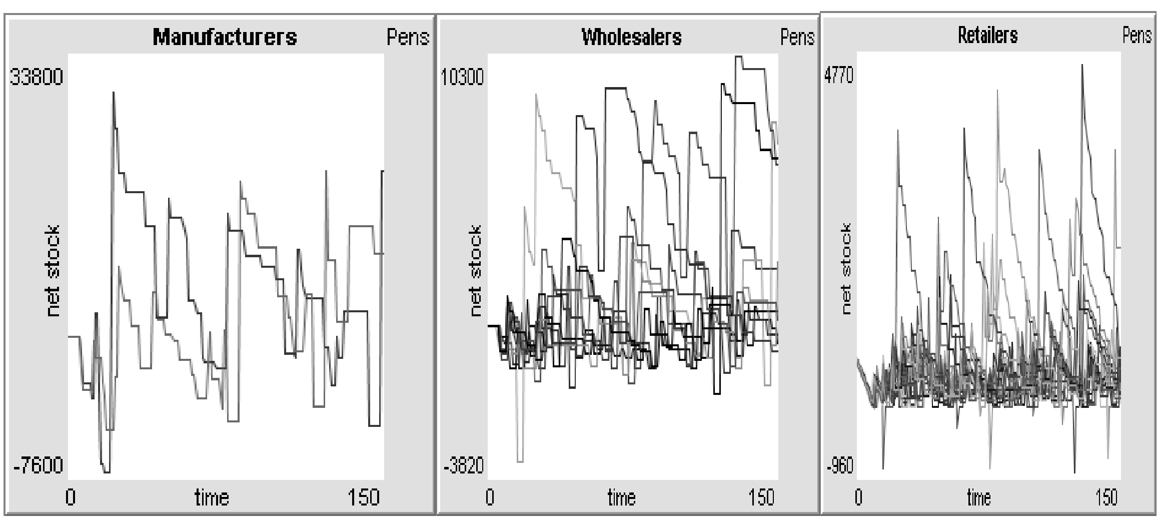

Figure 4.2.2.3 Supply Chain ABM Model Individual Inventories at each level –Parameter Setting 1
(Order Amount Affected by Price)

4.3 Consideration of Loyalty in the Supplier Selection

Another factor that shapes the systemic behavior of Supply Chain is 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 model can only be formulated in ABM; since there are no distinctions among individuals in SD aggregation.

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

In ABM model each customer is assigned a random retailer, each retailer a wholesaler and each wholesaler a 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 level at that point of time. 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 ABM 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 upper tier" the best for the all occurs.

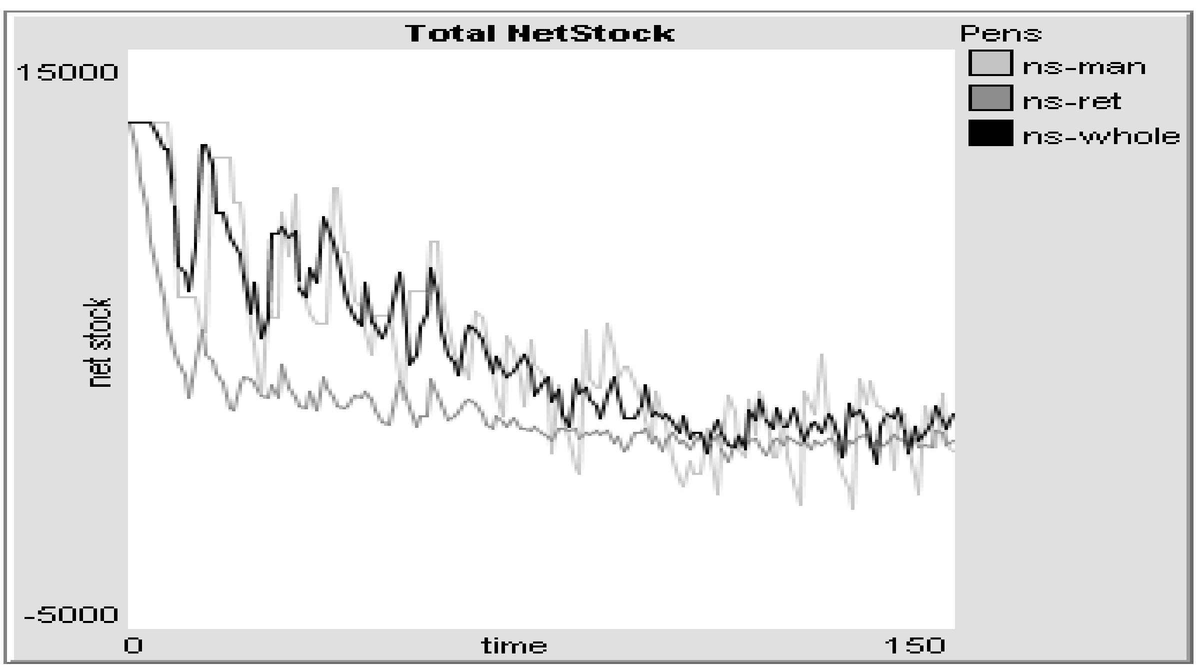

Figure 4.3.1 Supply Chain ABM Model –Parameter Setting 1
(Consideration of Loyalty in the Supplier Selection)

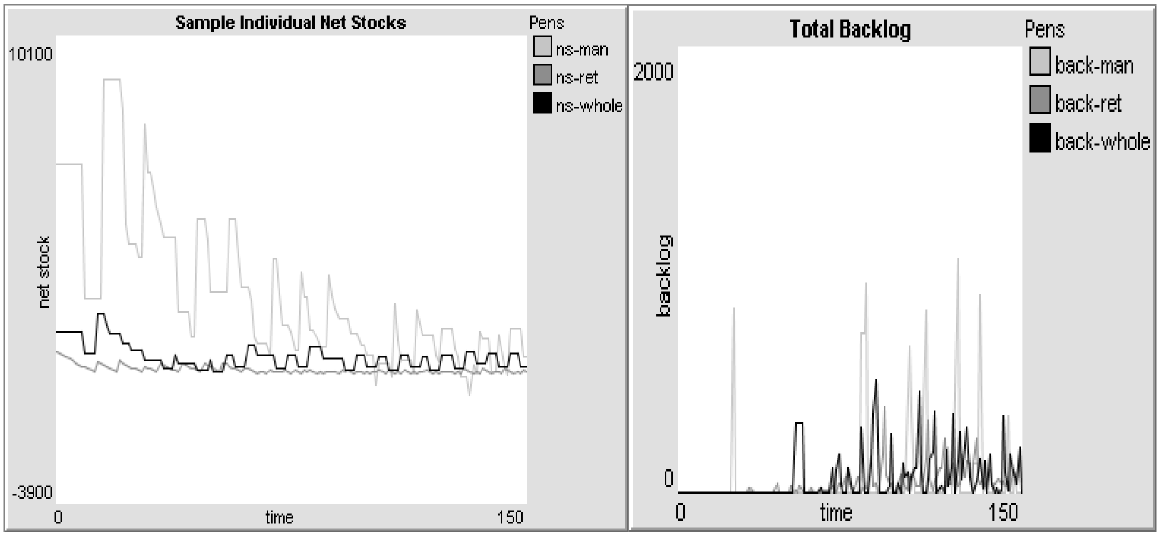

Figure 4.3.1 Supply Chain ABM Model –Parameter Setting 1
(Consideration of Loyalty in the Supplier Selection) [ctd.]

4.4 Effect of Shadow Orders[1]

The firms may consider giving shadow –phantom- orders when the lead time of the products exceeds a sustainable level. The firms' main aim in doing this action is to be able to get the most portion of the available supply. Since the supply is scarce there is a competition among the firms demanding these goods. Each demanding firm will show its demand more than the 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 –firms are guaranteed this right in the contracts. [9]

Since there is delay in the system and the suppliers can not perceive the actual demand levels; shadow ordering phenomenon creates great booms in the inventory of suppliers. As a result, all the agents in the Supply Chain lose their credit in others' eyes. Shadow Ordering is added to the SD and ABM models. The assumption here is that the cancelled orders will stay in the supplier's inventory.

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. This decision is given by looking at the expected average delay time. The phantom ordering policy is defined as the action of customers and retailers. The firms still use price-inventory decision mechanism in specifying the order amount.

Figure 4.4.1 shows the ABM model output with shadow orders effect. Compared to Figure 4.1, it can be seen that the inventories of retailers, wholesalers and manufacturers fluctuate around higher inventory levels resulting from shadow orders.

Figure 4.4.2 shows the SD model output with shadow orders effect. General conclusions are similar to those of ABM model.

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[1] In this section, loyalty among agents is not considered.

It is concluded that the SD model can capture the dynamics generated by phantom orders at an aggregate level. But again when the behavior characteristics are compared, a difference is observed. The inventory levels fluctuate in SD model almost in a cyclic pattern; but this cyclic pattern is more blurred in ABM model. This is due to the fact that SD model captures the trends in an aggregate manner; it can not capture the dynamics generated by the autonomy of the agents since SD can not handle each agent separately. The increased heterogeneity among individuals can be seen from Figure 4.4.3.

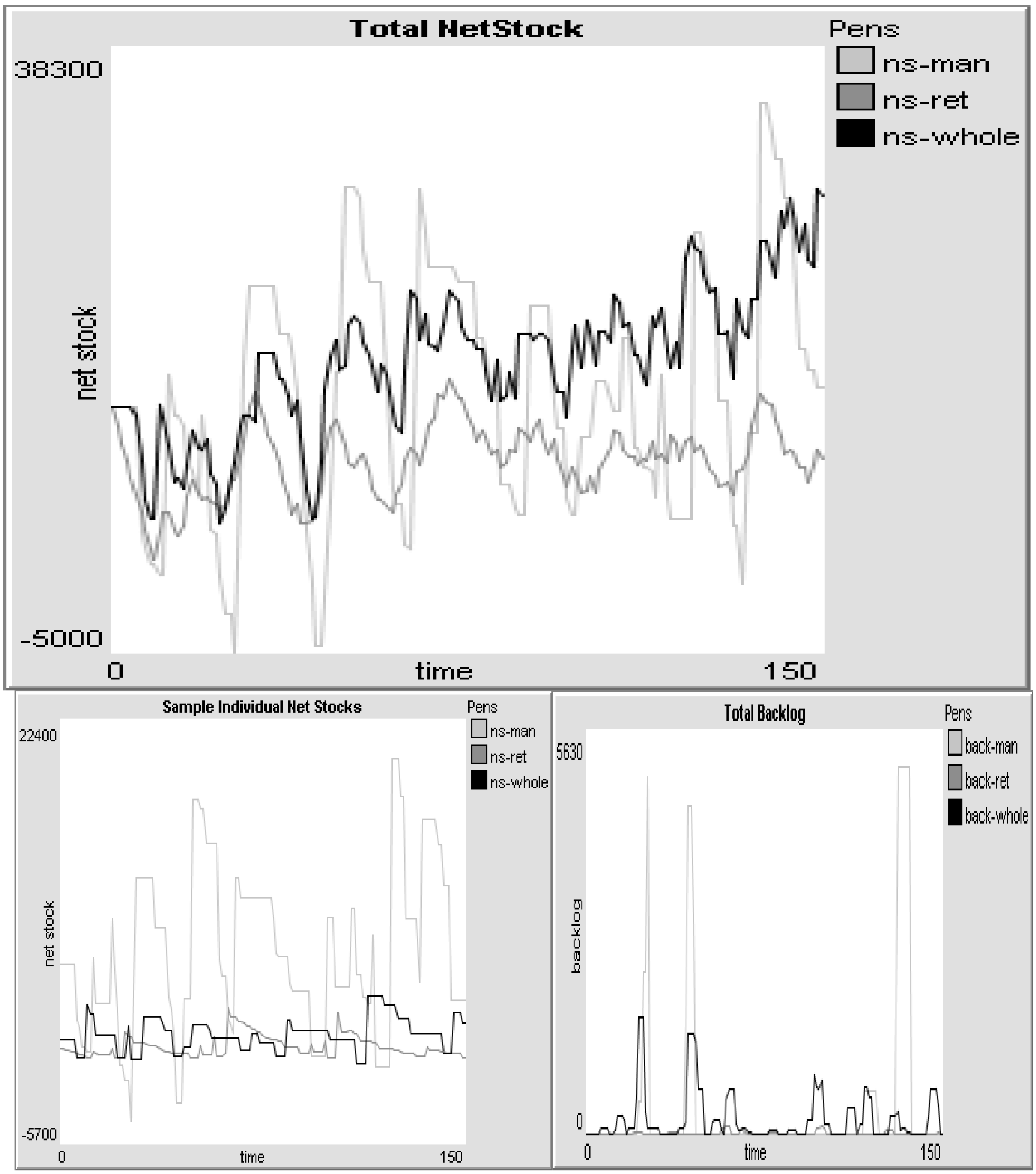

Figure 4.4.1 Supply Chain ABM Model –Parameter Setting 1
(Order Amount Affected by Price & Shadow Orders)

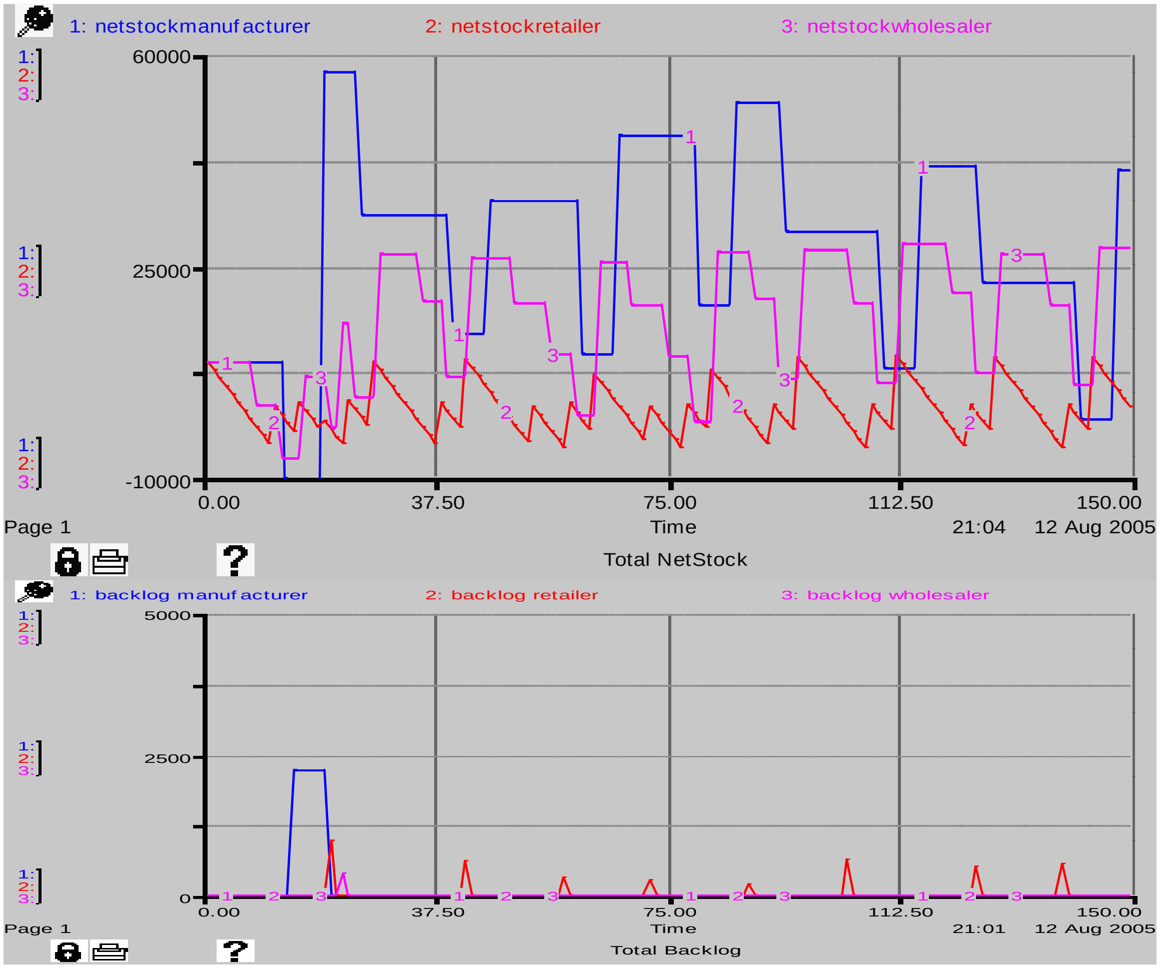

Figure 4.4.2 Supply Chain SD Model –Parameter Setting 1
(Order Amount Affected by Price & Shadow Orders)

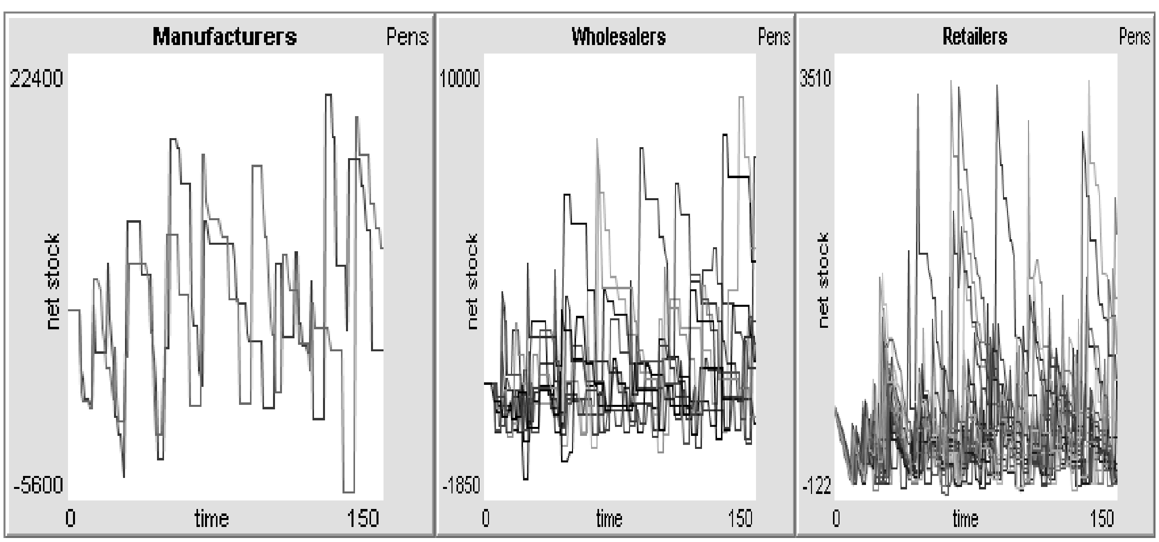

Figure 4.4.3 Supply Chain ABM Model Individual Inventories at each level –Parameter Setting1
(Order Amount Affected by Price & Shadow Orders)

4.5 Effect of Safety Stocks

An important factor in supply chain dynamics is the specification of safety stocks. To overcome backlogs, safety stocks should be considered but this creates inventory holding costs. Thus there is a trade-off between inventory holding cost and ordering and backlog cost.

When the graphs in sections 4.1-4.4 are analyzed; it is seen that backlogs occur in the system, especially at the beginning of the time horizons. To overcome backlogs, it is decided to assign higher SS values to the agents at higher levels of the supply chain. Parameter Setting 2 is used for this purpose.[2]

The graphs 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 Section 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.

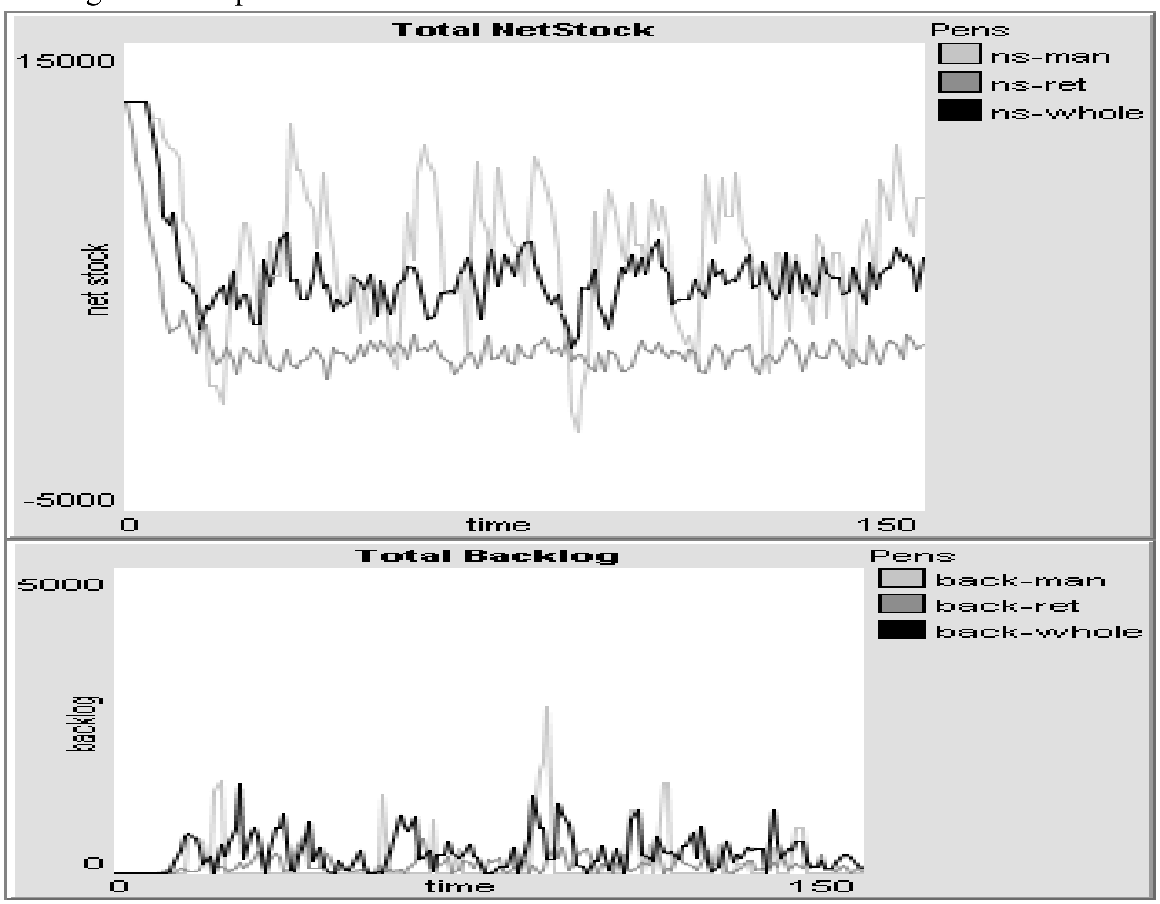

Figure 4.5.1 Supply Chain ABM Model –Parameter Setting 2
(Random Supplier Selection)

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[2] 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.

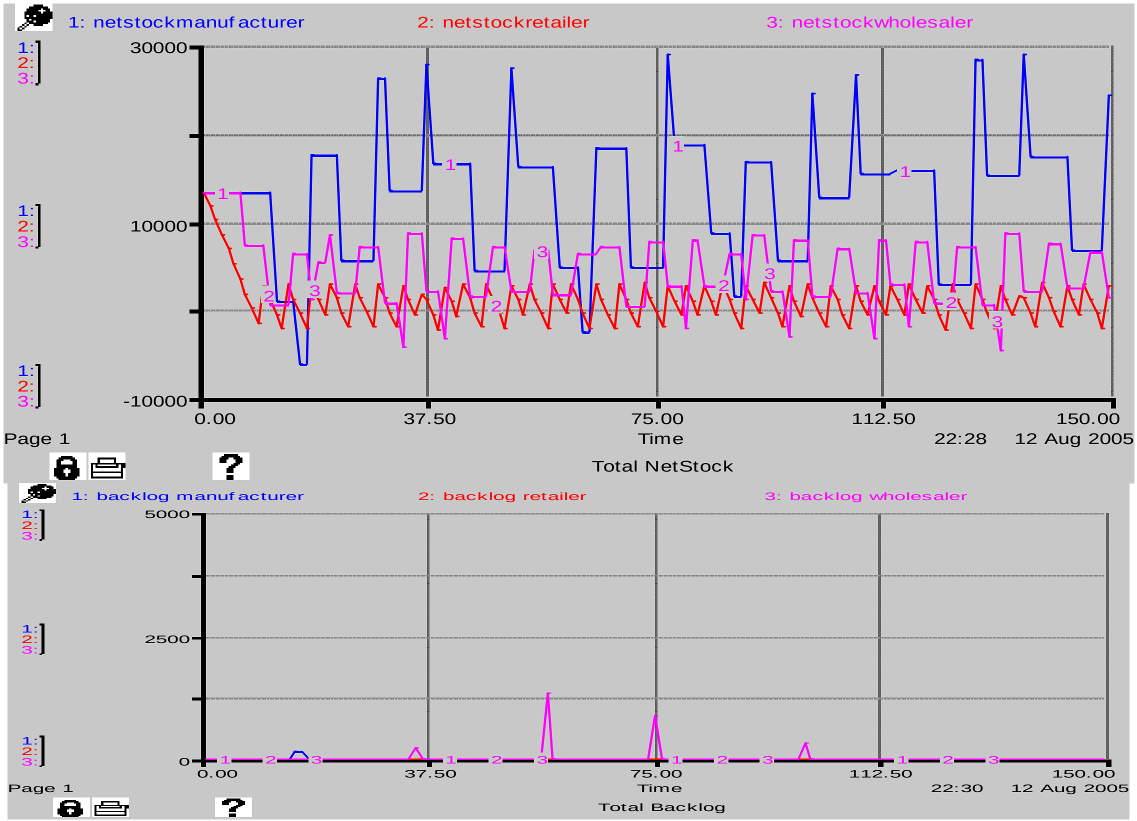

Figure 4.5.2 Supply Chain SD Model –Parameter Setting 2 *(Random Supplier Selection)*

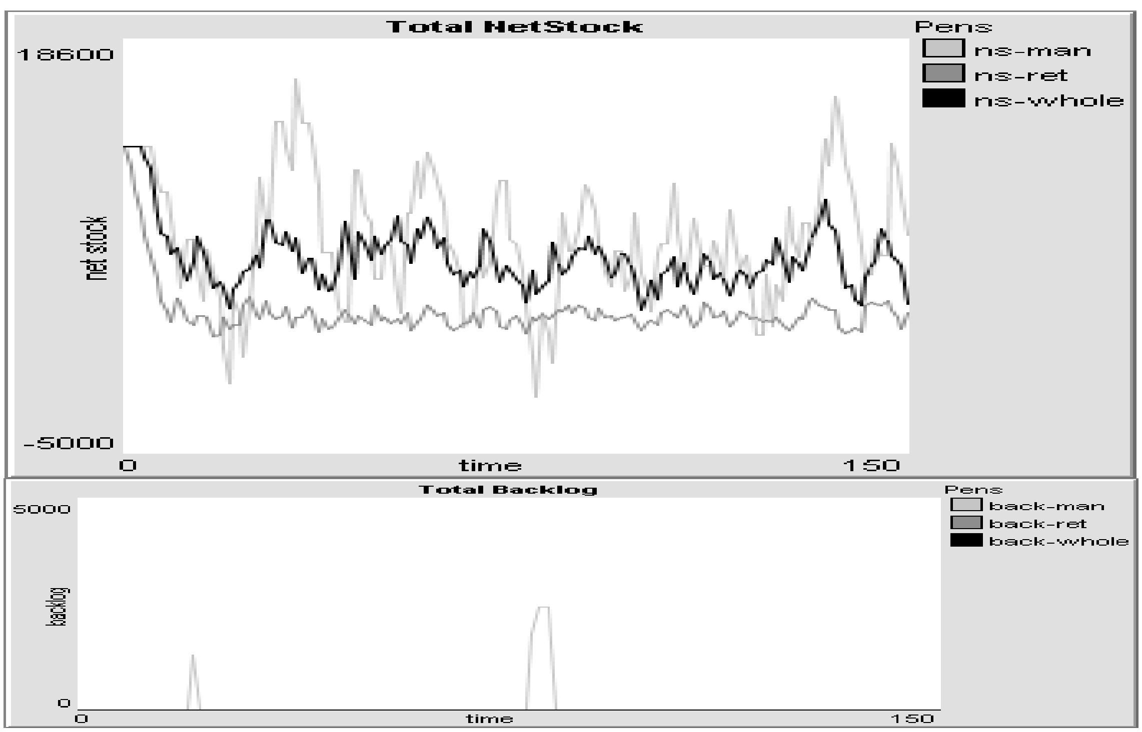

Figure 4.5.3 Supply Chain ABM Model –Parameter Setting 2
(Consideration of Inventory Positions in Supplier Selection)

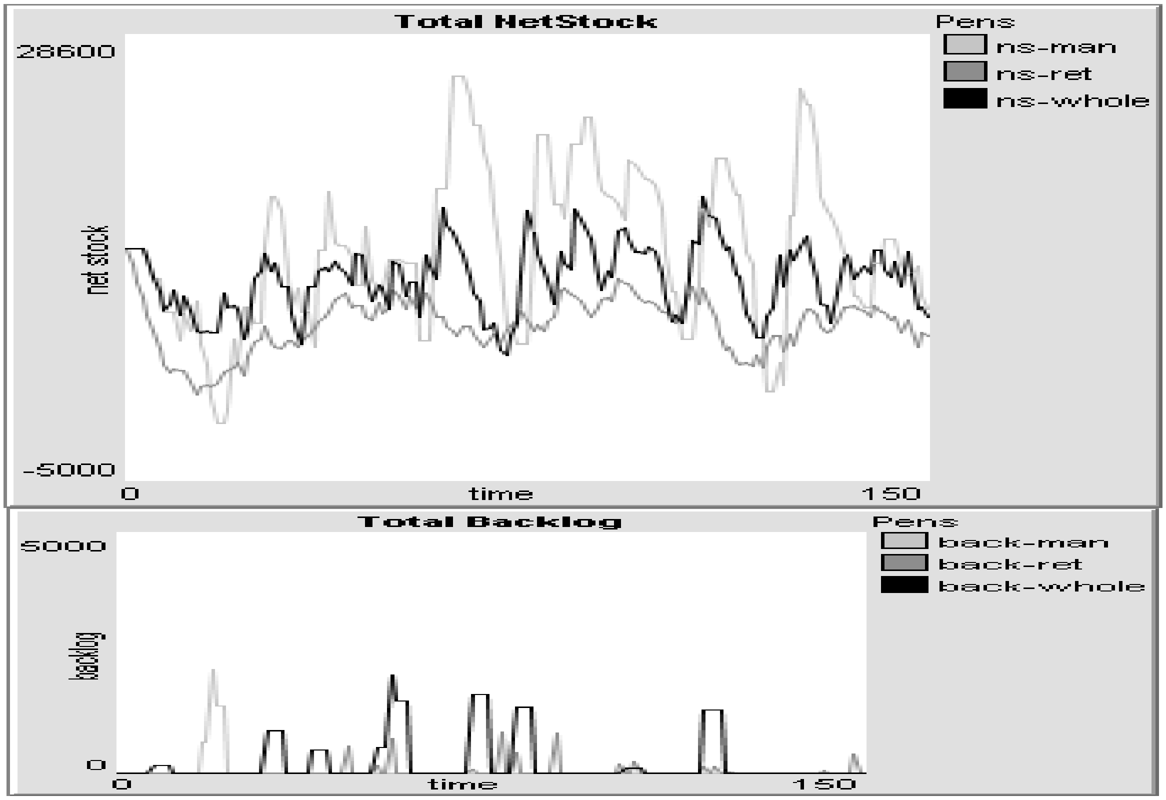

Figure 4.5.4 Supply Chain ABM Model –Parameter Setting 2
(Consideration of Price in Supplier Selection)

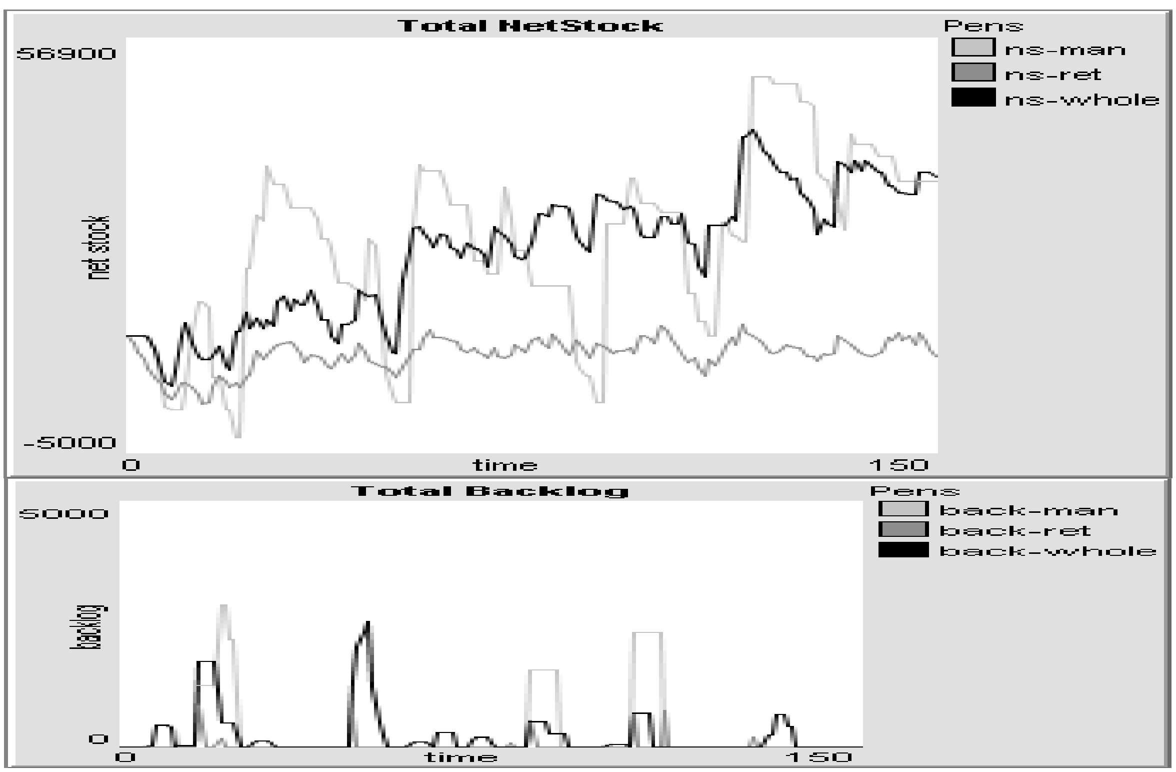

Figure 4.5.5 Supply Chain ABM Model –Parameter Setting 2
(Order Amount Affected by Price)

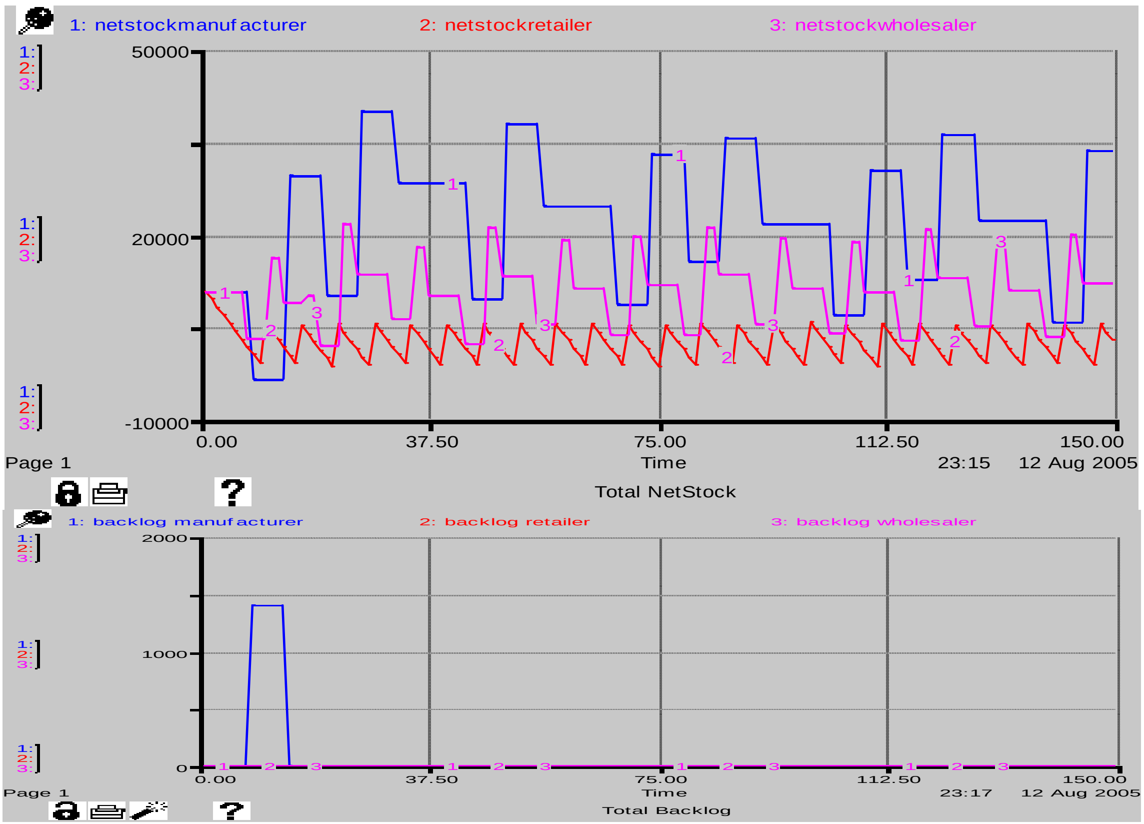

Figure 4.5.6 Supply Chain SD Model –Parameter Setting 2
(Order Amount Affected by Price)

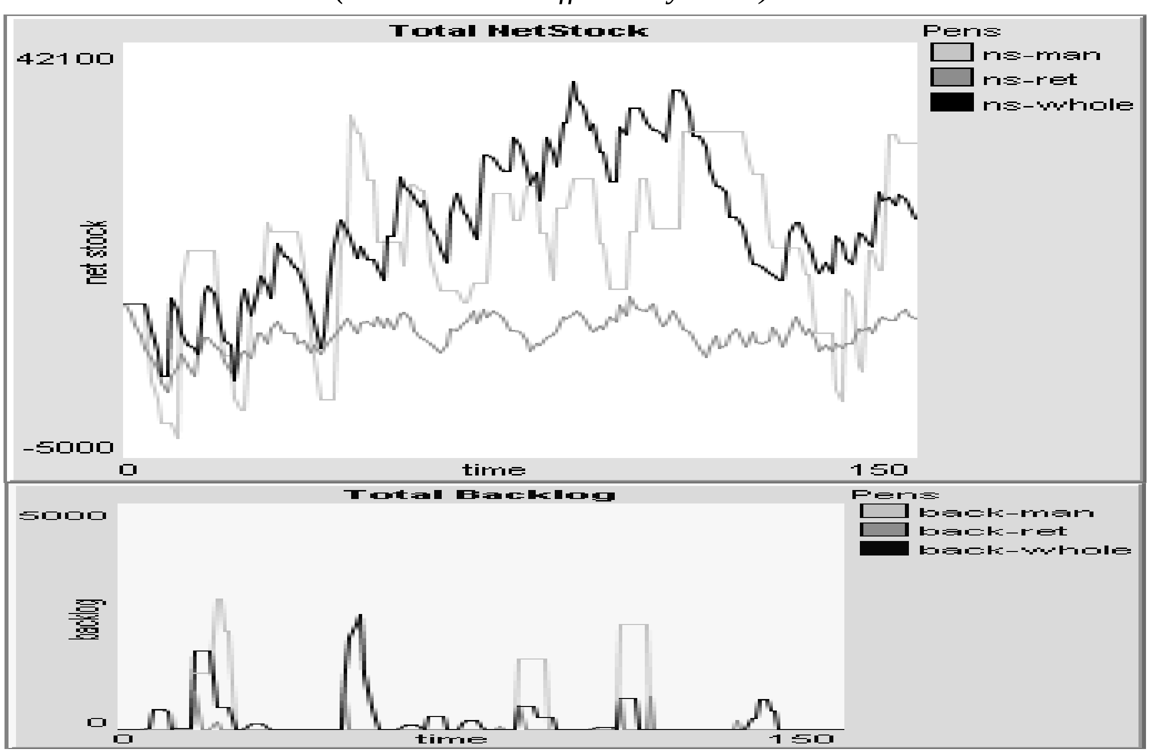

Figure 4.5.7 Supply Chain ABM Model –Parameter Setting 2
(Order Amount Affected by Price & Shadow Orders)

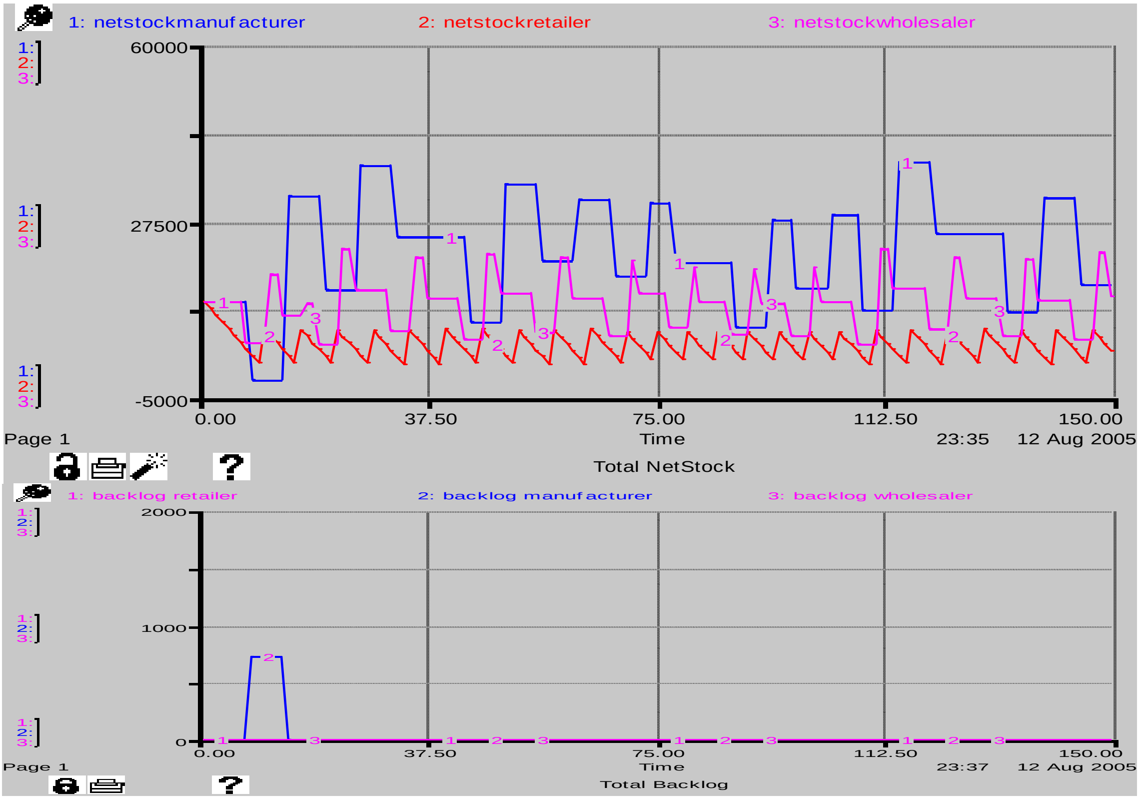

Figure 4.5.8 Supply Chain SD Model –Parameter Setting 2
(Order Amount Affected by Price & Shadow Orders)

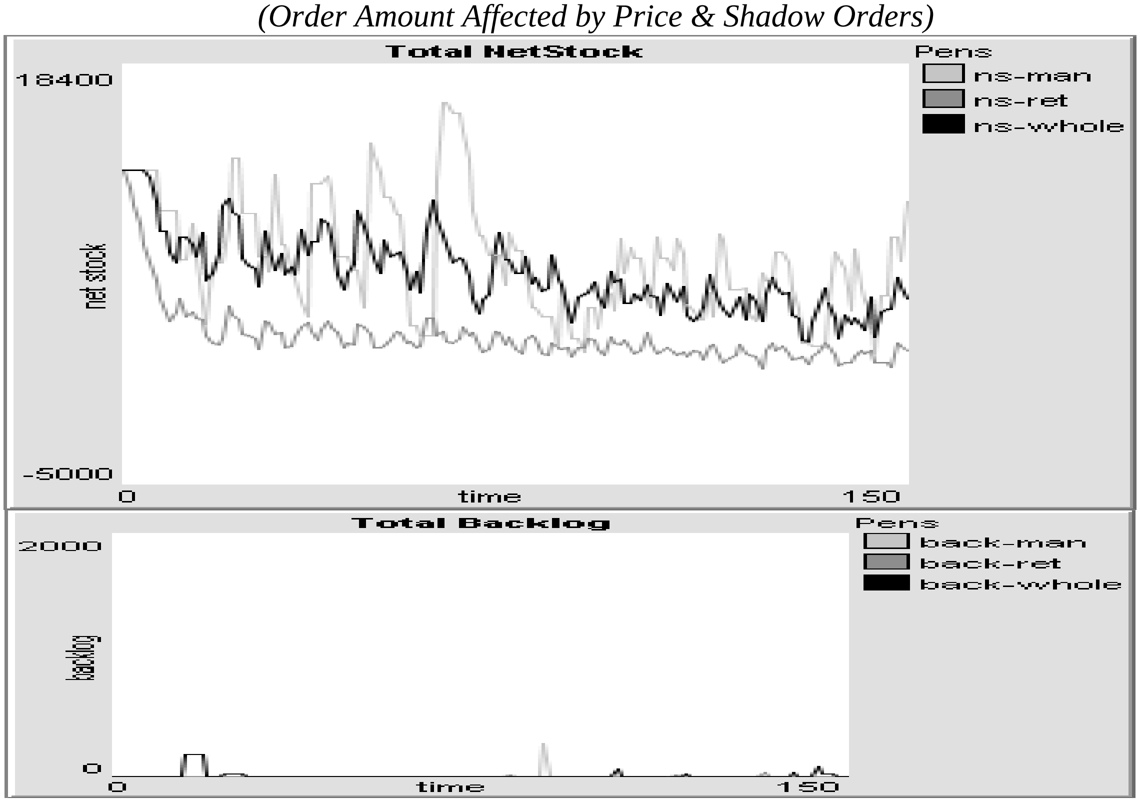

Figure 4.5.9 Supply Chain ABM Model –Parameter Setting 2
(Loyalty)

4.6 Consideration of Different Ordering Policies

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 – where there is a fixed order up level and every time the inventory position falls below this level there is an order placed in the amount of the difference between the order up level and the inventory position- reduce the fluctuations in the system?"

Parameter Setting 3 is used for this purpose.[3] Figures 4.6.1-4.6.6 show the related outputs of the models. It is apparent from Figures 4.6.1 -4.6.6 that the fixed order up policy mostly removes the oscillations in the system. Even if the price mechanism is active, the oscillations are not exaggerated; because the price is a function of inventory and the firms try to stabilize their inventories around an amount near to order up level. Shadow orders are not dominant because there is no extra delay in the system depending on the backlogs. But since this ordering policy requires giving orders at each period –more often than Reorder Point Order Up policy- , it implies ordering cost-inventory cost trade off. It may not be profitable to give orders each period considering this trade-off.

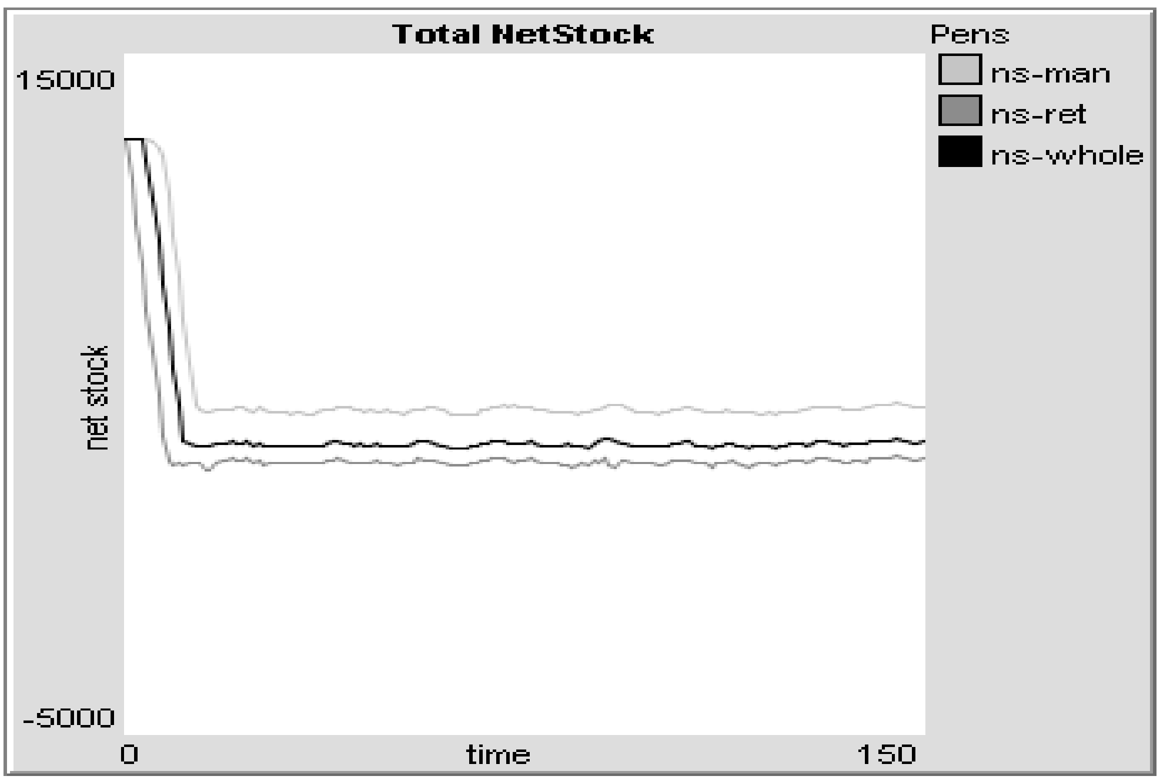

Figure 4.6.1 Supply Chain ABM Model –Parameter Setting 3
(Random Supplier Selection)

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

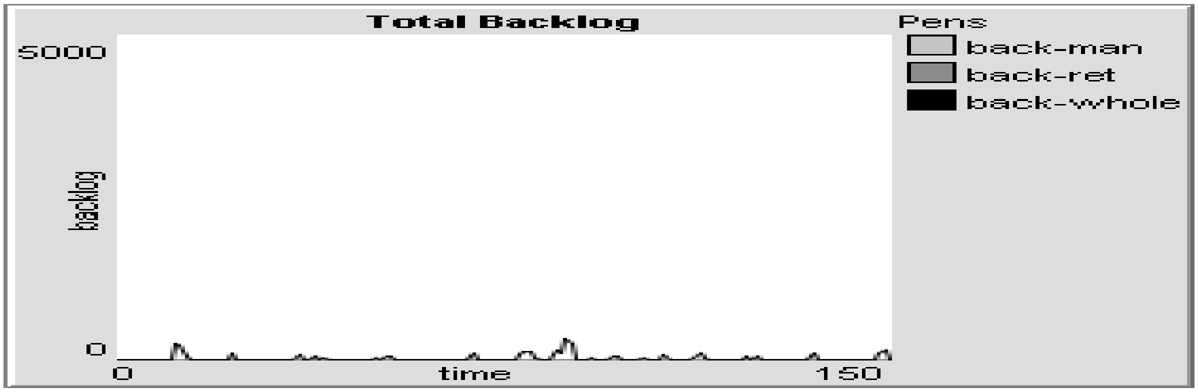

Figure 4.6.1 Supply Chain ABM Model –Parameter Setting 3
(Random Supplier Selection)

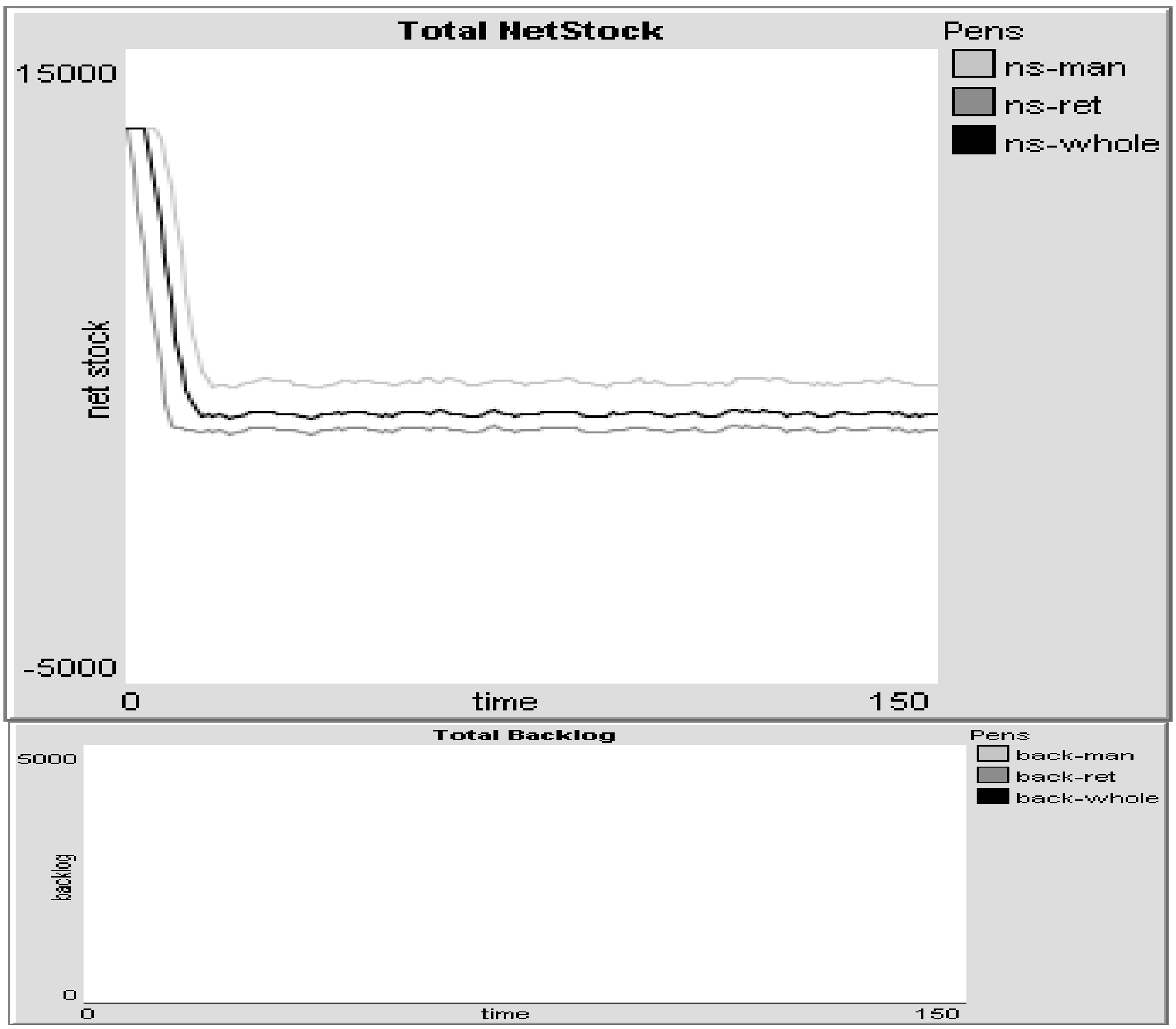

Figure 4.6.2 Supply Chain ABM Model –Parameter Setting 3
(Consideration of Inventory Positions in Supplier Selection)

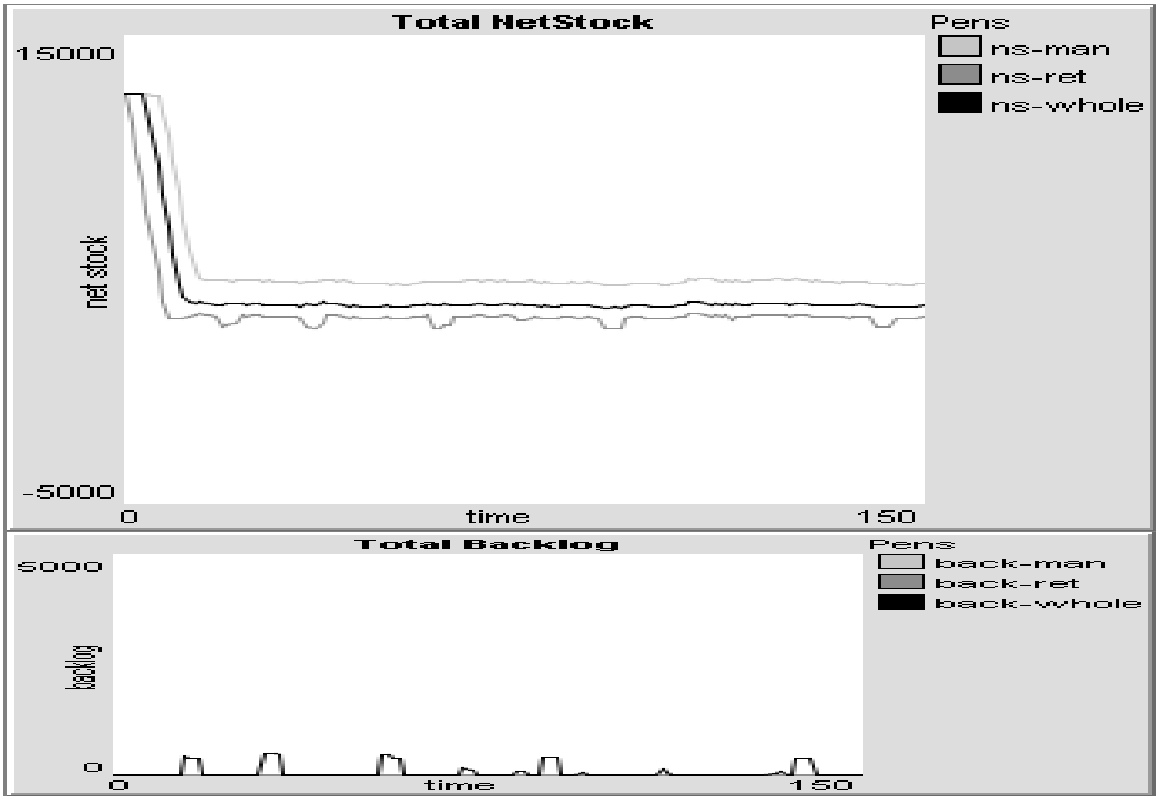

Figure 4.6.3 Supply Chain ABM Model –Parameter Setting 3
(Consideration of Price in Supplier Selection)

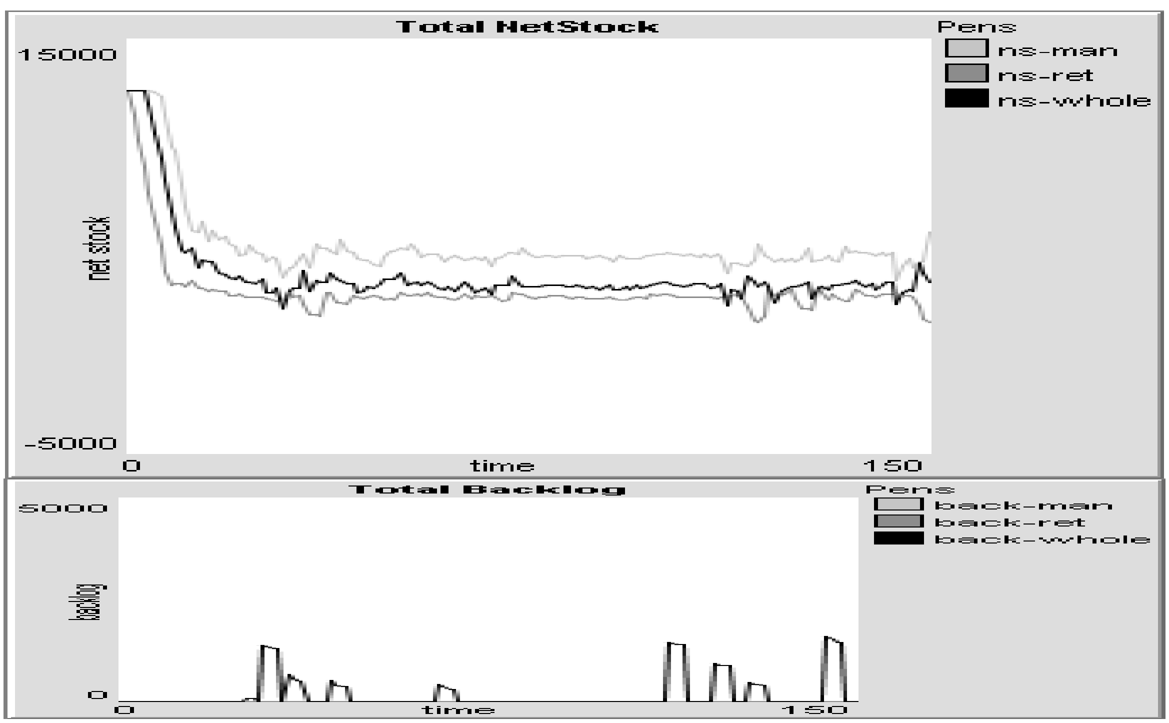

Figure 4.6.4 Supply Chain ABM Model –Parameter Setting 3
(Order Amount Affected by Price)

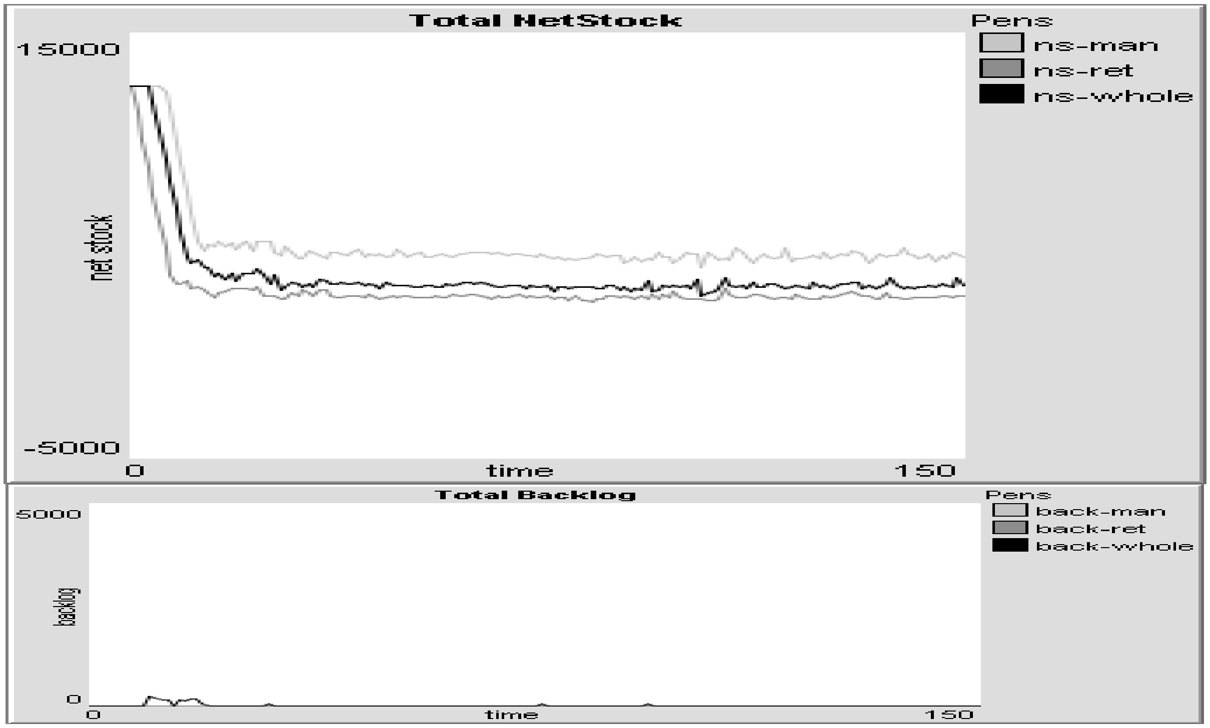

Figure 4.6.5 Supply Chain ABM Model –Parameter Setting 3
(*Order Amount Affected by Price & Shadow Orders*)

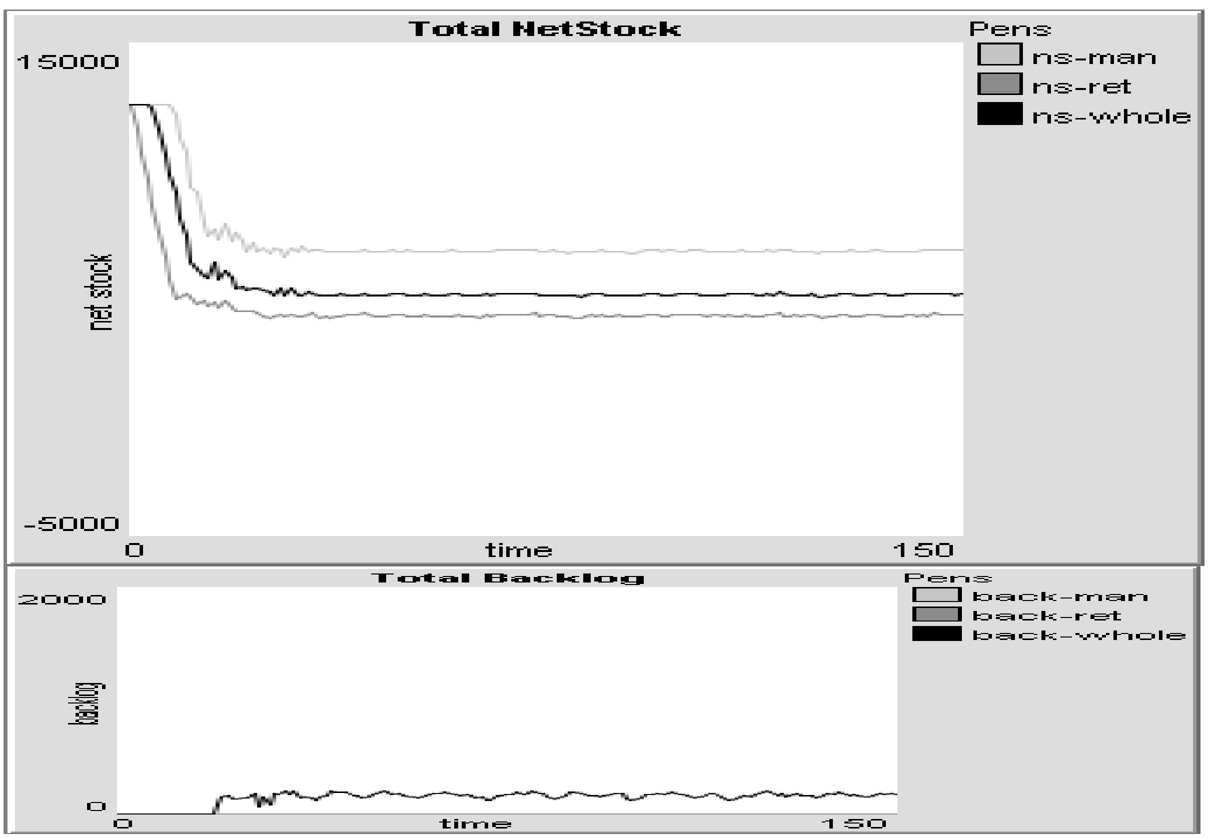

Figure 4.6.6 Supply Chain ABM Model –Parameter Setting 3
(*Loyalty*)

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

(Table 4.1) Summary of Experiments with Supply Chain Model		
FACTOR	**SD&ABM COMPARISON**	**SUPPLY CHAIN DYNAMICS**
Consideration of Inventory Positions in Supplier Selection	It can not be defined in SD model, thus SD can not capture the dynamics.	Agents act in a more 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 a more 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. Cyclic pattern in SD, more blurred pattern in ABM.	Agents act in a more 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. Differences exist in model behaviors.	Agents act in a more 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.	Decreases oscillations in inventory levels in a price-driven market environment.
Effect of Safety Stock	--------	Choosing appropriate SS values prevents backlogs.
Fixed Order Up vs. Reorder Point Up	----------	Fixed Order Up decreases oscillations, but increases ordering cost.

5. Conclusions

In this research, the aim was to investigate the capabilities of macro and micro level modeling approaches on multi-agent systems. An analysis on the capability of these System Dynamics and Agent-Based modeling approaches is made based on a supply chain model. Effects of several factors including inventory positions, price mechanisms, shadow orders, loyalty and ordering policies are analyzed and general implications are made regarding the comparison of System Dynamics and Agent-Based modeling methodologies. And also the dynamics in the supply chain systems are analyzed using the models.

Based on the analysis of the supply chain system, it is concluded that there are cases where System Dynamics can not define the modifications in the ABM model even at an aggregate level. These are the situations where there is a change in the interaction patterns of agents; in the sense that one agent selects another to interact with based on some decision criterion. But the quantitative nature of the relation is preserved, not affected from this decision criterion. An example of this form is the selection of supplier according to the price -its supplier is selected by looking at the price level; but the order amount it will request from the supplier does not change. System Dynamics can not capture this detail dynamics, because there is no distinction among individual agents in the SD model.

On the other hand there are factors that can be included into SD models. System Dynamics can capture the generated dynamics at an aggregate level, but may miss the heterogeneity among the individual agents related to their increased autonomy. An example of this form of relationship is the following case: an agent selects its supplier by looking at its price level, and then by looking at the supplier's price level determines how much order to give. This can be included into the SD model at an aggregate level, by feedback loop structure. But when the behaviors generated by the two models are analyzed, it is seen that although System Dynamics can capture the general dynamics, it can not capture the dynamics resulting from the heterogeneity among the agents; thus differences occur among the emergent ABM behavior and aggregated SD behavior.

Regarding the supply chain dynamics, it is concluded that as the agents think they are acting more rationally –in terms of price modifications, shadow orders, etc. - the emergent system behavior becomes more destructive for the whole. Loyalty in the supply chain is proposed as an alternative to overcome the destructive effects of "rationality". The ordering policies and safety stock levels are also concluded to be important factors affecting the system behavior.

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