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A SIMULATION MODELING FRAMEWORK FOR SUPPLY CHAIN SYSTEM ANALYSIS

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ABSTRACT

This paper describes a supply chain simulation by using hybrid-models that combine discrete-event models and system dynamics models. The discrete-event models represent operational processes inside of supply chain, and the system dynamics models represent supply chain reactions under management circumstance. The scope is a real supply chain system with a large scale and complicated operational rules. The simulation results clarified supply chain features in a long-term manufacturing management environment.

1 INTRODUCTION

Modern manufacturing enterprises must collaborate with their business partners through their business process operations such as design, manufacture, distribution, and after-sales service. Robust and flexible system mechanisms are required to realize such inter-enterprises collaboration environments.

Supply chain management is one of the hottest topics in production and operational management areas. A supply chain system is a chain of processes from the initial raw materials to the ultimate consumption of the finished product spanning across multiple supplier-customer links (Dugal, Healy, and Tankenton 1994). The primary goal of a supply chain is to provide manufactured products to end-customers. Supply chain planning is, in a sense, restructuring a business system for supply chain members to collaborate with each other by exchanging information.

A supply chain is a network of autonomous and semiautonomous business units collectively responsible for procurement, manufacturing, distribution activities associated with one or more families of products. Individual process in the chain can be affected by technology, marketing, and transportation. Such enterprise environment can also influence system performance of supply chain. Supply chain managers, in both planning phases and operational phases, face various kinds of problems, such as capacity planning, production planning, inventory planning and others (Umeda and Jain 2004). Systematic approaches are needed to support planning and control of such supply chain systems.

Simulation is an effective tool to optimize designs and operations of manufacturing and logistics systems. Especially terminated simulation provides predictions of system's behavior and potential status through "what-if scenario" (Banks 1998) . Thus, simulations have been used as a powerful solution tool for operational management problems, such as capacity planning, resource planning, lead-time planning, supplier selection, and outsourcing planning.

Performances of supply chain systems often depend on its business environments such as marketability, traffic congestions, and other management environments. Meanwhile, the supply chain activities simultaneously have relevance to such business environment. For example, a high serviceability of the chain would enlarge customers' orders. Such increased demands would give higher work-loads to the

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chain than before. Such interactions between the chain and its business are often seen in long-term supply chain management.

This paper proposes a novel simulation-modeling framework that combines discrete-event simulations with system-dynamics simulations. The former represents both operational processes inside of a supply chain, and the later represents management environment outside of a supply chain. Further, the paper also discusses modeling capabilities of the proposed framework for supply chain systems in real world by using several example simulation models.

2 A SIMUALTION-MODELING FRAMEWORK FOR SUPPLY CHAIN SYSTEM ANALYSIS

2.1 Supply chain feature model

Supply chain system is a network of the chain members. There are many kinds of supply chain systems: although, the types of supply chain members are countable. "Feature model" gives definitions of such typical members included in a chain, and business process activities of them. This model provides the following six types of supply chain members.

- Supplier: Supplier provides materials, parts, or products in the chain. Supplier belongs to either "Stock-driven" type or "Schedule-driven" type. Stock-driven supplier observes material stocks of an item in a particular supplier. The observation target is usually a stock of input materials at an immediate downstream supplier. When the stock volume is below the replenishment point, supplier autonomously starts to work to replenish the target part / product inventories. While, Schedule-driven Supplier receives production orders from Planner, which generates a Master Production Schedule (MPS). It executes the order, when it receives production orders from the Planner.
- Source: Source starts the material-flows in the chain. Parts and material suppliers are sources, where material-flows start in the chain. This member has the same types as the "Supplier". Activities are similar to "Supplier". Stock-driven type one observes material stocks of an item in a particular supplier. The observation target is usually a stock of input materials at an immediate downstream supplier. When the stock volume is below the replenishment point, source autonomously starts to work to replenish the target part / product inventories. While, Schedule-driven one receives material orders from the Planner, which generates a Master Production Schedule (MPS). It executes the procurement orders per the schedule received from the Planner.
- Storage: It only stores materials, parts, or products. It receives materials from other chain members to hold on. Stock-driven one autonomously ships materials to replenish stock inventories at particular suppliers. While, schedule-driven one ships materials when it receives delivery orders from a planner.
- Consumer: Consumer sends purchase orders to the chain, and it acquires products. It also inspects the incoming products for quality and tracking.
- Deliverer: Deliverer receives delivery order from other chain members, and it works according to the delivery order. It transports products, parts, and/or materials between chain members.
- Manager: An organization that controls material-flows and information-flows in the chain. Manager receives orders from Consumers, and sends delivery orders to deliverer. Planner stores the order as a demand-log. It predicts products demand in next phase and generates Master Production Schedule (MPS). This MPS is updated by orders that are given by the Consumer. The functions of this organization include: master scheduling, receiving orders from Consumer, forecasting demands, making commitments on replenishment with stock-driven members and sending orders to chain members. For stock driven stages in the supply chain, the role of the planner is to set the replenishment points and change them as required over time due to changes in market and demand.

2.2 Control models

Supply chain members defined in the feature model are so-called “agents”, which get in actions according to the predefined mechanisms. The model provides two kinds of control mechanisms for each member agent in a chain (Schedule-driven control and Stock-driven control) (Umeda and Lee 2004). Schedule-driven control uses a production schedule, the so-called “Master Production Schedule” (MPS), which the supply chain planner generates. MPS is a schedule on the time when finished-goods should be delivered to consumers. The manager periodically collects demand data from marketing channels in a constant cycle time, and it accumulates them. And, it also transforms the MPS by predicting the future demands.

To generate the MPS, the chain manager should be linked with the data of purchase orders from consumers, the data of availability of materials and major facilities in suppliers, the data of suppliers’ capacities, and parts structure tables, which is so-called “Bills Of Materials” (BOMs). The main function of the chain planner is to give periodic operational orders to schedule-driven members in the chain.

A schedule-driven supplier regularly works with the manager (Figure 1). The activities of manager are summarized as follows:

- It receives purchase orders from consumers.
- It accumulates this purchase data.
- It generates future demand predictions by using the accumulated demand data.
- It updates MPS by using the predicted demand and feedback data from supply chain members.
- It gives orders (sourcing, manufacturing, and shipping) to corresponding chain members.

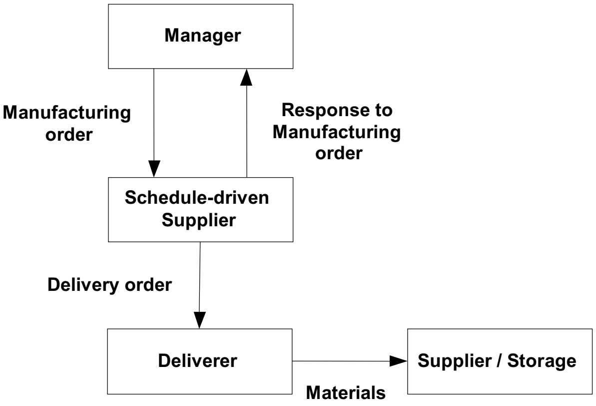

Figure 1: Schedule-driven control

While a schedule-driven supplier works according to the orders sent by the planner, a stock-driven supplier gives orders to itself. “Stock-driven” control method uses stock information of a particular chain member. This member is usually located downstream in the material flow. This member should own two parameters of input material stock volume: stock-replenishment level and stock-volume level.

Manager changes two parameters according to the demand trends. A stock-driven supplier autonomously replenishes material inventories based on these two parameters.

Each “Stock-driven” member continuously observes stock volume at a particular chain member. It starts to produce products when the stock volume is smaller than the stock-replenishment level, and continues to work until the stock volume is equal to or greater than the stock-volume level. Figure 2 is a diagram of the stock-driven supply chain control.

This stock-driven supplier generally works according to the following operational sequences:

1. It periodically observes stock-volume data of a particular chain member.
2. It starts producing when the stock volume goes down below the stock-replenishment level.
3. It stops producing when the stock volume reaches the stock-volume level.

The task of manager is to change dynamically the stock-replenishment level and stock-volume level according to the market demand transition.

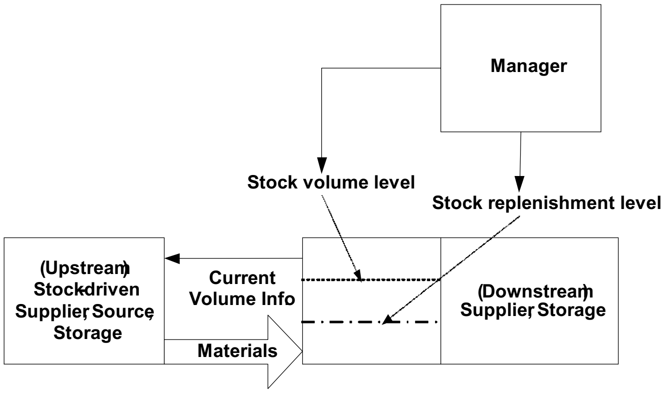

Figure 2: Stock-driven control

2.3 Business environment models

Supply chain activities have relevance to its business environment. Suppose that a supply chain system realizes a high performance and it shortens the consumers' purchase lead-time. In this case, the demand volume in market would increase because of the shortened purchase lead-time; the system would be busier by the increased demands. These activities give favorable or harmful influences to its external world, and their feedbacks can also give similar influences to the supply chain.

Similar scenarios would be applicable to relations between other supply chain systems' activities and their feedbacks. They are, for examples, quality improvement programs in factories, manufacturing process automation programs, and operational improvement in parts/products transportation between suppliers.

System dynamics (SD) has been defined as "A method of analyzing problems in which time is an important factor, and which involve the study of how the system can be defended against, or made to benefit from, the shocks which fall upon it from outside world" (Sterman 2000). There are many SD applications on manufacturing systems, such as relations between demand-supply operations and manufacturing system performance, cause-and–effect relations among equipment maintenance, productivity, manufacturing cost, and others (Riddalls, Bennett, and Tipi 2000).

This approach is useful to capture complex real-world situations, which include delays and feedback mechanisms. Practical applications include understanding market environments and assessing possible future scenarios. Dynamics complexity is not related to number of nodes or actors concerned, but the behavior they create when acting together.

One of the advantages of SD is to describe complex systems including uncertainty and cause-and-effect relations in a system. The SD models represent interdependency in a system by using elements, such as "Stock", "Flow", and the relative variables. SD evaluates both systems' effect on a particular element and its feedback effects on the system in itself.

We tried to implement a model that describes product supply capability, market demands, and their mutual feedback mechanisms. Figure 3 illustrates a conceptual mechanism that the consumers in market react to supply chain performance and it gives feedbacks to the chain as order volumes. This figure represents a cause-and-effect mechanism between supply chain performance and market order volumes using system dynamics notations.

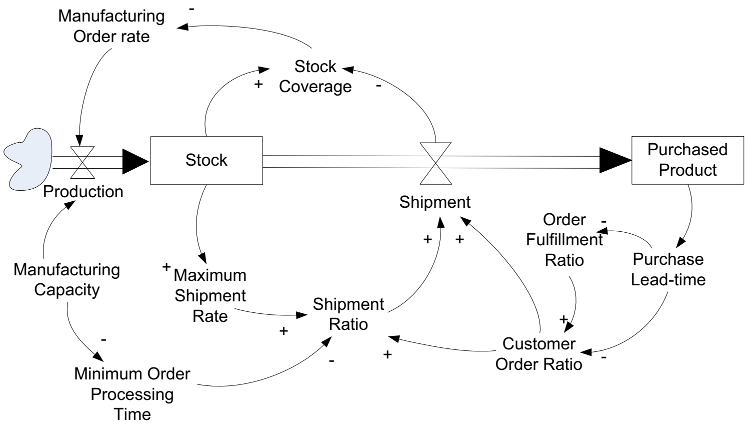

Figure 3: Cause and effect relations using System dynamics modeling

2.4 A generic hybrid modeling framework

Based on the above discussions, this paper proposes a generic hybrid-modeling framework for supply chain simulation. Figure 4 represents a conceptual chart of this modeling framework. Rectangles represent supply chain members' model, which is discrete-event-based, and rounded rectangles represent dynamics of supply chain management environment.

Supply chain feature model represents abstracted supply chain members. The manager get purchase orders from consumers, and it gives orders to suppliers and transporters.

Market dynamics model represents reaction mechanism of consumers to supply chain system performance. If serviceability of supply chain would be measurable in market, the consumers' satisfactions to its serviceability would influence their future purchase preference. Plant dynamics model represents influences of process performance improvement in supplier's plants on the system performance. And further, traffic dynamics model represents changes in outside transportation systems

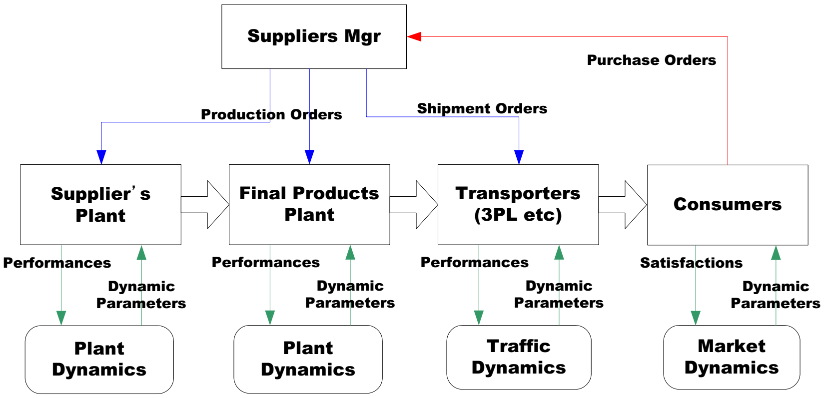

Figure 4: A hybrid-modeling framework for supply chain simulation

2.5 Implementation of models

Implementation of the simulation models requires definitions of the description "levels" of activities. We defined five levels for the supply chain business processes.

1. **Level IV: Feature-Elements Model** This level defines members in a chain. These are "Supplier", "Source", "Storage", "Deliverer", "Consumer", and "Planner". Among them, "Supplier",

"Source", and "Storage" have two operational types: Schedule-driven and Stock-driven, whose roles are previously described.

2. **Level III: Function-Element Model**: This level defines business process functions in chain members. The examples of these are "purchasing", "procurement", "delivery", "manufacturing", and "planning".
3. **Level II: Implementation Model**: This level provides a neutral discrete-event simulation language. The models in this level are descriptions of activities elements by using these neutral modeling notations. The examples of these elements are "generate entities", "set attributes", "get attributes", "queuing", "activity", "set global variables", "get global variables", "generate entities", "erase entities", and others. A description example of this level is shown in Figure 5.
4. **Level I: Execution Modules**: This level transfer neutral discrete-event language into simulation program source codes. Many of these codes are general discrete-event simulation languages, such as SIMAN, GPSS, Extend, or general programming languages, such as C, C++, Java.

```
(1) Enter (Order_Entity_From_Planner)
(2) Get_Attribute (Manufacturing_order_volume, Order_Entity_From_Planner)
(3) Get_Attribute (Scheduled_manufacturing_time, Order_Entity_From_Planner)
(4) If (Manufacturing_order_volume > Maximum_manufacturing_volume) then
      Unbatch_Entity(Order_Entity_From_Planner, Order_Entities)
      else do nothing;
(5) For each (Order_Entities) do
(6) Set_Attribute (Manufacturing_volume)
(7) Call Calculate_Manufacturing_Leadtime(Manufacturing_volume, Maximum_
    manufacturing_volume, Manufacturing_lead_time, Manufactur-
    ing_Output_volume)
(8) Set_Attribute (Manufacturing_lead_time, Manufacturing_volume)
(9) Enter_Queue
(10) Wait_Until (Input_Material_Volume < Input_Buffer_volume)
(11) Enter (Material_Entity_From_Upstream)
(12) Call Calculate_Input_Material_Volume (Input_Material_Volume)
(13) Delay_Entity (Manufacturing_lead_time)
(14) Call Calculate_Output_Material_Volume (Output_Material_Volume)
(15) End_do
(16) Exit_Entity (to 3PL_deliverer)
```

Figure 5: An example description of "manufacturing" at LEVEL III by using LEVELII models

3 PERFORMANCE EVALUATIONS OF A SUPPLY CHAIN SYSTEM

3.1 Target system and parameters,

This supply chain system originally possesses more than ten first-tier suppliers. Several of them own subordinate second-tier suppliers. The scale of the whole system is very large. It includes eight parts suppliers and a final product plant. The distinctive features of them are described as the following items.

- This supply chain system belongs to a schedule-driven type. The planner builds a master schedule based on a demand prediction mechanism.
- The final product is manufactured in a product factory that possesses an assembly line.
- The final product plant works according to daily production orders from the planner.

- The final product plant controls the manufacturing line so that a variance of daily- going-rate is limited to a small range.
- Majority of first-tier and second-tier suppliers work according to a periodic ordering method. The period is almost a week and the order volume is variable.
- The particular first-tier suppliers work according to the daily-based manufacturing orders as well as the final product plant.
- A particular second-tier supplier owns a long order lead-time.
- A particular first-tier supplier works according to stock-driven operations.
- Third party logistics companies deliver between suppliers; Accordingly every delivery time is a constant regardless of volumes.

There is a variance of every order from consumers; however, the demand trend does not change in the long term. A configuration of the target system is shown in Figure 6.

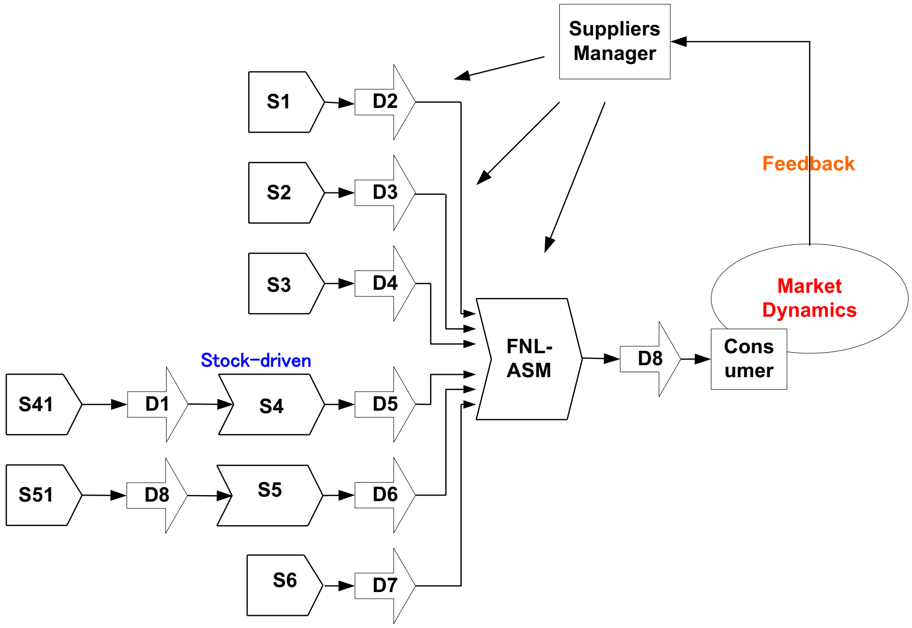

Figure 6: A configuration of the target supply chain system

Supplier S4 is the only supplier that is controlled by "Stock-driven" method. The planner decides both stock replenishment level and stock volume level. S4 autonomously provides parts to the final assembly parts by using these stock volume information.

The outlines of activities and controls of every chain member (agent) are based on the description in the previous section. Every chain member owns its processing capacity. When it receives an order that is over its capacity, the overflowed one is transferred to the next one.

The feedback mechanism works by using a monitoring data of supply chain performance in an observation phase and decisions mechanism for demand volume in the next phase. The outline of this mechanism is as follows.

Purchase orders from market occur every day. When products are moved to consumers, system observes order lead-time in all of these orders. At that time, the system also calculates its moving average and variance. When the moving average and its variance is large, system restrains purchase order volume in next term. System then uses smaller random variables on orders' generation. Meanwhile, when the moving average and its variance is small, system releases purchase order volume in next term. System then uses larger random variables on orders' generation.

System uses a system-dynamics model at that time. In this model, the mainstream data flow starts "source" (data generation), and go through "flow" (data modification that make a decision of demand volume), and finally reaches "stock" (data store). In these processes, system uses the past observation data and their variance data.

3.2 Implementation of Market-dynamics model

Current version does not provide regular forms for dynamics model. This is because relationships among variables depend on model's configurations. Accordingly, there is no generic system-dynamics modeling libraries described in section 2.5. The implementation method is as follows.

A system-dynamics model forms a flow from a beginning point "Source" to an ending point "Sink", by way of "Stocks" and "Valves." This flow includes processes of reading/writing data that are relative to "variables." Implementation of this logic uses "Element" models in discrete systems as follows.

1. It generates a open network by replacing both "Source" in system-dynamics model with "Generate" in discrete-event model and "Valve" in system dynamics model with "Delay" in discrete-event model. It replaces variables in system-dynamics model with "Global-variables" in discrete-event model, and it rewrites calculation logics of variables to "Call" sentences in discrete-event model.
2. The "Delay" node spends a small time ⊿t with all entity.
3. Every process reads, calculates, and replaces value of "Global variables"

3.3 System performance evaluations by sensitivity analysis

We do not have any information on distribution functions of market demands. First of all, we examined two patterns of demand distribution: Normal distribution and Uniform distribution. The difference of these does not give any influences on performance of the supply chain system. System performance is measured by parts inventory volumes at supplier S4 and S5, parts inventory volumes at the final assembly plant, and order lead-time of consumers.

When the demand mean is set on low level, the difference of its variances does not give any influences on system performances. Meanwhile, when the demand mean is set on middle and high level, keeping demand variance at low level, differences in performance are observed (see Figures 7, 8, and 9).

The transitions of order lead-time are shown in Figures 10, 11, and 12. When demand mean is in high level, lead-time transition raises up immediately after the simulation starts, and it stays in high level through the simulation. This phenomenon explains that the delay of orders has passed into a chronic state. Transitions of parts volume at final assembly plant are shown in Figures 7, 8, and 9. The part volumes stocked there are proportional to the average of demand distribution that is given as the parameters.

3.4 A long-term simulation considering business environment

Supply chain activities have relevance to its business environment. We consider here this issue according to the scenario discussed in 2.4. The principal cause is the observed purchase lead-time in every purchase activity.

Short purchase lead-time gives favorable impression to customers, and the order volume increases. Accordingly, the chain system becomes busy; order processing at every task in the chain becomes tight. While, long purchase lead-time gives unfavorable impression to customers, and the order volume decreases. Accordingly, the chain system becomes calm; order processing at every task in the chain becomes loose.

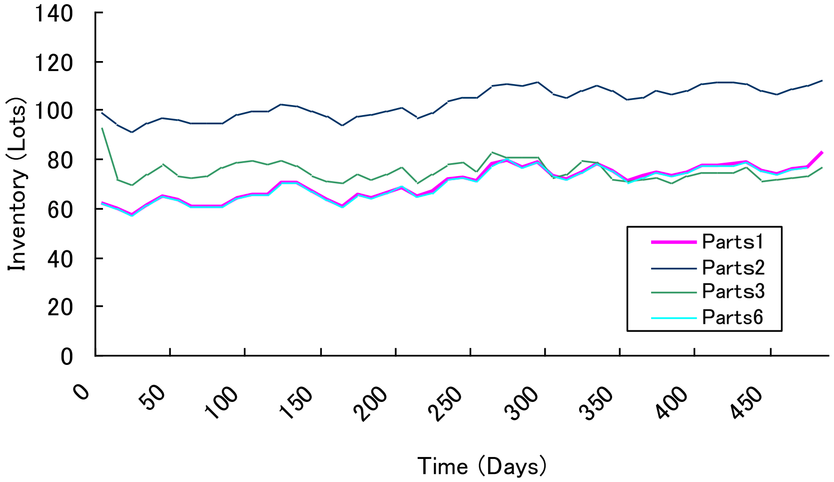

Figure 7: Transition of the parts volumes at final assembly plant (Demand distribution = N(40,6^2))

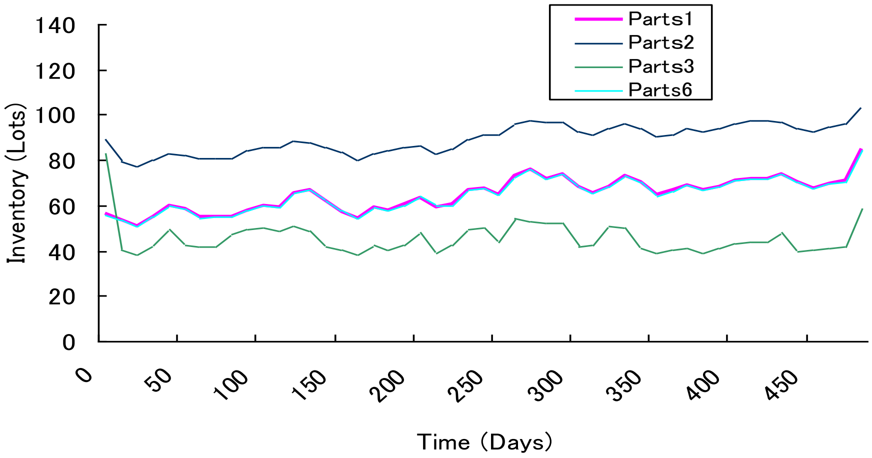

Figure 8: Transition of the parts volumes at final assembly plant (Demand distribution = N(60,6^2))

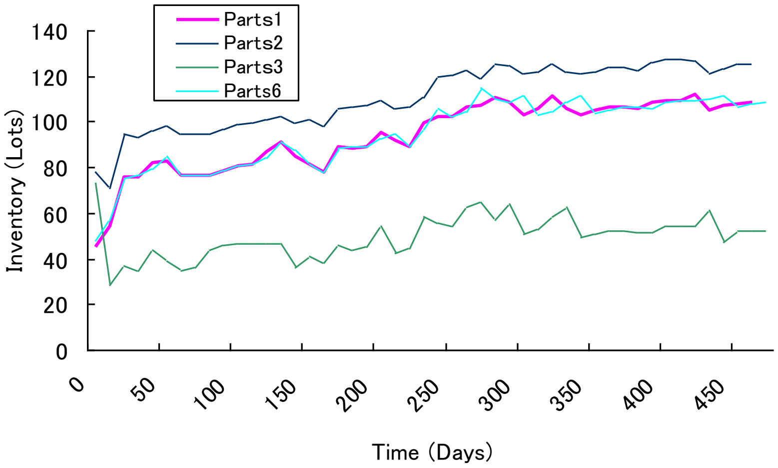

Figure 9: Transition of the parts volumes at final assembly plant (Demand distribution = N(80,6^2))

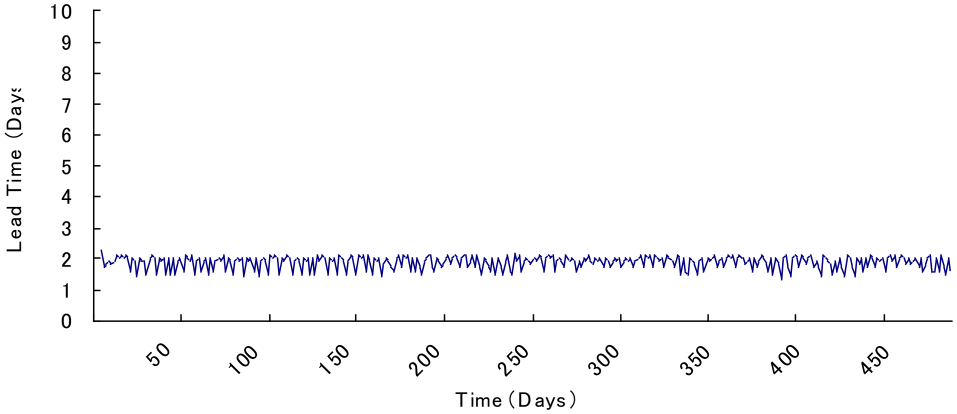

Figure 10: Transition of the purchase lead-time (Demand distribution = N(40,6^2))

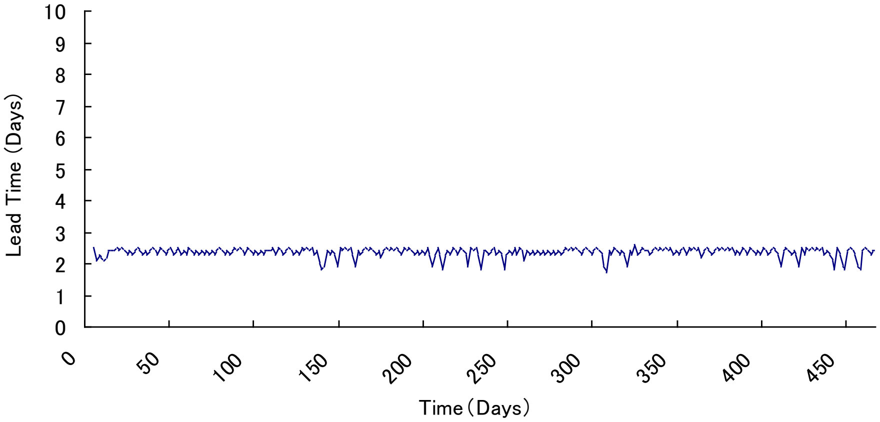

Figure 11: Transition of the purchase lead-time (Demand distribution = N(60,6^2))

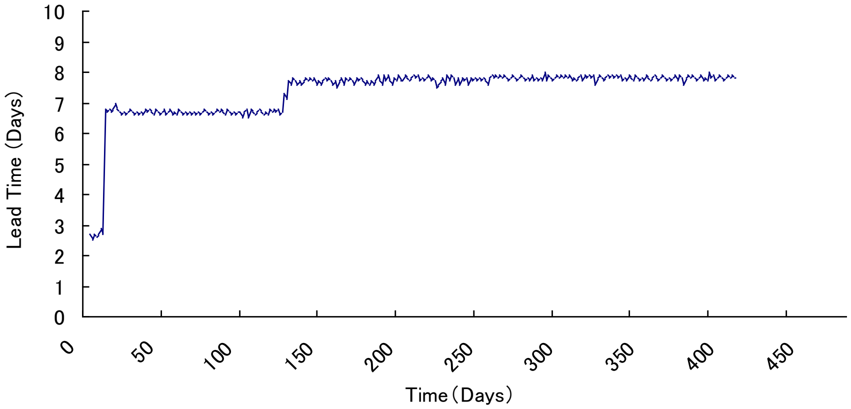

Figure 12: Transition of the purchase lead-time (Demand distribution = N(80,6))

Figure 13 represents the transition curves of purchase order volume by customers and demand prediction by a planner. The value draws a cyclical curve in initial duration of simulation, and it becomes stable later. This phenomenon is based on the fact that a chronic order delay occurs. The curve of purchase lead-time also shows the same patterns as this transition. And further, there is no case that parts experience shortage. This is the reason why the purchase order volume becomes stable.

Rising serviceability increases demands in market. When this increase of demands rapidly occurred, a large quantity of jobs produces delays in process.

This delay decreases serviceability, and it accordingly prevents demands from increasing in market. Consequently, the serviceability does not increase immediately, even if orders continue to decrease. Therefore, the demand does not recover again. After that, as the system holds accumulated delay jobs, so it gives no influence on fluctuation of serviceability and demands volumes.

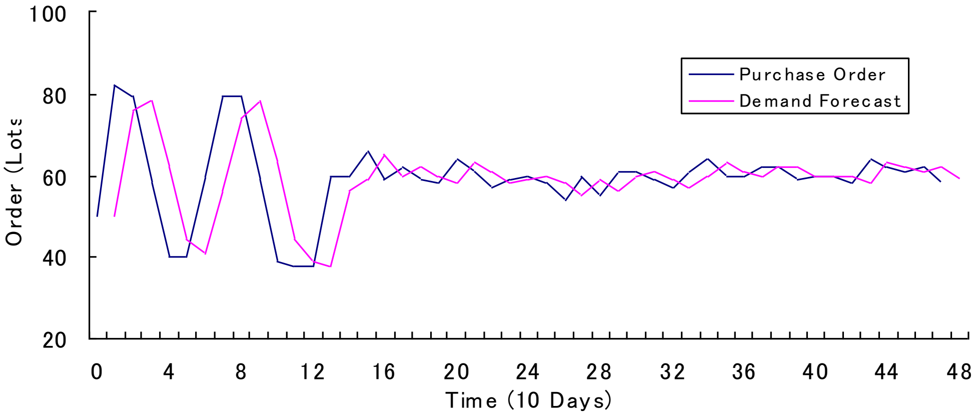

Figure 13: Transitions of purchase order volume by customers

4 CONCLUSIONS AND FUTURE RESEARCH

The developed prototype is based on a configuration of an actual manufacturing supply chain system. This supply chain system poses a prime contractor with a chain manager, six first-tier suppliers and two second-tier suppliers. The transportations between suppliers are managed by 3rd–Party-Logistics companies. Further, the market system dynamics model represents consumers' decisions and behaviors such as recession and upturn.

The scale of this simulation is complex and very large. Accordingly, it includes lots of simulation parameters. We applied "Taguchi method" to simulation experiment design to analyze system performances. This method uses orthogonal arrays to assign simulation parameters; accordingly, the numbers of experiments are reduced to its optimal size.

The developed simulation models are basically applicable to various types of discrete manufacturing supply chain. Several case studies will be shown as potential scenarios. These will display both supply chain operations and behaviors in external world of the chain. Similar scenarios would be appropriate to other supply chain systems' activities such as quality improvement programs, manufacturing processes automation programs, and efficient transportations operational programs. The proposed approach will be the first step to a simulation & gaming methodology to support supply chain operations.

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