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THESIS

A SYSTEM DYNAMICS BASED
MULTI USER NETWORK GAME

by

Hunkar TOYOGLU

June 1999

Thesis Co-Advisors:	Shu S. Liao Keebom Kang

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The purpose of this decision support tool is to provide hypothetical business scenarios in which players—managers—can practice decision-making processes in their companies. The simulation game, built in this thesis, can support planning, decision-making, and policy-setting processes by analyzing the effect of changes in the operations and resources that impact inventory level and cost and by providing a means to test and present the proposed policies under different scenarios.

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A SYSTEM DYNAMICS BASED MULTI USER NETWORK GAME

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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We develop a multi-user computer network simulation game model as a decision support tool in a manufacturing and distribution system. The model, written in Powersim® software package, based on system dynamics theories. The game is a "dynamic business environment" in which the outcome is determined by interactions within and between the players in the framework of the industrial system. This game can accommodate simultaneous play by a maximum of seven players. Management's job in the game is to employ its company's resources and to manage its operations in such a way as to minimize the inventory fluctuations and costs.

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DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at risk of the user.

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I INTRODUCTION

A. BACKGROUND

The goal of this thesis is to equip the factories, distributors, and the retailers in a manufacturing-distribution system with a desktop, system dynamics simulation based decision support tool to integrate and rationalize the functional areas of management, and to improve the design of their companies and systems. The simulation model is intended to serve as an online interactive decision-making environment for inventory management at each level in the system.

The decision support tool will be a system dynamics simulation game, which models a manufacturing-distribution industrial system, that may be run in a network environment, involving up to seven competing players or group of players. The game will be a continuous simulation model, which runs concurrently on several computers. At fixed points in time, the simulators pause, and the players are allowed to make decisions.

The vision is to provide the manufacturing-distribution system with a mechanism; (1) to give the managers of the system a better understanding of the organizational and industrial system they work in, and (2) to add value to their companies with improved decision support "if-then" analysis, and scenario planning "what-if" analysis.

The decision support tool will act as "a business laboratory," allowing managers to interact with business scenarios in a safe environment, experiment with ideas and ultimately learn to make strategic decisions that improve their businesses. For instance, a manager can experiment with critical company and industry factors such as prices, company strategies or policies and other items in his organizational environment. This improves his awareness, judgement and intuition. The idea is to offer frequent, flexible, and optimal response to either regular business functions or contingencies.

Jay Forrester is the prime developer of the ideas now known as system dynamics and these were first published in a book called *Industrial Dynamics* [Ref. 1]. System dynamics represents elements in the real world, such as inventory or customer base, as variables of a computer model, and focus attention on how they influence each other and change over time.

Kenward reported that system dynamics simulation employs modern computer techniques to reduce complex business processes to a handful of simple features that managers can understand. Because of this high dependency on computers, while Forrester's work dates back to the 1960's, system dynamics only began to catch on in the 1990s, due to the falling cost of computing power. This, and the availability of relatively simple software make it possible to bring system dynamics to the companies' desktops. [Ref. 15] Forrester concluded as follows,

> Computing machines are now so widely available, and the cost of computation and machine programming is so low relative to other costs, that the former difficulties in activating a simulation model need no longer determine our rate of progress in understanding system dynamics. [Ref. 1:pp. 19]

B. OBJECTIVE

The purpose of this thesis is to formulate a simulation model of "Manufacturing and Distribution" industrial dynamics model[1] by using the software Powersim®[2] and to

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1 Originally developed by Professor Forrester in the 1960s.

determine how an industrial system as a whole behaves in different business environments under uncertainty.

Since system dynamics methodology has been invented, some public and private sectors have applied this methodology to a wide variety of problems to gain insights about the complex issues and to make their systems more effective and efficient. Despite the acceptance of the system dynamics methodology, it is not well known in the business environment. When Professor Forrester first published *Industrial Dynamics*, he used DYNAMO®, which was a computer programming language. With this software it was not practical to build wide-scale simulation models. In addition, even for a normal size of problem, a manager had to hire a team of highly trained individuals for simulation formulation and its maintenance.

However, today, there are many system dynamics software packages that are easy to use and learn. In addition, with the help of a high quality user interface any manager can run the simulation model, try different decision scenarios and understand the resultant behaviors.

This thesis is an attempt to give a particular group of managers[3] a tool to understand the complex manufacturing-distribution systems they are controlling. The tool will be a multi-user simulation game, which models the factory, the distributors, and the retailers in a manufacturing-distribution industrial system. The game will run in a

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2 Powersim® is a trademark of Powersim Corporation.

3 Managers of manufacturing-distribution systems.

network environment and up to seven players may participate in the simulation game at the same time.

A manager can gain important insights and learn the dynamics of the business situation, by using this decision support tool and by trying different combination of decisions in different kinds of scenarios. In addition, such a tool is a safe environment for managers to make tough decisions under uncertainty. In this environment they can find and try new ways of looking at and solving complex problems, gaining valuable experience in decision-making. Thus, with such a tool, a manager can acquire the necessary experience and a system-wide view of the effect of "local" changes to the whole system without "field" work.

C. METHODOLOGY

The methodology is to develop a simulation model as a tool for decision-making under uncertainty. The decision support tool in this thesis is a simulation model that can be used to investigate the intimate relationship that exists between the structure and the behavior of the dynamic system.

The simulation of the dynamic manufacturing-distribution system is accomplished with the commercial computer software package Powersim®. The manufacturing-distribution model used in this thesis is based upon the industrial model of Forrester that was published in *Industrial Dynamics* in 1961 [Ref. 1]. The original mathematical notation of the model will be changed so that any user (manager) can understand the relationship between the equations (variables) and the real system.

D. RESEARCH QUESTIONS

When considering the determination of how a dynamic manufacturing-distribution system as a whole behaves under uncertainty by constructing a simulation model, the following is a list of primary and secondary research questions that are addressed by this thesis.

Primary:

- Can a simulation model be useful to formulate policies and decisions under uncertainty in an industrial setting such as factory, depot, or logistics supply chain?

Secondary:

- How small changes in retail sales or customer demands can lead to large swings in upstream suppliers such as factory production?
- How does reducing administrative delays in one segment of the supply chain alone fail to improve management decisions significantly?
- How does uncertainty in retail sales influence the factory production and the inventory levels?

E. ORGANIZATION

Chapter II provides background for the main concepts of system dynamics. It defines the fundamental ideas underlying the system dynamics method. Chapter III explains the characteristics and the organizational structure of the dynamic industrial system that is modeled in this thesis. Chapter IV discusses the principles of model formulation. It establishes the mathematical background of equations and describes the nature of the delays that exist in all dynamic systems. Chapter V introduces the network game developed in this thesis. Chapter VI discusses running the simulation model, judging the validity of the model and its output. Chapter VII describes the designed experiment conducted to find the optimum values of the parameters. Chapter VIII presents a case study in which the use and the value of the network game are explained. Conclusions and recommendations are provided in Chapter IX.

II BACKGROUND

A. SYSTEM DYNAMICS

System dynamics was developed in the 1950s at the Massachusetts Institute of Technology, by Professor Jay W. Forrester. It is a computer–based simulation modeling methodology that relates the structure of a system to its behavior over time. The purposes of systems dynamics are (1) to provide managers with a better understanding of the complex systems that they are controlling, (2) explaining the system's behavior in terms of its structure, and (3) suggesting changes to system's structure which will lead to an improvement in the behavior.

System dynamics takes the information about a system's structure and formalize it into a computer model. Then, the model is simulated and the behavior generated by that particular structure is revealed. To better understand the use of system dynamics, consider the following question.

> How can a manager, in a corporation whose only constant is change, cope with daily crises and still make the big decisions that keep the company running? [Ref. 9:p. 16]

Many changes are currently occurring in all parts of enterprises. Corporations compete at high levels of complexity. As Profozich noted, entire business processes are being revised to leverage the explosion in communication and computer technologies. Therefore, managers throughout the enterprises are facing the challenge of predicting the performance of new and changing systems [Ref. 10:p. xi]. In this highly complex business environment, managers need to be able to identify and solve dynamic problems.

All those changing corporations are dynamic systems. Since dynamic systems change constantly and get more complex over time, it becomes more and more difficult to grasp the big picture and understand the system's behavior as well as its structure.

System dynamics methodology fundamentally asserts that all dynamic behavior is a consequence of structure [Ref. 9:p. 17]. More clearly, this concept means that a system's own structure is the cause of its behavior. Structure refers to how the system elements are put together, that is, how they are connected to one another.

The first publication in systems dynamics was the classic book *Industrial Dynamics* [Ref. 1]. It was the first successful systems dynamics modeling and simulation project. Forrester defines industrial dynamics as follows;

> Industrial dynamics is the study of the information-feedback[4] characteristics of industrial activity to show how organizational structure, amplification in policies, and time delays in decisions and actions interact to influence the success of the enterprise. [Ref. 1:p. 13]

In short industrial dynamics deals with the time-varying interactions between the parts of the management system. It integrates different areas of management, such as production, distribution, marketing, and investment.

How does the concept of industrial dynamics methodology apply to industrial and economic systems? Basically, as Forrester noted, first it identifies the problem and isolates the factors that have a relationship with the problem. Second, it constructs a mathematical model of the interactions of the system components and cause-and-effect information feedback loops in the system. Third, it builds a simulation model of the mathematical formulation and observes the behavior of the system through time. Then, it

4 Information-feedback characteristic of system dynamics is discussed in Chapter II.

revises and redesigns the model until it is an acceptable representation of the actual system. Finally, it alters the real system in the directions that simulation model experimentation has shown will lead to improved performance. [Ref. 1:p. 13]

B. SYSTEM DYNAMICS METHODOLOGY

This section provides some general principles that will guide the development of a simulation model of an industrial system. It explains the elements necessary to build a system dynamics model, including the purpose it serves in system dynamics methodology.

1. Feedback loops

Feedback can be defined as the transmission and return of information. When an element of a system indirectly influences itself, the portion of the system involved is called a *feedback loop* or a *casual loop.* In another saying, feedback loops are elements and interconnections structured so that each element acts on the next, over and over around the loop.

Economic and industrial activities (such as the dynamic industrial system in this thesis) are closed loop, information-feedback systems. Any specified behavior is produced by a combination of interacting components that lie within a boundary that defines and encloses the system across which nothing flows. Forrester explains closed feedback systems as,

> In concept a feedback system is a closed system. Its dynamic behavior arises within its internal structure. Any interaction, which is essential to the behavior mode being investigated, must be included inside the system boundary. [Ref. 2:p. 4-2]

Understanding the feedback loops is essential to observe what elements are acting on other elements and whether the interaction is positive or negative. However, feedback loops alone can not determine what the entire system's behavior will be. System dynamics, as Cover noted, places greater emphasis on the concepts of levels (stocks) and flows and how they relate to feedback loops [Ref. 9:p. 26]. A large number of elements—variables, relationships, and continues interactions—can be shown as levels (stock) interconnected by flows that are controlled by decisions.

2. Levels

Levels are the accumulations in the system, such as inventories or goods in transit. They describe the condition of the system at any point in time by accumulating the net difference between inflow and outflow rates. If time suddenly stopped, levels would remain and be observable and measurable. For example, stopping taking of orders or shipping of goods does not terminate the inventory.

Levels do not change instantaneously. They do change, but it takes time. If the inventory in the factory has to be increased 1,000 units, it takes time to produce those additional units. Therefore, there is a delay involved in changing the level of any stock (level).

3. Delays

Delays are inherent in almost every real life system, and in many management processes. It takes time to make or deliver a product. It takes time to make any decision about the manufacturing processes. Such kind of delays that can be encountered in industrial processes must be investigated, and how such delays can be modeled in the mathematical model should be made clear.

Forrester applied the following three simplifications to his "Industrial Dynamics" model in formulating delays: (1) Delays exist in everywhere in the real system. Nevertheless, to formulate every single time delay will create an immense amount of detail, and make the model very difficult to understand. Some of the system delays can be considered to be so short that their effect on the system is negligible. Hence, they are ignored. (2) Delays that are cascaded one after the other are combined into a single delay. (3) Delays that are entering a common flow channel from different channels are combined into a single delay in the common channel. [Ref. 1:p. 86]

Various computational processes might be used to create a delay in a system within a mathematical model. However, Forrester implemented only exponential delays[5] in his model, and noted,

> The exponential delays are simple in form, and they have adequate scope to fit our usual degree of knowledge about the actual systems to be represented. [Ref. 1:p. 87]

4. Flow Rates

Flow is the movement or flow of a variable from one level to another. They create the dynamics in the system when they accumulate in levels, such as shipment of goods. It may seem that feedback loops are causing the changes to occur. However, dynamic behavior can occur without feedback loops. As Cover stated, without flows, stocks would never change, and there would be no dynamic behavior [Ref. 9:p. 28]. Simply, flow rates determine levels in the system; they tell how fast the levels are

[5] For more information about delays see [Ref. 1:p. 86].

changing. In addition, flows depend on the values of levels, never on the values of any other flows. Kirkwood explains the difference between levels and flows as follows:

> Another way to distinguish levels and flows is to ask what would happen if we could freeze time and observe the process. If we would still see a nonzero value for a quantity, then that quantity is a level, but if the quantity could not be measured, then it is a flow. That is, flows only occur over a period of time, and, at any particular instant, nothing moves. [Ref. 5:p. 18]

C. TOOLS TO REPRESENT THE REAL SYSTEM

While it is possible to create an entire model with only stocks and flows, system dynamics have a few more tools to help us capture real-world phenomena in a model.

1. Auxiliaries

The rate equations can become very complex including so many levels and constants in it. Sometimes, it is convenient to divide a rate equation into parts that are written as separate equations to enhance the clarity and meaning of the rate equation. These separate components are called auxiliary variables. Auxiliaries have no standard form. They can be the combinations of levels, flows, constants, and other auxiliaries. They model information flow in the model, so they can change instantaneously.

2. Constants

Constants are those values that are constants throughout the time period of the simulation. For instance, in a one-year simulation a company may have a fixed inventory coverage ratio that can be represented as a constant.

3. Sources and Sinks

Forrester's "Industrial Dynamics" model is a closed-boundary model. However, some variables or flows that lie outside the considerations of the model may control the rates. For instances, orders must come from somewhere into the model, but the source of orders is not an element of the model. In this case orders are thought as coming from an *infinite* source. Likewise, orders must be discarded into a file, after they have been filled. This file has no significant influence on the model.

4. Information Take-off

Material and order flow connections move a quantity from one variable to another and are controlled by rate equations. However, information flow carries information about variables and they do not affect the variable from which the information is taken. Information take-off is not a removal of the content from a variable, but only the transfer of information about the magnitude of the content of the variable.

III THE "MANUFACTURING-DISTRIBUTION" MODEL

This section deals with the characteristics and the structure of a typical manufacturing-distribution system[6] that is simulated in this thesis.

A. OBJECTIVE

Forrester states the objective of the "Industrial Dynamics" model as follows,

> We shall define our immediate objective as an examination of possible fluctuating or unstable behavior arising from the principal organizational relationships and management policies at the factory, distributor, and retailer. [Ref. 1:p. 137]

B. THE CHARACTERISTICS OF THE MODEL

General characteristics that guide the construction of the industrial system model must be made clear before proceeding with the specific details of the model.

1. Closed-Boundary Model

The manufacturing-distribution model is a closed loop, information-feedback system. A closed dynamic model functions without connection to exogenous variables that are generated outside the model. In a closed model the values of the variables are generated internally through time by the interaction of the variables, one on another.

As Forrester stated, closed dynamic models are self-regulated and their internal dynamic interactions are of primary interest.

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6 Originally developed by Forrester [Ref. 1].

> The general concepts of information-feedback systems are essential because such systems exhibit behavior as a whole, which is not evident from examination of the parts separately. The pattern of system interconnection, the amplification caused by decisions and policy, the delays in actions, and the distortion in information flows combine to determine stability and growth. [Ref. 1:p. 61]

2. Time Relationships

In a dynamic system time delays arise in every stage—in decisions, in transportation, and in inventories. Without time delays dynamic systems would not exhibit the characteristics of the real life. To permit time delays, points of accumulations (levels) are introduced in the model. Therefore, the incoming rate of goods or orders need not match exactly the outgoing rate. The fluctuating rate of levels makes up the difference in flow rates.

3. Amplification

Forrester defines amplification as a response from some part of a system, which is greater, than would at first seem to be justified by the causes of that response [Ref. 1:p. 62]. For example, it is expected that fluctuations in factory production rate greatly exceed the magnitude of retail sales rate changes.

4. Model and Real-System Variables

The model variables correspond to those in the real-system being represented. They are measured in the same units as the real variables, such as; materials are measured in physical units, logical relationships among the model variables are the same as those among the real variables. For example, more orders coming from customers lead to shortages of goods that increase factory production.

C. DECISION MAKING PROCESS

McMillan states that management is the process of converting information into action and the conversion process is what we define as decision-making [Ref. 4:p. 265]. Kirkwood also notes that decision-making processes are the glue that binds together the information and material flow networks in an organization [Ref. 5:p. 83]. In the model, decisions determine how to use information and what actions to take on material flows. To clarify this concept, the decision process modeled in the manufacturing-distribution system should be examined. In the model decisions fundamentally involve three variables as shown in Figure 3.1.

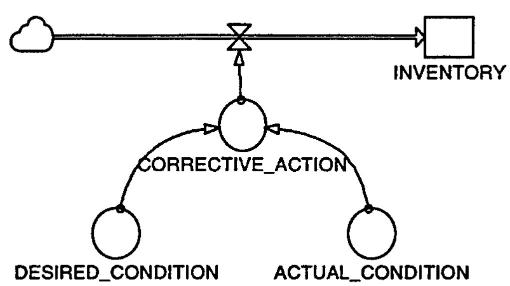

Figure 3.1 Decision making process

Desired states are what we like to have the condition of the system. *Actual conditions* are the present state of the system. *Actions* will be taken in accordance with any discrepancy, which can be detected, between the actual and the desired conditions of the system. In other words, when there is a discrepancy between the actual and the desired conditions, corrective action is to be taken to move the actual level closer to the desired level.

A very important characteristics of the decision making process is the directional relationship between the variables. Levels are the only inputs to decisions in the model. Forrester explains this characteristics as follows;

> The levels are the inputs to the flow of decisions. Decisions control flow rates between the levels. The flow rates between levels cause changes in the levels. But flow rates themselves are not inputs to the decisions. Instantaneous present rates of flow are in general unmeasurable and unknown and can not affect present instantaneous decision-making. [Ref. 1:p. 95]

D. STRUCTURE

To explicitly model the industrial system structure, within which the decision-making process exists, Forrester specifies the existence of six interconnected networks, which constitute the structure of the basic model. In four of the networks *(the material, money, personnel,* and *capital equipment* networks) resources flow. The fifth network is the *orders* network and the sixth one is the *information* network. The networks are distinguished one from the other by the kind of material or resource contained.

In the manufacturing-distribution model in this thesis only the materials network (flows from the factory to the consumer), orders network (flows from the consumer to the factory), and information networks are modeled.

The materials network includes flows and levels of physical goods in all stages of processing, including raw materials, in-process inventories, or finished products. Orders network includes orders for goods from consumers, retailers, and distributors. Information network serves to link the other two networks and is an integrating network. It transfers level information to decision points, and rate information in the other networks to the levels in the information network. Forrester gives the following example;

information about the actual, current rate of incoming orders is averaged to produce the level of average incoming-order rate. This is a level in the information network and will usually be one of the inputs to an ordering decision in the order network [Ref. 1:p. 71].

1. The Manufacturing-Distribution System

Figure 3.2 [Ref. 1:p. 22] represents the manufacturing-distribution system[7], which is simulated in this thesis. Three networks are modeled in the system, the materials, orders, and information networks. A demand function has been specified in order to generate orders from the consumer. At the factory, the distributors, and the retailers inventories are held and periodically replenished. Delays in processing orders at each level are assumed, as well as delays in the transmission of orders between levels. Material flows are delayed between levels to represent time required for shipment. In the system, inventories are adjusted to replace goods, which are sold, and to keep the level of inventory at the desired level as the level of sales changes. More insight about the system can be obtained by examining the system of equations, which is presented in the Appendix.

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7 For more information about the manufacturing-distribution system see [Ref. 1:p. 137].

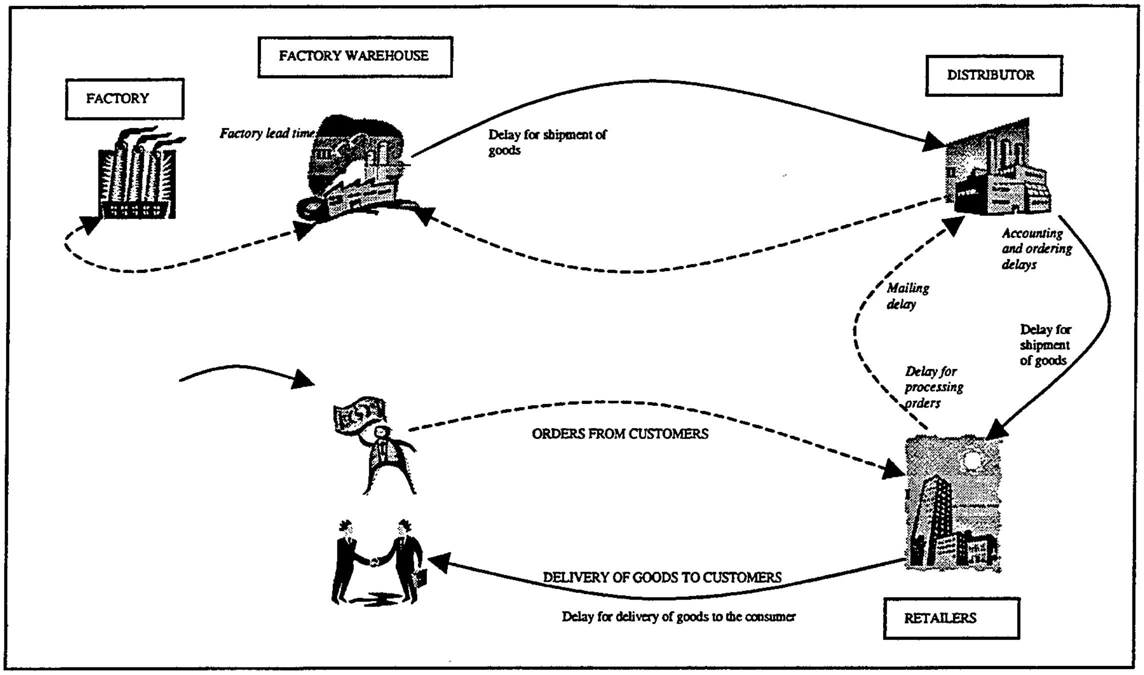

Figure 3.2 Organization of manufacturing-distribution system

IV PRINCIPLES FOR FORMULATING DYNAMIC SYSTEM MODELS

A. THE CHARACTERISTICS OF THE MODEL

Bellinger states that a model is a simplified representation of a system at some particular point in time or space intended to promote understanding of the real system [Ref. 8]. A useful model of a real system should be able to represent the nature of the system. It should help to enhance understanding and to clarify our thinking about the real system. In addition, a model, compared to the real system it represents, should obtain information at lower cost and more quickly.

The purpose of Forrester's "Industrial Dynamics" model that is being simulated in this thesis is to represent a manufacturing-distribution industrial system in such a way that the interactions among elements of the system can be meaningfully studied and understood and new policies and parameters can be tested before their use in actual operations.

Assumptions about Forrester's model must be made before simulating the model. Only after having reasonable characteristics that fit the real industrial system model, the formulation of the model can be introduced.

Models might be classified in many ways. Physical models are replicas of objects under study on a reduced scale. The model[8] is an *abstract* model rather than a physical model since it will be constituted of symbols. It will substitute in our thinking for the real industrial system that is being represented.

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8 Hereafter "the model" refers to Forrester's "Industrial Dynamics" model.

The model is a *mathematical* model. A mathematical model has greater clarity, more explicit logical structure, and can be manipulated more easily than most verbal models. In addition, mathematical models make controlled experiments possible, such that the effects of changing one variable can be observed while holding all other variables unchanged.

The model is a *dynamic* model since it represents situations that change in time.

Linear models fail to represent real industrial and economic systems even if they are much simpler than nonlinear models in obtaining explicit mathematical solutions. The model is a *nonlinear* model since nonlinear phenomena are the causes of much of the system behavior that will be seen later in this thesis.

Stable systems tend to return to their initial conditions after being disturbed—like a pendulum. The model is an *unstable* model since it starts at rest and an initial disturbance is amplified leading to growth or to oscillations whose amplitude increase. In this model small disturbances may grow in an unstable manner until restrained by nonlinearities—like production capacity or inventory capacity.

A model can be transient if the characteristics of the system changes over time—like a system that exhibits growth. However, growth is not included in the model. Therefore, the model will be a *steady-state* model, which is repetitive with time and in which the behavior in one time period is of the same nature as any other period.

B. FORMULATION OF THE VARIABLES

Roberts states that, equations permit expressing model relationships in explicit quantitative terms that can be simulated by the computer [Ref. 6:p. 23]. To continue to explain the construction of the mathematical formulation of Forrester's model we need a suitable system of equations that can state precisely what each element in the model does. The system of equations should be able (1) to describe any statement of *cause-effect* relationships, (2) to handle *continuous* interactions among variables, and (3) to generate *discontinuous* changes in decisions. Fundamentally, there are two types of equations in the model: level equations and rate equations.

1. Computing sequence

The equations in the model control the continuously changing interactions of variables as time advances. To be able to control the dynamic behavior of the system and to yield the successive changing states of the system they need to be computed periodically at successive time steps. The computation progresses in time-steps that are shown in Figure 4.1 [Ref. 1:p. 74]. The continuous advance of time is broken into small intervals of equal length DT—difference in time, delta time or solution interval—that is used for the length of the time interval between computations.

Figure 4.1 shows the basic idea of time handling. K refers to the current point in time or the point in time in which the current computation applies. J refers to the previous point in time—one time interval ago—, or the time at which the preceding computation was made. L represents the next point in time—one time interval into the future. The most recent time interval is denoted by JK. It has just past, and information about it and earlier times is available to use. The next time interval is denoted by KL and no information about it is available. In principle, no information from a time later than K is available at present time. Only information that is available for use in equations being evaluated at present time K is from the interval JK (previous period) and earlier times.

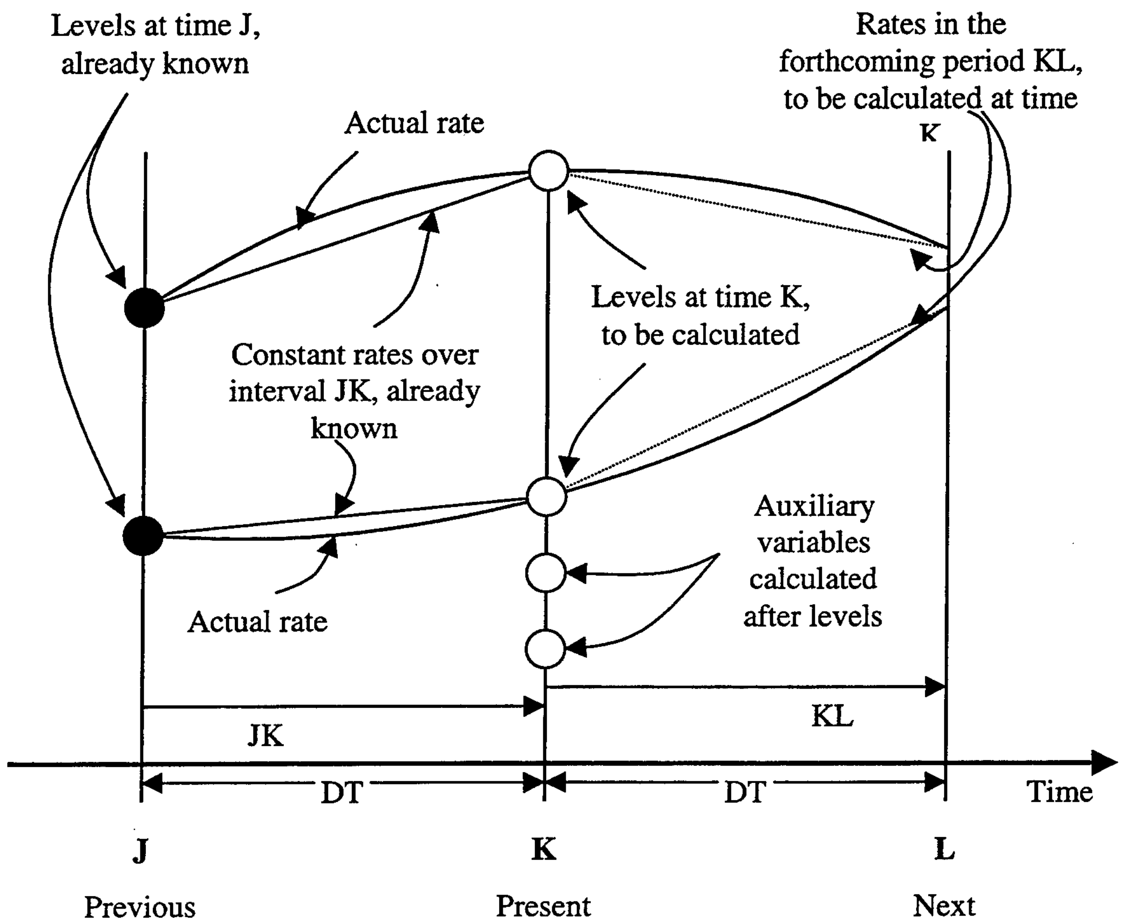

Figure 4.1 Computation sequence

There are two groups of equations: *level* equations and *rate* equations. Level equations describe the system's state at each point in time. Rate equations are based on the state of the system at the current point in time (K), and indicate rates of change that will occur over the next time interval (KL). In the simulation, the simulated time is moved from point to point and computations are made at each point before moving to the next one. The method of handling time and computing in the model is as follows:

1. At time K (now) compute the new values for the levels by using the values of rates for the previous time interval (JK).

2. Compute the values of rates and auxiliaries for the next time interval (KL). These values may depend on the current values of the levels.

3. Move time forward by one DT time interval and repeat the process.

It is clear that levels are computed first for the current point in time and then the rates are computed over the following interval by using the values of the levels. Once they are computed, rates are assumed to be fixed over the time interval DT. Figure 4.1 shows the straight lines that connect the levels at points J, K, and L. These straight lines are the constant rates over the time interval DT.

2. Level Equations

Levels describe the changing contents of the accumulations in the system and show the state of the system at each point in time. The general form of a level is as follows:

LEVEL (Now)=LEVEL (Previous)+DT[INRATE-OUTRATE]*

This equation form indicates that the value of a level, at the current time, is its previous value plus the net change over the time interval, which has passed since the level was last calculated. Net change is the resultant of flows into and out of the level multiplied by the solution interval DT. In short, as Forrester concluded, *what we have equals what we had plus what we received less what we sent away*[9] [Ref. 1:p. 76].

3. Rate Equations

The rate equations are the *decision functions (policy statements)* in the system. They control what is to happen next in the system by defining rates of change in levels that will occur over the next time interval. In other terms, they indicate how the pertinent information is to be converted into a decision (rate).

A rate equation finds the flow rates that will occur over the next time interval. The only information needed to evaluate rate equations is the present values of the levels. The form of a rate equation is as follows:

$$RATE = f\,(LEVEL\ \&\ AUXILIARY\ \&\ COSTANT)$$

The equation above tells that rates during the next time interval are functions of the present values of levels and some constants. As can be seen from the general equation, rates depend only on the present values of levels, auxiliaries, and some constants.

4. Auxiliary Equations

Auxiliary values are computed at the current point in time from levels and other auxiliary values at the present time. Therefore, they must be evaluated after the level equations on which they depend, and before the rate equations of which they are a part.

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9 Notice that the level equations perform the process of *integration.* The level equation above also be written as follows:

$$LEVEL = PREVIOUSLEVEL + \int_0^t (RATEIN - RATEOUT)dt$$

Hence, if auxiliary equations exist at the present time, the sequence of the computation will be; *levels, auxiliaries,* and *rates.* Auxiliary equations take the following form:

AUXILIARY = f(LEVEL & AUXILIARY)

5. Initial-Value Equations

All level equations must be given initial values before the computation of the system of equations begins. These beginning values of the levels are needed to determine the forthcoming flow rates since the initial values of flow rates are not known yet. They are evaluated only once at time zero—before the start of the computation of system of equations. It is possible to make an initial value equal to a constant. It is also possible to state an initial value of one level equation in terms of the initial value of some other level.

C. SYSTEM OF EQUATIONS

The foremost objective of constructing a mathematical model of an industrial dynamic system is to examine the possible fluctuating and unstable behavior arising from the principal organization relationships and management policies at the factory, distributor, and retailer.

There are six interacting flow networks in an industrial system—materials, orders, money, personnel, capital equipment, and information. Forrester's model includes the materials, the orders and the information flow networks. Therefore, during the mathematical formulation of the system the concentration is on the main channel of material flow from the factory to the consumer and on the principal stream of information flow in the form of orders moving from consumer toward factory. In the model, the equations for the three sectors—retailer, distributor, and factory—are formulated. The formulation begins from the retail sector.

Forrester's original mathematical notation is changed so that the symbols can be kept close to the vocabulary of business. In addition, all subscripts that indicate time are removed from the notation so that the required mathematics to understand the formulation is within the reach of every manager who attempts to understand the logic behind the simulation of the manufacturing-distribution model. The system of equations can be seen in the Appendix.

V THE NETWORK GAME

A. OBJECTIVE

The manufacturing-distribution industrial dynamics model, described above, is converted into a network game form by using the principles proposed by Forrester and the Powersim® software package. The network game captures much of the factors in the inventory management situations of the manufacturing-distribution systems. It forces the participants to deal simultaneously with all the complex problems in such situations—manufacturing, distribution, order processing, inventory handling, etc. As Jackson points out, practice in dealing with these problems does not guarantee that the participants will become expert managers. However, they certainly will develop insight and appreciation for the importance of considering the overall company situation when making what may have previously seemed to them to have been largely isolated decisions regarding manufacturing or distributing or inventory handling, etc. [Ref. 22:p. v]

B. OVERVIEW OF THE GAME

The network game examines the fluctuating and unstable behavior of the inventory level arising from the organizational relationships and management policies at the factory, the distributors and the retailers. The concentration is on the main channel of the material flow from factory to the consumer and on the order flow from consumer toward factory. The following features are incorporated into the game:

- Decisions of the players are entered by using mouse and stored in decision files separately, one for each player.

- Each player manages its company by making the following weekly decisions: Inventory coverage ratio, inventory adjustment time, order processing time, order mailing time, inventory handling time, delivery time, time to handle out-of-stock situations.

- The length of the game is made equal to one year.

- The players are provided with the dynamic graphs showing temporal changes in the variable values during the simulation.

C. TECHNICAL BACKGROUND

The network game is a group simulation and requires a network of seven personal computers (PCs) connected to a central server. The server is used to store common files. All PCs must have access to the same network drive on the server. Up to seven players may participate in the simulation at the same time.

The game is an asymmetric game in which all players play different roles. Each player runs his own version of the simulation model. The needed data are transferred to ensure each simulator produces the same result as on the other computers in the game. Since all players use the same simulation model, the structure and the initial state of the game is the same for all players.

The decisions players make are the external factors influencing the model. At fixed points in time (every week), the simulators pause, and the players are allowed to make decisions. When all players have made their decisions every week, the simulators automatically start running until the time for the next decision, namely next week. Decisions may come from two different sources during the simulation: the player, and the simulation model. If fewer players participate than the maximum number allowed the simulation model provides dummy decisions for nonparticipating players.

There is a local simulation model and a player file for each player on the PCs. There is a game file on the server, which defines the mode in which the game can be played. Finally, there is a text file for each player on the server to store the decisions of each player.

D. THE GAME

The procedures for using the simulation model can best be understood by illustrating a player (Retailer1) who participates the game currently. When the simulation model is opened by the player on a PC, "Select game to be played " dialog box will be opened, as seen in Figure 5.1. The player is asked to select from the list of game setups previously defined. Game setups can be seen in Table 5.1.

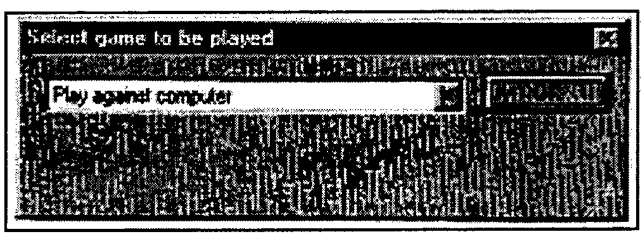

Figure 5.1 "Select game to be played" dialog box

When playing a game, each player is running a separate copy of the simulation model defining the game. Therefore, the player sees his own version of game interface. Figure 5.2 shows the game interface of the player at the beginning of the game, after selecting a game setup from "Select game to be played" dialog box.

Game setup no	Game setup name
1	Three Retailers-Three Distributors-Factory
2	Two Retailers-Two Distributors-Factory
3	One Retailer-One Distributor-Factory
4	One Retailer-Two Distributors-Factory
5	One Retailer-Three Distributors-Factory
6	Two Retailers-One Distributor-Factory
7	Two Retailers-Three Distributors-Factory

Table 5.1 Game setups

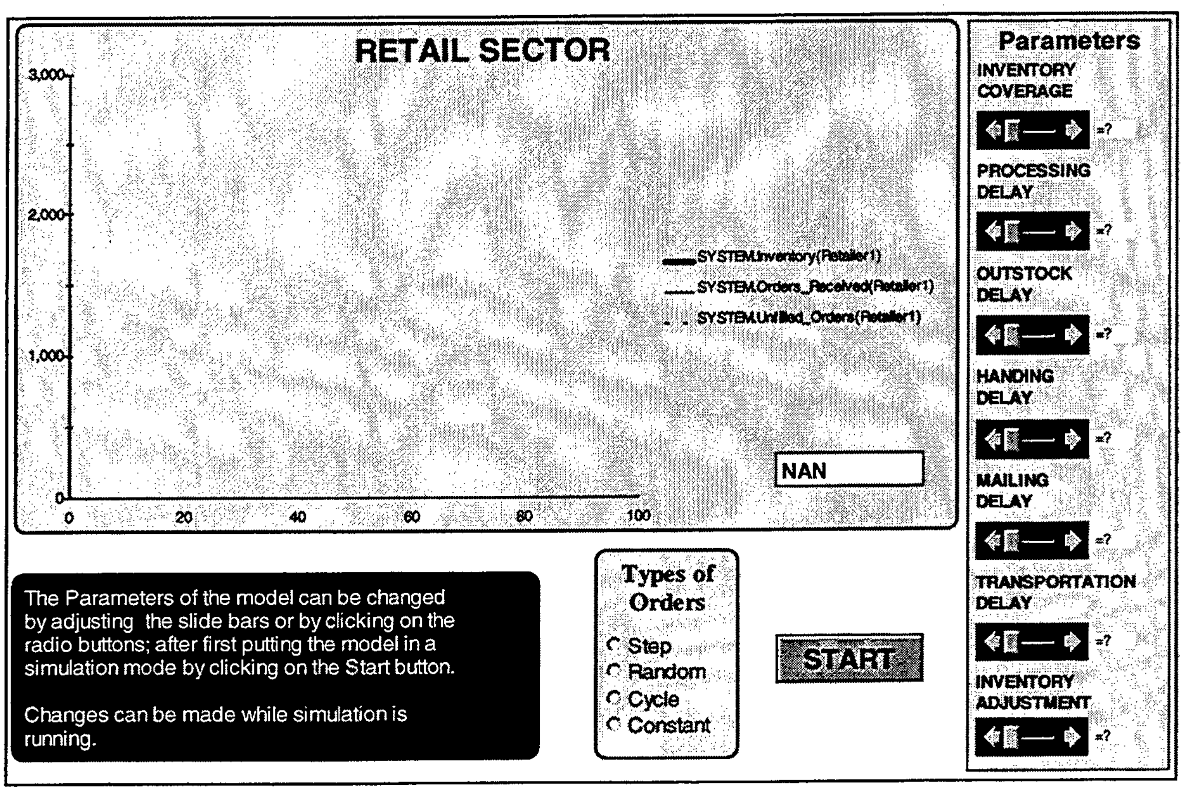

Figure 5.2 Game interface of Retailer1

There are three main sections in this game interface. The graph shows the current level of inventory level, orders received from customers, and the level of unfilled orders. The "Parameters" section shows the parameters in the model, whose values can be adjusted by the player during the simulation. "Types of Orders" section shows alternative customer order rates which can be changed by the player during the simulation. Constant rate is 1,000 units per week. Random rate is a uniformly distributed random order rate between 900 and 1,100 units per week. Cycle rate shows seasonality. In the 13th week the order rate reaches to a maximum of 1,100 units per week and in the 39th week it drops to a minimum of 900 units per week. Step rate is a 10% increase in order rate immediately after the beginning of the simulation.

The player can start the game by pressing the "START" button in the game interface. After pressing the "START" button the game interface in Figure 5.2 will look like Figure 5.3. After the simulation is started, at time zero (at the beginning of the first week) the "Game Control" dialog box will appear, as seen in Figure 5.4. The player may now make decisions in the game. He may test decisions by pressing the "Try Decisions" button. He may test several decision periods by making decisions and pressing "Try Decisions" again. The player may use the "Revert to Game" button to reset the simulation to the current time and state. A dialog box will appear asking, "Keep current decision?" He may test here a new set of decisions, or he may accept the current set of decisions. When the player presses "Accept Decisions", the game will wait for all other players to accept their decisions, and then continue the simulation to the next decision period.

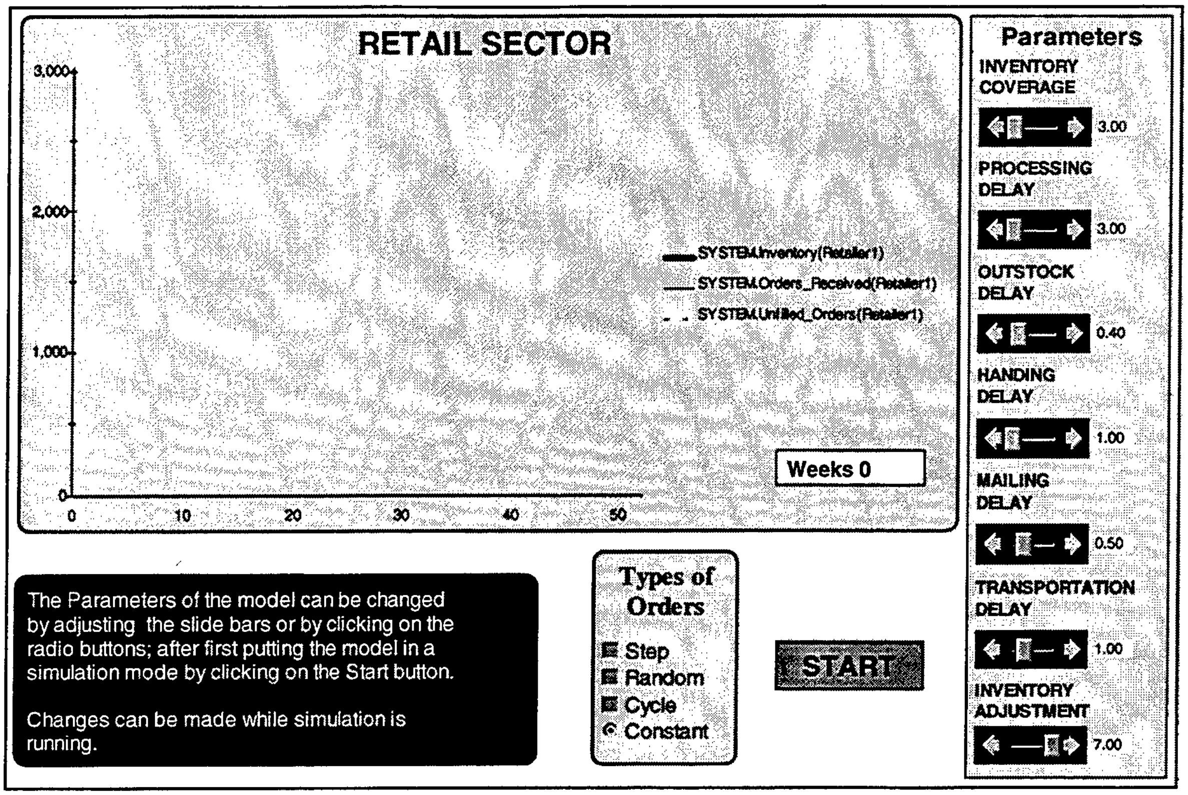

Figure 5.3 Game interface at the beginning of the first week

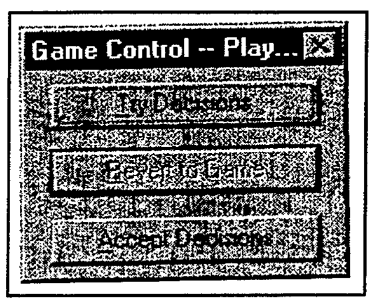

Figure 5.4 "Game control" dialog box

It can be seen that all parameters and customer orders are set to their default values. For example "Inventory Coverage Ratio" is set to 3 by default as can be seen in Figure 5.5 and "Customer Orders" is set to "Constant".

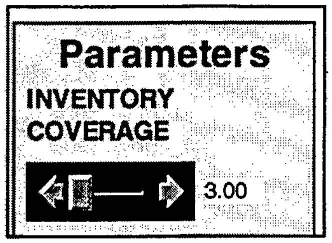

Figure 5.5 Default inventory coverage ratio

Now the player may either accept these values or he may adjust them to desired levels. Assume that he accepts the parameter values but he also wants to change the customer order rate to "Cycle". He can simply do this by clicking on the radio button next to "Cycle" as can be seen in Figure 5.6.

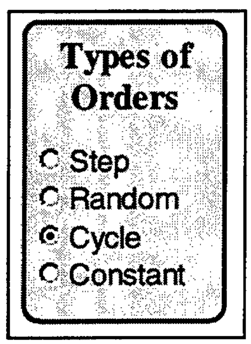

Figure 5.6 Adjusted customer orders

This time the player has to options; try decisions, or accept decisions. Assume that the player made up his mind and press "Accept Decisions". The simulation continues for 13 weeks and the Game Control panel is presented again (Do not confuse. In this example the decision period is set to 13 weeks for simplicity. In the real game decisions are made every week.) Figure 5.7 shows the graph in the game interface at the end of the first decision period.

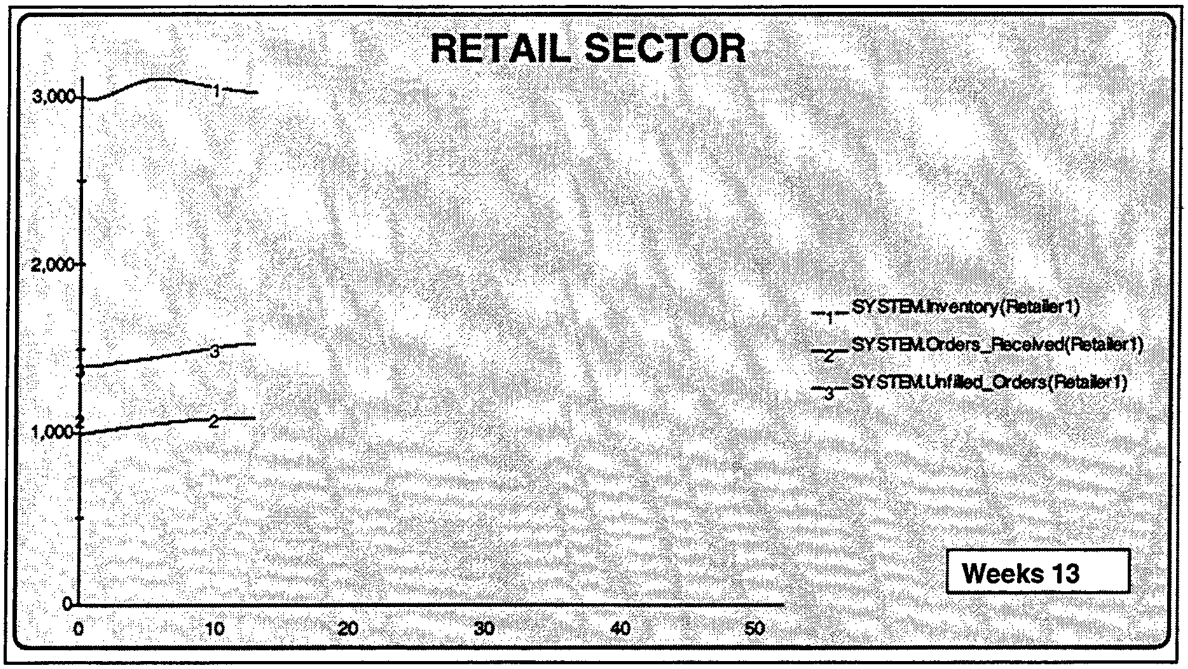

Figure 5.7 The graph in the game interface after the first decision period

The graph shows the current level of inventory level, unfilled orders level, and the customer orders at Retailer1. Now assume that the player want to see the affect of an increase in inventory coverage to the inventory level. He can adjust the inventory coverage ratio to the desired level simply by adjusting the slide bar in the "Parameters" section and under the "Inventory Coverage", as can be seen in Figure 5.8. He increased the ratio to 5. Furthermore, assume that he wants to see the affect before accepting the adjustment. Therefore, he clicks on "Try Decisions". Figure 5.9 shows the graph at the end of the decision period second.

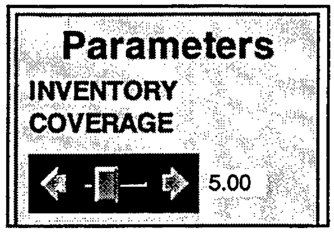

Figure 5.8 Adjusted inventory coverage ratio

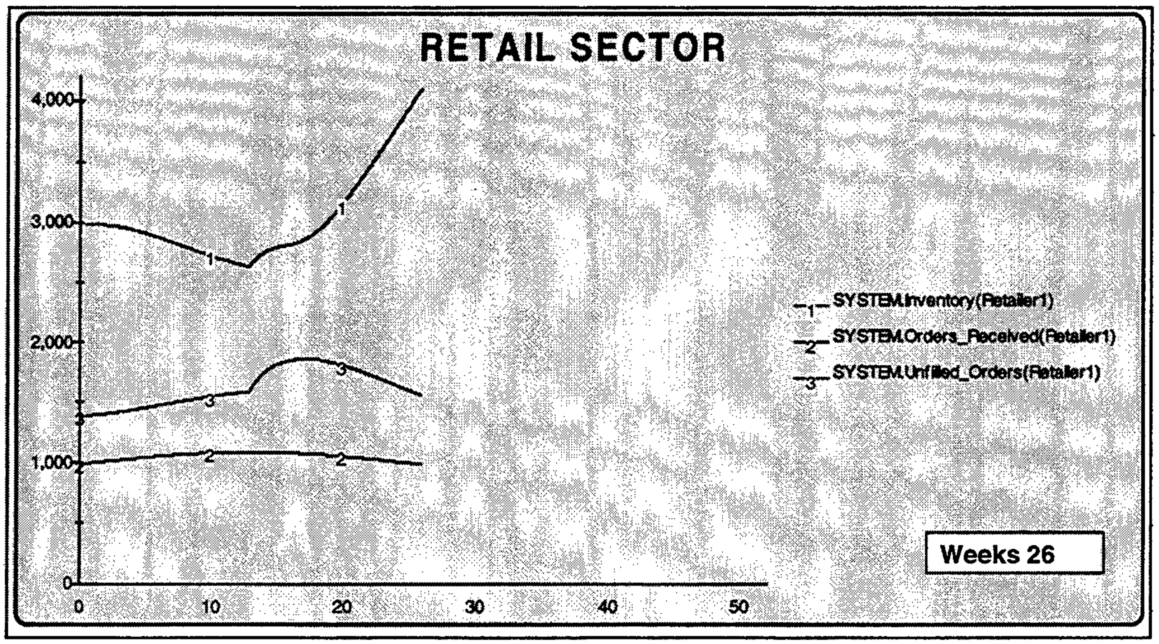

Figure 5.9 The graph in the game interface after the second decision period

Assume that he did not like the effect of coverage ratio increase, because of the climbing inventory level. Clearly, he does not want to accept his last decision. Now, he may either want to try some other decisions, or he may revert to the game by clicking "Revert to Game" in the Game Control dialog box. If he reverts to game, the simulation is set back to the point where he first pressed "Try Decisions", the 13th week. If he answers "Yes" to the question "Keep current decisions?" the previously accepted decisions will be kept until the Game Control panel appears again in week 13. In other words, the graph will be exactly the same as in Figure 5.7 and he may continue the game from the 13th week. If he does not want to keep the previously accepted decisions, he will answer "No" and the game will begin from time zero.

VI MODEL VALIDATION

Once we have a working model we have to validate the model. Coyle defines model validation as the process by which we establish sufficient confidence in a model to be prepared to use it for some particular purpose [Ref. 11:p. 181]. According to this definition we need to know the purpose of the model to judge the validity of it. Forrester states that *the purpose of industrial dynamics models is to aid in the design of improved industrial and economic systems* [Ref. 1:p. 115].

Kelton notes that validation is the task of ensuring that the model behaves the same as the real system [Ref. 12:p. 444]. We need to determine how the system (model) as a whole behaves and figure out whether the results make sense. To do that, we should compare the simulation model's output data to those from the actual system. As Law and Kelton state, if the two sets of data compare "favorably," then the simulation model of the actual system can be considered "valid." The greater the commonality between the actual and simulated systems, the greater our confidence in the simulation model [Ref. 13:p. 311]. To obtain the output from the model, we will use some patterns of consumer purchases (retail sales) as input.

A. STEP INCREASE IN SALES

This is a sudden increase in retail sales to a some new value, which is then held constant. Forrester notes that if the system has oscillatory behavior, the step increase in the input gives an immediate indication of the natural period of oscillation and the rapidity of damping or of growth of the oscillation. In other words, the step input will usually serve to trigger any cumulative tendencies toward sustained growth or decline. [Ref. 1:p. 172]

In this two-year test retail sales is assumed to be constant (1,000 units per week) before the beginning of the simulation. Immediately after the beginning of the simulation, retail sales is increased by 10% to a value of 1,100 units per week.

Figures 6.1 and 6.2 show the manufacturing-distribution system's response to a sudden 10% increase in retail sales. In the beginning of the simulation retail sales increases by 10%. Because of the processing, handling, and mailing delays the increase in distributors' orders from retailers lags about a month in reaching the 10 percent level as can be seen in Figure 6.2. However, the distributor orders continue to rise reaching to a peak of 1,160 units per week (16% increase) around March. Two sources of amplification cause this over increase in orders; (a) increasing the level of desired

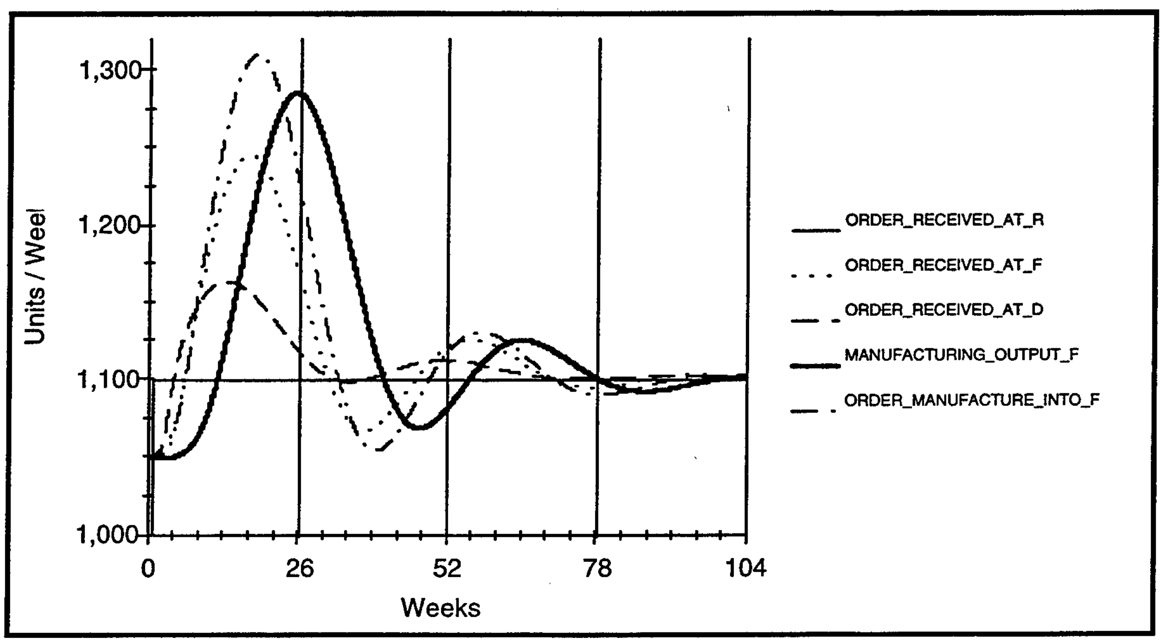

Figure 6.1 Order rate response to a sudden 10% increase in retail sales

inventory as the level of average sales increases, (b) increasing the level of orders and goods in transit in the supply pipeline by 10% to correspond to the 10% increase in the sales rate. These two sources are *transient* and *nonrepeating* amplifications. Therefore, distributors' orders from retailers reach steady-state level (level of 10% increase) after a year.

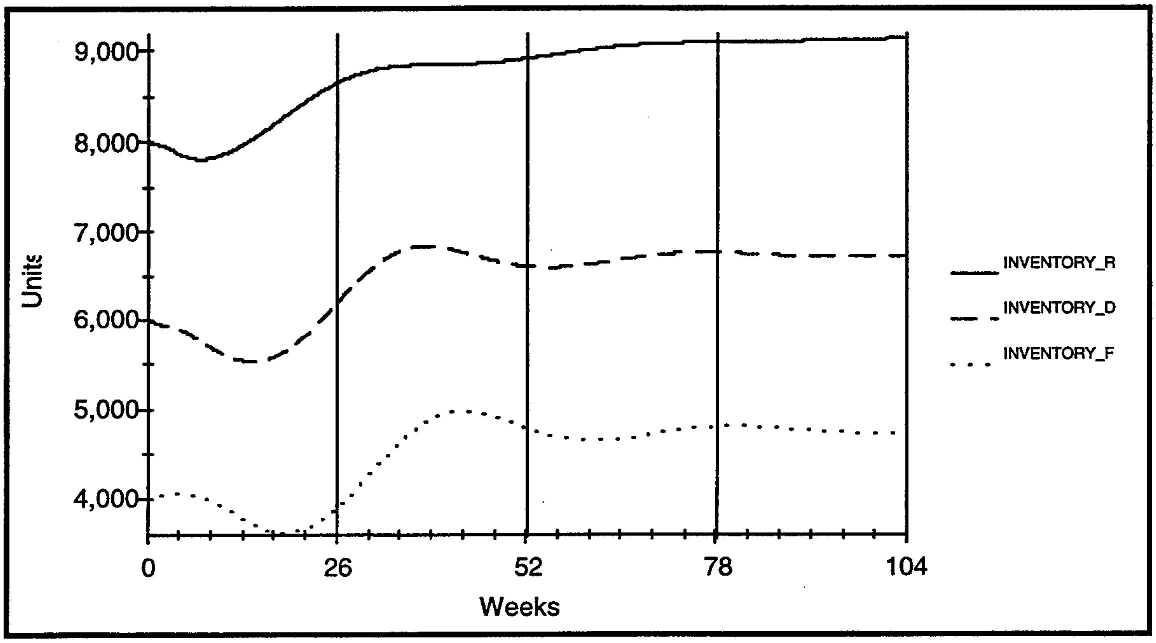

Figure 6.2 Inventory level response to a sudden 10% increase in retail sales

The distributor orders from retailers are above retail sales (1,100 units per week) for six months. The distributor mistakes this temporary order increase for a true sales volume. Therefore the mistaken sales volume becomes the new basis for ordering decisions at the distributor causing distributor orders to show a greater swing.

The distributor orders to the factory include not only the over increase in orders from retailers but also a corresponding increase in desired level of inventory and in orders and goods in transit. Because of these amplifications factory orders from distributor reach a peak of 24% increase in April.

After building up to a new higher but mistaken business level, the distributors find their sales rate declining between 12th and 32nd weeks. Then, the distributors reduce their desired inventory and the level of orders and goods in transit. This reduction causes the orders to the factory drops by 4% below the retail sales (Retail sales are 1,100 units per week and orders received at the factory 1,060 units per week). Finally, the factory orders from distributors reach steady-state level at 1,100 units per week in two years.

After the 10% increase in retail sales, there will be extra orders at the retailers and distributors. This increase increases the level of finished goods in the system (inventories and goods in transit). These changes require the production rate to be higher than retail sales. Manufacturing orders at the factory is delayed by a lead-time of six weeks and multiple processing, handling and mailing delays at each level. Therefore, the factory output reaches a peak in June, which is 28% above the retail sales. The factory production is almost three times as many. The factory begins to decrease its production rate in the 24th week after the distributors begin to reduce their orders in the 16th week. This reduction continues until December and stops at 3% below the retail sales. The production rate reaches its equilibrium in two years. Like in the ordering and production rates, the inventory fluctuations are greater as the disturbance is amplified upward in the system as can be seen in Tables 6.1 and 6.2.

Variable	Order rate rises from initial value)	Weeks after Retail sales increase	Order rate falls from initial value	Weeks after Retail sales increase
Retail Sales	+10%	1		
Distributor orders from Retail	+16%	12	-1%	28
Factory orders from Distributors	+24%	16	-3%	30
Manufacturing orders to Factory	+31%	18	-5%	34
Factory Output	+28%	24	-3%	46

Table 6.1 Response of order rates to a sudden 10% increase in retail sales

Level	Inventory rises from initial value	Weeks after Retail sales increase	Inventory falls from initial value	Weeks after Retail sales increase
Retail Inventory	+12.5%	60	-2.5%	8
Distributor Inventory	+13.5%	34	-8.5%	14
Factory Inventory	+25%	40	-10%	18

Table 6.2 Response of inventories to a sudden 10% increase in retail sales

As seen in Figures 6.1 and 6.2, it takes two years before all ordering and manufacturing rates stabilize, to respond a one time sudden increase of 10% in retail sales. Successive peaks in factory output of 28% and 13% above the initial values occur at 24 and 64 weeks. As Forrester explains, the 40-week interval separating the peaks indicates approximately the "natural period" of the manufacturing-distribution system. This indicates that the system would be highly sensitive to any disturbances, which contain a periodic component in the vicinity of a 40-week duration. This interval is almost a year, and we should expect any annual seasonal changes at retail to be amplified at the factory level. [Ref. 1:p. 175]

B. ONE-YEAR PERIODIC RETAIL SALES

In this three-year test retail sales is assumed to be constant (1,000 units per week) before the beginning of the simulation. Immediately after the beginning of the simulation, retail sales rise and fall gradually over a one-year interval. In January retail sales start rising toward a 10% increase (1,100 units per week) at the end of March. Then they fall to 10% below normal (900 units per week) by the end of September and return to normal by the end of December.

It is also assumed that the change in retail sales is an unexpected annual seasonal change. In other words, there has been no past seasonal history. Therefore, no plans and policies recognizing a seasonal business exist. As Forrester notes, this test might then be interpreted as the response of the system to errors between the predicted and the actual seasonal sales patterns [Ref. 1:p. 176].

Figures 6.3 and 6.4 show the response of the system to one-year seasonality. The fluctuations in both inventory levels and order rates in the first year are transient fluctuations. They are caused as the system moves from the steady-state, constant conditions (1,000 units per week) into a new periodic condition.

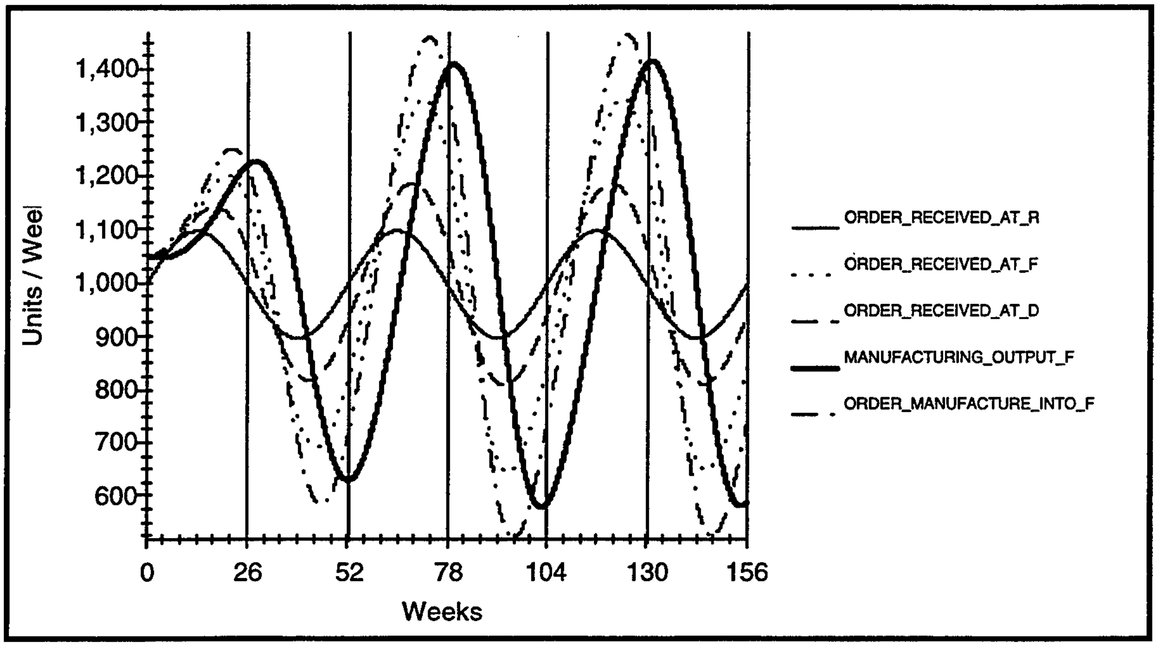

Figure 6.3 Order rate response to a 10% unexpected rise and fall in retail sales over a one-year period

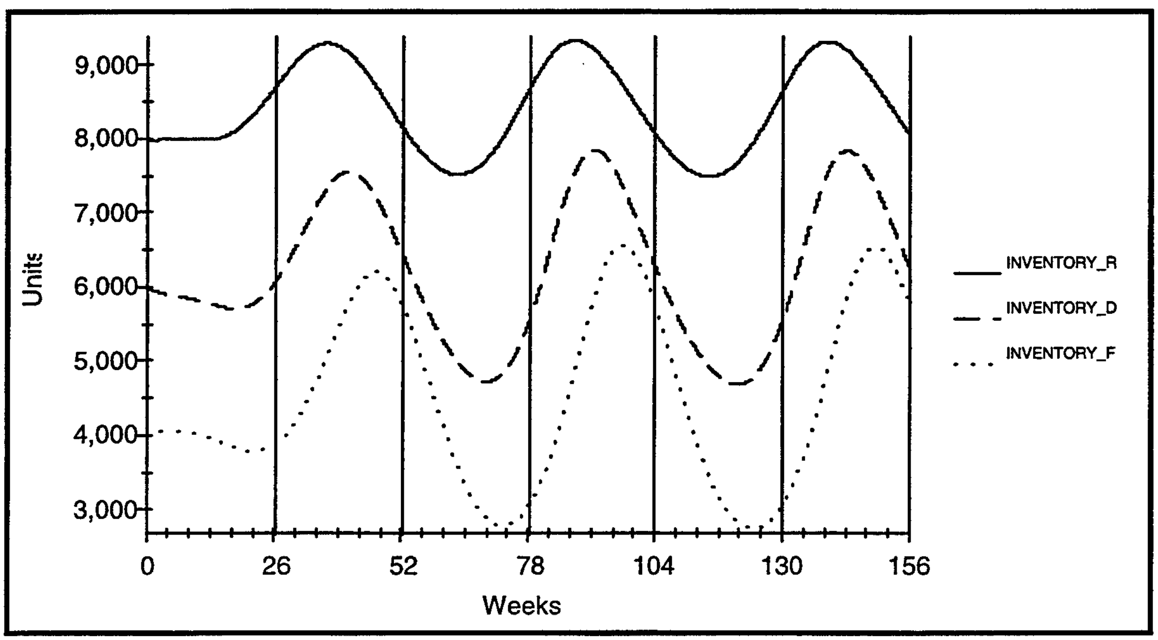

Figure 6.4 Inventory level response to a 10% unexpected rise and fall in retail sales over a one-year period

Distributor orders from retailers reach to its peak (11% above the initial value) in the 16th week. Factory orders from the distributor peak (20% above) in the 18th week. Manufacturing orders in the factory rise to its peak (25% above) in the 20th week. These first fluctuations include a combination of transient and periodic conditions. It can be easily seen that these peaks are different than the ones in the second year, which include only the periodic conditions and repeat annually.

Like in the step increase test, it takes almost one and a half-year for transient disturbance to subside. In the second and third years we see the periodic response of the system. All of the order rates and the factory output peaks for the first time around the 52nd week. The levels of the first peaks are very similar to those around the 100th and 150th weeks. The levels of the second and the third peaks are the same. Therefore, it is clear that the after the first year there is only the repeating periodic disturbance left in the system.

In the first year because of the transient disturbance the shapes of the curves are similar to those in Figure 6.2. Retail sales peak at the 12th week, distributor sales at the 16th week, factory sales at the 18th week, and the factory manufacturing orders at the 20th week. However, during the second and the third years all peaks occur approximately at the 68th and the 120th weeks because of the remaining periodic disturbance.

It is important to note that the fluctuations in factory inventory are substantial. It reaches to a high of 60% above and to a low of –27.5% below its normal level as can be seen in Tables 6.3 and 6.4. In addition, note that all inventories are high when orders are low.

Variable	First Year		Second Year		Third Year	
	Max	Min	Max	Min	Max	Min
Retail Sales	+10%	-10%	+10%	-10%	+10%	-10%
Distributor orders from Retail	+12.5%	-17.5%	+17.5%	-17.5%	+17.5%	-17.5%
Factory orders from Distributors	+20%	-30%	+32.5%	-35%	+32.5%	-35%
Manufacturing orders to Factory	+25%	-40%	+45%	-45%	+45%	-45%
Factory Output	+22.5%	-35%	+38%	-40%	+38%	-40%

Table 6.3 Maximum and minimum order rates during three years

Level	First Year		Second Year		Third Year	
	Max	Min	Max	Min	Max	Min
Retail Inventory	+12.5%	-5%	+12.5%	-5%	+12.5%	-5%
Distributor Inventory	+25%	-5%	+28%	-20%	+28%	-20%
Factory Inventory	+55%	-2.5%	+60%	-27.5%	+60%	-27.5%

Table 6.4 Maximum and minimum inventory levels during three years

C. RANDOM FLUCTUATION IN RETAIL SALES

The preceding tests are free of random fluctuations. However, ignoring random disturbances would be unrealistic, because uncertainty and random behavior exist in real situations. Therefore, they must be inserted into system studies.

In this four-year test, the size of the orders placed by customers has been made subject to a week-by-week random variation around average level of sales. Figures 6.5

and 6.6 show how the system responds to random fluctuations in retail sales. The system, due to its decision-making policies and delays, tends to amplify the fluctuations in retail sales. Retail sales fluctuate from week to week over a range of 10%. Factory output rises and falls over periods of several months with amplitudes of 20% away from the average.

The manufacturing-distribution system modifies and suppresses the independent week-by-week random fluctuations in retail sales until it is no longer evident in the factory output rate. Moreover, if we carefully examine Figure 6.6, it looks like some seasonal sales pattern is present in the system, even though there is not. This is created by the nature of the system structure itself, i.e., the policies, and the delays.

Forrester concludes the effect of the suppression of random fluctuations in the input parameter as follows,

> I know of company situations in which such an erroneous conclusion about seasonal sales has led to the establishment of employment, inventory, and advertising policies which in succeeding years caused a seasonal manufacturing pattern and thereby confirmed the original error. The possibility of this happening in any company should be carefully considered in the design of management policies to give optimum stability to operations. [Ref. 3:p. 14]

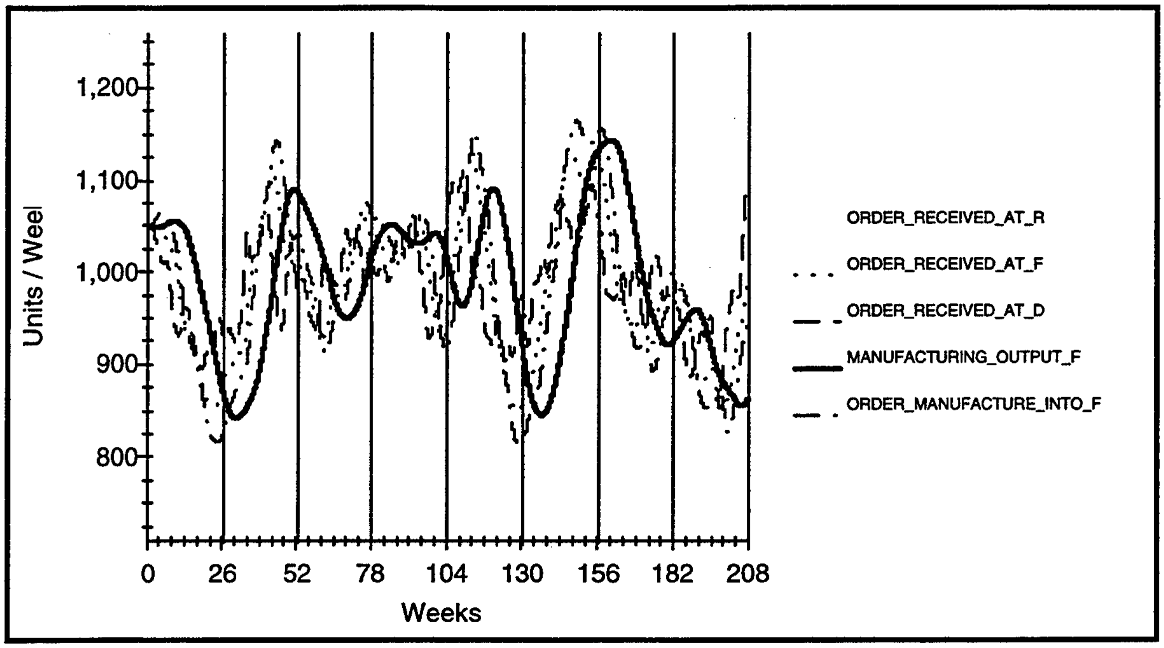

Figure 6.5 Order rate response to random fluctuations in retail sales

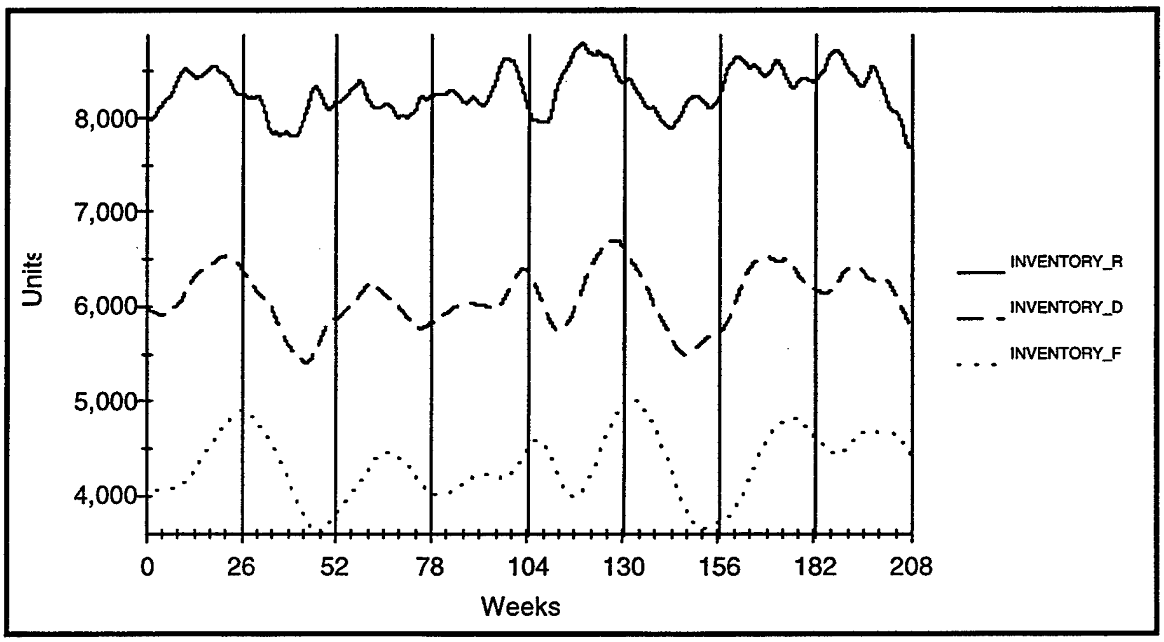

Figure 6.6 Inventory level response to random fluctuations in retail sales

D. LIMITED FACTORY MANUFACTURING CAPACITY

In the preceding tests it is assumed that the factory is able to produce at whatever level is desired. However, in real life, there is a limited manufacturing capacity, due to available factory space and capital equipment. In this three-year test the manufacturing capacity of the factory is limited to 20% above the average sales.

Figures 6.7 and 6.8 show the effects of maximum factory capacity 20% above the average sales level. As before, it is assumed that the system is completely stabilized at the start of the simulation; then retail sales rise and fall 10% during each year. This fluctuation causes the retail sales to rise to 1,100 units and fall to 900 units per week. Since manufacturing capacity limit is 1,200 units per week (20% above average sales), the manufacturing limit will be always at least 100 units per week above retail sales. At first it seems that the factory manufacturing capacity would not be a problem for the system. However, because of the amplifications in the system the factory capacity will turn out to be a bottleneck in the system.

Because of the delays and ordering policies, distributor orders exceed the manufacturing capacity as can be seen in Figure 6.8. This makes the factory unable to meet the demands on time. In addition, as factory deliveries become slower, distributors begin to order further in advance of their needs, putting more orders into the factory. As a result, the factory operates at the full capacity for two months during the first year.

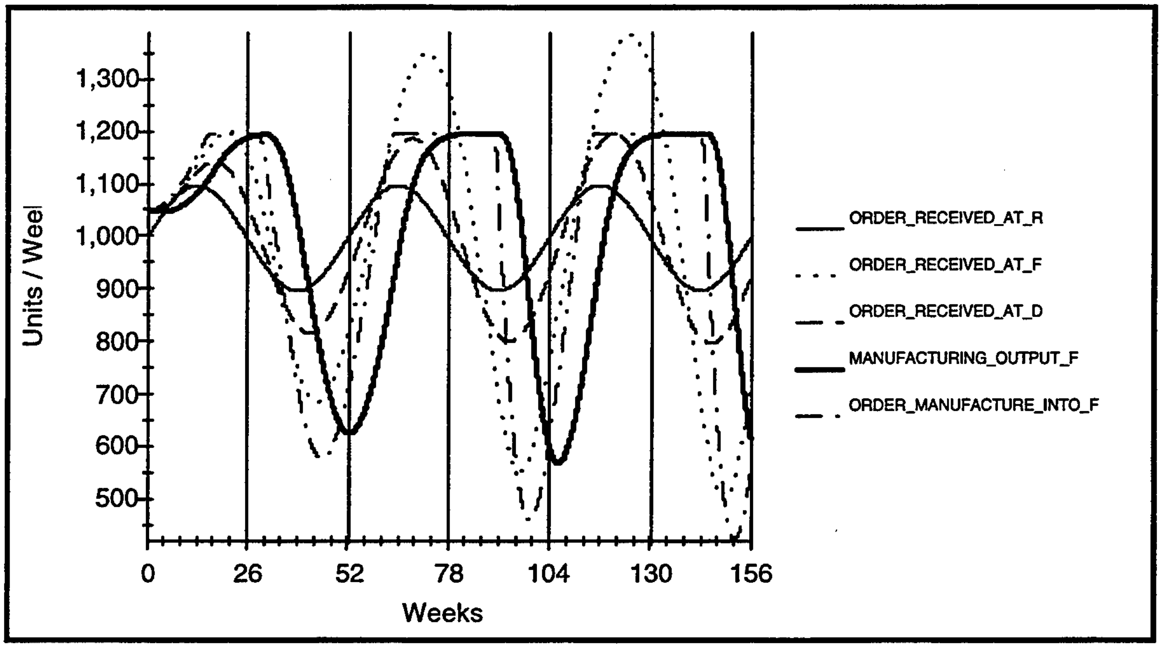

Figure 6.7 Effect of manufacturing capacity on order rates

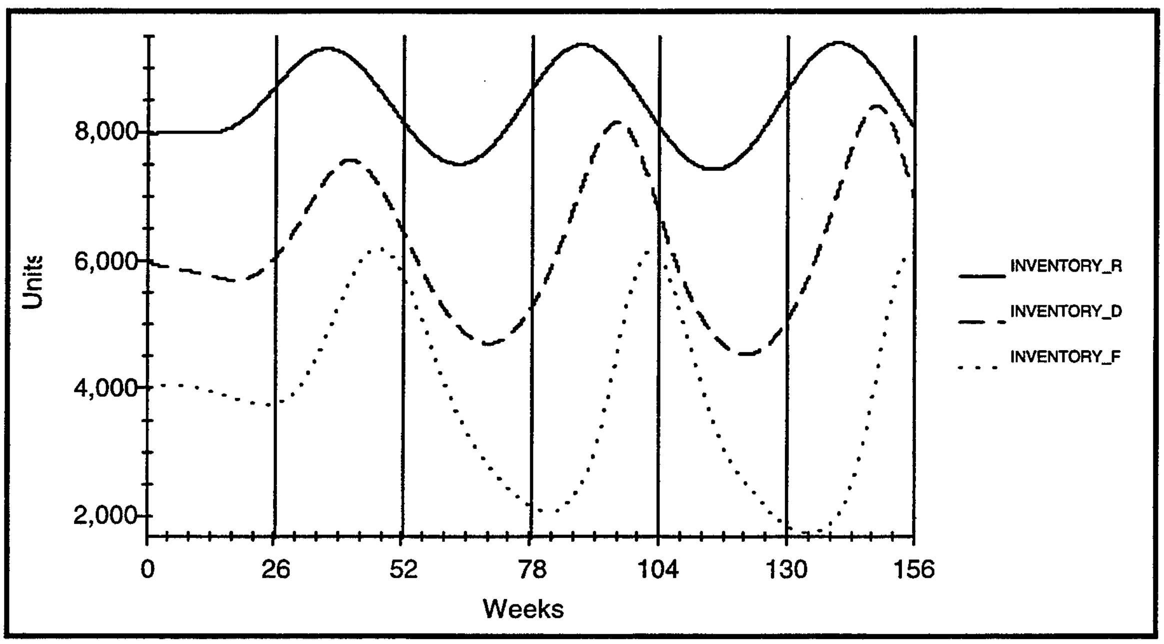

Figure 6.8 Effect of manufacturing capacity on inventory levels

The amplification at the distributor can be best seen by comparing the manufacturing orders into factory in Figures 6.4 and 6.8. Distributor orders fluctuate over a wider range as shown in Figure 6.8.

In the first year, inventories are filled while retail sales are falling. At the end of the year we see a rapidly rising factory inventory, with the help of the two-month at capacity working. As a result of the rising inventory, the factory curtails manufacturing from its maximum level to 35% below normal.

The system enters the second year with manufacturing curtailed, orders rising, and inventories falling. During this year factory orders from distributors rise to 40% above normal due to the distributors' tendency to order ahead when deliveries become slow. Factory manufacturing runs at full capacity for five months to meet the demand from the distributors. In the mean time factory inventory has been depleted from the normal four weeks' manufacturing to two weeks.

In the third year, and possibly the succeeding years, the system would act much as it did in the second year. This situation may lead a company to overexpand its manufacturing capacity. We see in Figure 6.7, for 8 months in the second year and for 9 months in the third year, factory inventory was below the desired level (4-weeks inventory coverage ratio). This condition might lead the management to expand the factory manufacturing capacity.

E. FASTER ORDER PROCESSING

As Forrester set forth to explain the behavior of an industrial organization is only the first step. After adequately representing the current operations of a particular industry, the next step is to determine ways to improve management control for company success [Ref. 3:p. 16]. To improve the industrial system's stability and response time, managers may consider various alternatives. A change frequently proposed is to reduce the order handling delays, which is often suggested as a quick and easy step toward better management control. Annual 10% periodic retail sales fluctuation is used as the test input. Order processing delays have been reduced to one-fifth their previous values, as shown in Table 6.5.

	Previous Value	Reduced Value
DELAY_PROCESSING_R	3	0.6
DELAY_PROCESSING_D	2	0.4
DELAY_PROCESSING_F	1	0.2

Table 6.5 Order processing delays

Figures 6.9 and 6.10 show, however, only a slight improvement. Only a small reduction has occurred in the amplification existing between the retail sales and factory production. Factory manufacturing fluctuation was four times as great as the fluctuation at retail sales with the original processing delays. After the reduction of the delays it is three times as great. The effect of the reduction in processing orders is small because processing delays are such a small factor in the system as a whole, no amount of speedup can change the system's performance essentially.

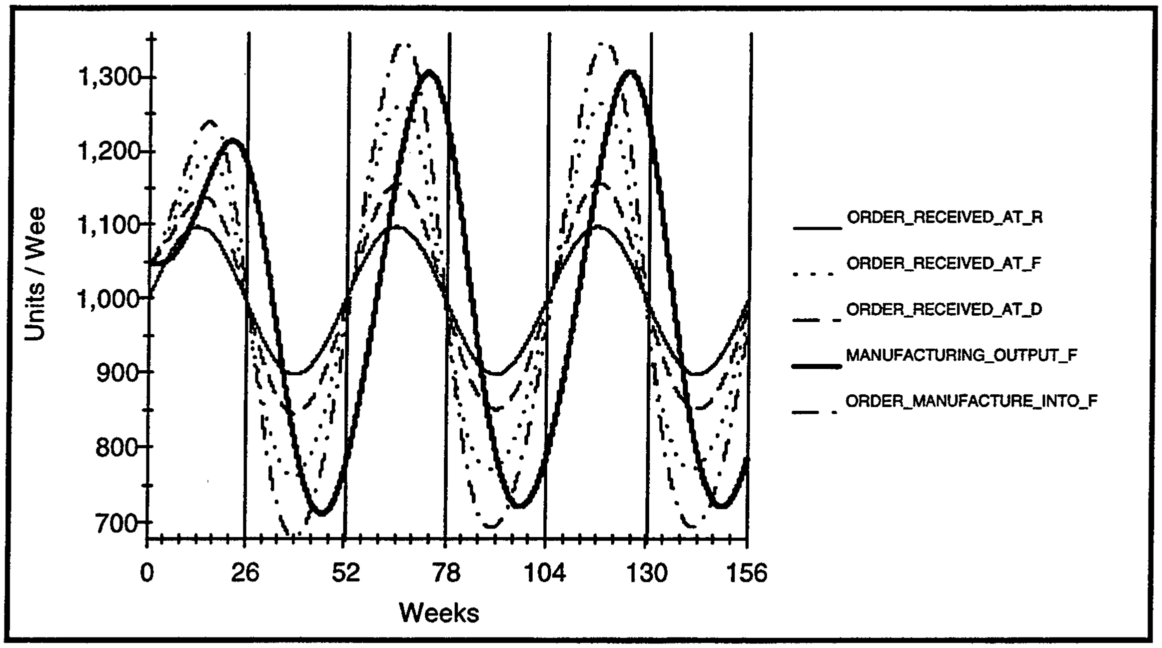

Figure 6.9 Effect of reducing order-processing delays on order rates

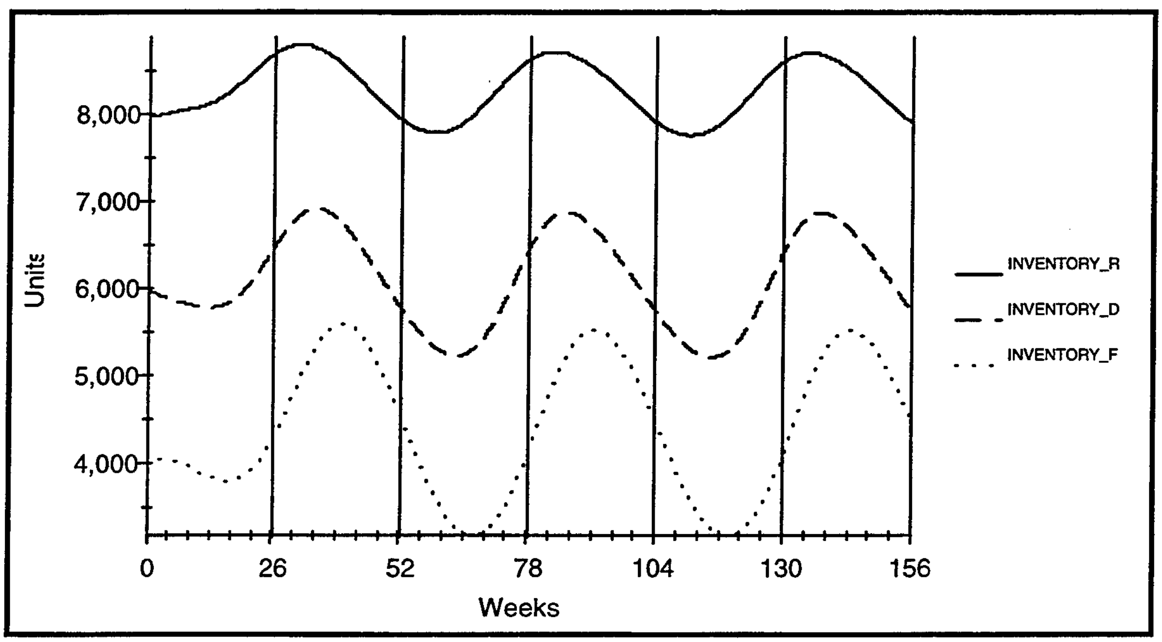

Figure 6.10 Effect of order processing delays on inventory levels

F. INVENTORY ADJUSTMENT TIME

The behavior of the manufacturing-distribution system may be affected by changing inventory adjustment times (the rapidity with which the inventory corrections are made). The effect of different values of inventory adjustment times is shown in Figure 6.11.

Each curve in Figure 6.11 is based on a different computer simulation run with different inventory adjustment rates. In any one run the three adjustment rates (for retailer, distributor, and factory) have the same value. As can be seen in Figure 6.11, these values are 1 day, 4 days, 16 days, and 32 days. All computer simulation runs use the 10% step input at retail sales, which is represented by the dotted line in Figure 6.11.

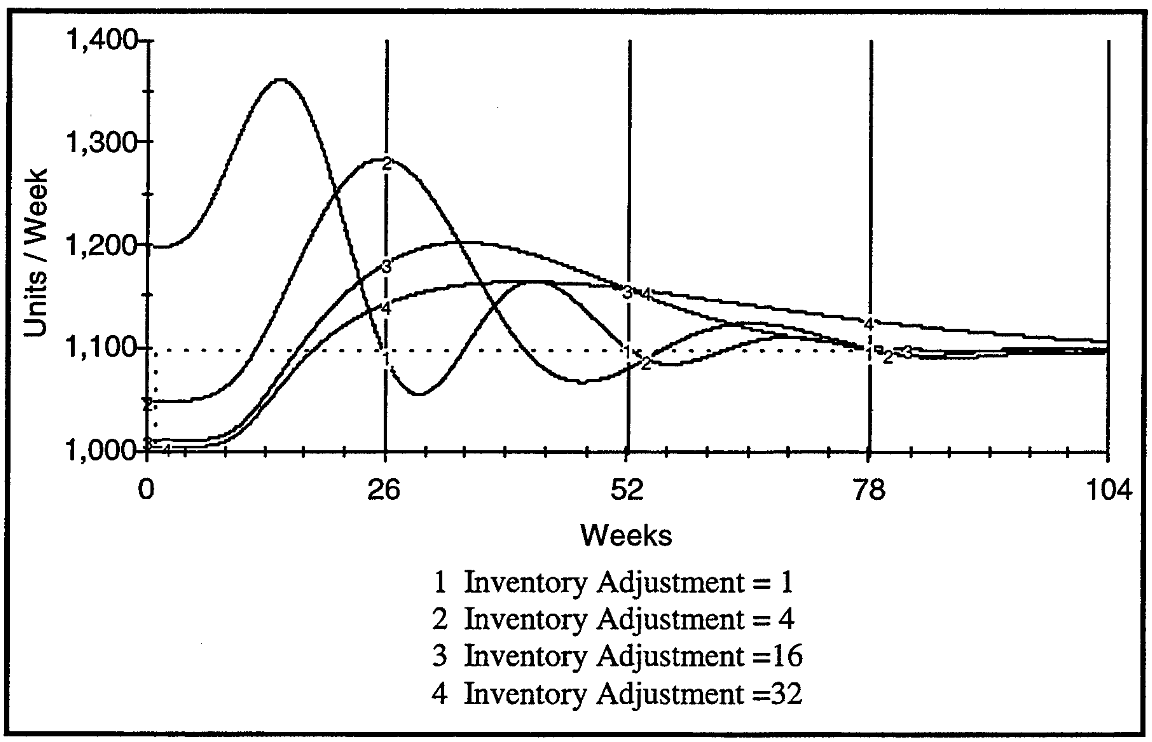

Figure 6.11 Effect of inventory adjustment time on factory manufacturing rate

To be more specific, 1-day inventory adjustment means that orders for any imbalance in inventory and in-process orders are fully placed in the following week. 16 days inventory adjustment means that 1/16 of any remaining imbalance is corrected in the following week.

It is seen in the figure that the production fluctuations for the 1-week correction reach 36% above the initial retail sales. Then seven months after the first peak it reaches 15% above. However, 16-week correction time leads to peak of 19% above the initial retail sales 10 months after the step increase.

We see in Figure 6.11 that the longer inventory adjustment value leads to improved stability in the system. In other words, as the inventory correction value is lengthened, manufacturing fluctuation in the system quickly reduces. In conclusion, we can say that inventory adjustment value is one of the sensitive parameters in the system that determines the system behavior.

VII DESIGN OF EXPERIMENTS

A. OBJECTIVE

We have stated that the primary purpose of the system dynamics is to develop policies that improve the dynamic behavior of a system and to aid in the design of improved industrial and economic systems. At first sight, it might seem that the purpose of the manufacturing-distribution model would be simply to understand why the system had behaved in a certain way. However, we become interested in how the inventory fluctuations, which we have seen during the model validation, might have been avoided had the managers of the manufacturing-distribution system acted differently.

In the previous chapters we have examined the manufacturing-distribution model and showed that, when the model was tested and validated, its mode of behavior could be changed quite noticeably. Knowing that the model's behavior can be changed leads us to the idea that we might be able to design the best possible robust behavior into the model.

The manufacturing-distribution model makes controlled experiments possible. The effects of different assumptions and environmental factors can be tested. Unlike real life, all conditions but one can be held constant and the effect of changing one factor can be observed. Circumstances can be studied that might seldom be encountered in the real world. Internal interactions of the variables can be learned and by doing so the system's sensitivities to various events can be made clear. Parameters (decision rules) may be modified to obtain a parametric value that optimizes a measure of effectiveness of system behavior.

B. DESIGN OF EXPERIMENTS

Condra defines design of experiments and designed experiment as:

> Design of Experiments is a method of systematically obtaining and organizing knowledge so that it can be used to improve operations in the most efficient manner possible. [Ref. 14:p. 8]
>
> A technique to obtain and organize the maximum amount of conclusive information from the minimum amount of work, time, energy, money, or other limited resource. [Ref. 14:p. 20] [10]

Designed experiments are one of the tools used to improve quality and productivity in many different business sectors. There are many benefits of a designed experiment, which are listed here:

- Many factors can be considered in one experiment.
- An optimum combination of parameters can be selected which will improve the operation and reduce the cost.
- The sample size and experimental cost can be reduced dramatically.
- Data can be collected rapidly and a decision can be made very quick.
- There are many factors, which are not specifically evaluated and may be uncontrollable, but contribute to the outcome. These factors are called *noise*. In a designed experiment, the noise can be left in the experiment.

There are several systems of design of experiments in use today. The two main types are classical and Taguchi methods. For the reasons which will be explained next "*Taguchi methods*" is used in this thesis.

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[10] For detailed information about "Design of Experiments" and "Designed Experiment" see Ref. 21, 22, 23, 24, and 25.

Three ways to obtain experimental data exist: one-factor-at-a-time, full factorial, and fractional factorial. All three types are discussed here briefly to illustrate the benefits of fractional factorial designs (Taguchi methods).

1. One-factor-at-a-time method

The one-factor experiment evaluates the effect of one factor[11] on performance while holding everything else constant. The experiment would go as follows: Set all parameters at setting one. Record the results. With all parameters at setting one, set parameter A to setting two. Record the results. Set parameter A to setting three. Record the results, etc. We do this until all combinations of settings for all parameters were observed and the results recorded. If there happens to be an interaction of the factor studied with some other factor, then this interaction can not possibly be observed.

2. Full factorial method

In a full factorial experiment all possible combinations of factors are evaluated in a single experiment. The benefit of a full factorial is that every possible data point is collected. However, it is very expensive and time-consuming. For example, to evaluate seven factors in a full factorial at two levels[12] (without interactions) would require (2^7), or 128 runs. For an eleven-parameter experiment at two levels, 2048 (2^{11}) runs are needed.

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11 Factors are the independent variables in an experiment, sometimes called the input variables. These are the variables, which are intentionally changed according to a predetermined plan.

12 Levels are the values at which the factors are set for experiment. These can be either parametric, i.e., 1 day, 7 weeks, or non-parametric, i.e., day A, short delay.

3. Taguchi Fractional factorial method

As Condra pointed out, the fractional factorial method allows the experimenter to obtain information on all main effects[13] and interactions[14] while keeping the size of the experiment manageable, and also conducting it in a single, systematic effort [Ref. 14:p. 40]. In a fractional factorial experiment, only a fraction of the possible combinations are evaluated. For a seven-parameter and two-level experiment fractional factorial method requires only 8 runs. For an eleven-parameter experiment at two levels, the number of the runs required is only 12.

4. Comparison of classical (full-factorial) and Taguchi experiments

Both types of experiments have their positives and negatives: (1) classical methods are more rigorous mathematically and statistically than Taguchi methods, and (2) classical methods collect data from a single, large experiment where as Taguchi methods collect data quickly and efficiently, and iterating the experiment several times if necessary.

Condra concludes that, classical methods preferred in applications; where the cost of the experiment is high (which is not true for our model and experiment); where the time required is long (we need the results quickly in our model and experiment); where uncontrollable factors can be limited (we have many uncontrollable factors in our model, such as customers). Condra also explains that Taguchi methods are more applicable

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[13] Main effects are the effects of the factors in an experiment, as opposed to their interactions.

[14] Interactions are the influence of the variation of one factor on the results obtained by varying another factor.

where there are many uncontrollable factors; where it is important for the experimenter to obtain results quickly; and where it is possible to iterate the experiment several times. [Ref. 14:p. 45]

Based on the above results, Taguchi methods are more applicable to our model and experiment. Therefore, Taguchi experiments have been chosen for our experiment.

C. DESIGN OF EXPERIMENT

In this section, we discuss the characteristics of the design of experiment, which we will design, involving both main effects and interactions among the parameters.

1. Statement of problem and objective of experiment

The problem is to find the best parameter levels, such as the length of the processing delay or handling delay, and the inventory coverage ratio, which influence inventory fluctuations of retail sector. The objective of the experiment is to find the optimum parameter levels which minimize the inventory oscillations, and the inventory stabilization time at the retail sector.

2. Selection of parameters and levels

Seven parameters are chosen for evaluation in this experiment. For this experiment, the parameter levels are kept at two levels, a low and a high value. The parameters and levels selected for the experiment are:

- A. Inventory coverage (2 levels). The number of weeks of average sales, which could be supplied out of the inventory at the retail. The two levels are seven weeks and twelve weeks.

- B. Processing delay (2 levels). Delay in processing the orders at the retail sector. The two levels are two days and four days.

- C. Out-of-stock delay (2 levels). Delay in filling orders at retail caused by out-of-stock items. The two levels are 0.2 day and two days.

- D. Handling delay (2 levels). Delay interval due to minimum handling time required at retail. The two levels are one day and two days.

- E. Mailing delay (2 levels). Delay interval in order mailing from retail. The two levels are 0.3 day and two days.

- F. Transportation delay (2 levels). Delay in transportation of goods to retail. The two levels are 0.5 day and two days.

- G. Inventory adjustment time (2 levels). Delay interval representing the rate at which the retailer acts on inventory deficit situations. The levels are two days and seven days.

All of the above parameter levels had numerical values, but they will not be used here in order to focus our attention on the analytical process. Instead, for example for seven weeks inventory coverage "Inventory coverage level 1" and twelve weeks inventory coverage "Inventory coverage level 2" will be used. In addition to the above seven main effects, the following six interactions are of interest:

- Inventory coverage * Processing delay A * B
- Inventory coverage * Out-of-stock delay A * C
- Processing delay * Out-of-stock delay B * C
- Inventory coverage * Handling delay A * D
- Processing delay * Handling delay B * D
- Out-of-stock delay * Handling delay C * D

3. Assignment of factors to array columns

Degrees of freedom

The degrees of freedom for each parameter is the number of levels minus one. The degrees of freedom for an interaction is the product of the interacting parameter's degrees of freedom. Thus, seven parameters (main effects) and six interactions have the following degrees of freedom:

Main effects: [7 parameters]*[(2-1=) 1 dF/parameter] = 7 dF

Interactions: [6 parameters]*[(1*1=) 1 dF/parameter] = 6 dF

Therefore, the total number of degrees of freedom in the experiment is 13, and at least thirteen runs are required. The selection of which *Taguchi orthogonal array*[15] to use depends on the total degrees of freedom in the experiment. Since there is no L_{13}[16] array, we must go to the next larger one, or the L_{16}, which has 15 dF.

Taguchi L_{16} orthogonal array

Table 7.1 shows the L_{16} array with the main effects and interactions assigned to the columns. It is important to note that there are two empty columns, labeled e1 and e2. Because we only had 13 factors to evaluate, this was inevitable. The empty

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15 Array is the set of all combinations of levels of all parameters evaluated in an experiment. In fractional factorial method some combinations are eliminated according to Taguchi orthogonal array tables. For detailed information about Taguchi orthogonal arrays and tables see Ref. 23, 24, and 25.

16 "L" represents the Taguchi orthogonal array. The number in the array designation indicates the number of trials in the array; an L_{16} has 16 trials (runs), for example. The total degrees of freedom available in a Taguchi orthogonal array is equal to the number of trials (runs) minus one.

columns will be used to evaluate the overall variation, or noise[17] in the experiment. This will help us to tell if we have considered all relevant parameters. Each row in the array represents a run. For example, the first run is conducted with all parameters and interactions at level one; the second is conducted with parameters D, E, F, G and interactions A*D, B*D, C*D at level two and the remainder at level one.

4. Selection of responses

There are two responses[18] to be evaluated in this experiment. They are (1) absolute value of the difference between the maximum and minimum value of the inventory, and (2) the length of the time interval in which the oscillation of the inventory falls below 10% of its stabilization value. It is important to note that the two responses (effects) are, for analytical purposes, independent of each other. For example, the results for the first response may be evaluated independently of those for the second response. Thus, two separate and independent analyses of the data from this experiment are conducted.

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[17] Noise is the effects of all the uncontrolled factors in an experiment. In some cases, all the noise factors are known, but in most cases only some of them are known.

[18] Responses are the dependent variables in an experiment, sometimes called the output variables. These are the results of the experiment.

Run no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	1	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	1	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	2	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	2	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	2	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	2	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	1	1	2	2	1	2	1	1	2
16	2	2	1	2	1	1	1	2	1	1	2	1	2	2	1
	A	**B**	**A*B**	**C**	**A*C**	**B*C**	**e1**	**D**	**A*D**	**B*D**	**E**	**C*D**	**F**	**G**	**e2**

Table 7.1 Taguchi L_{16} array showing assignment of main effects, interactions, and empty columns

D. ANALYSIS OF VARIANCE (ANOVA)

In this section, we will conduct an analysis of variance on the data collected from the experiment designed and conducted in the previous section.

1. Calculation of mean and signal-to-noise ratio [19] for the responses

The responses in our experiment are: (1) absolute value of the difference between the maximum and minimum value of the inventory (DIF), and (2) the length of the time interval in which the magnitude of the oscillation of the inventory falls below 10% of its stabilization value (TIME). We have chosen the first response because we do not want the inventory level to fluctuate in large amounts. It is always better to have a stabilized inventory level. By stabilizing inventory level at the minimum possible level; (1) we avoid the extra cost of carrying inventory more than we need, (2) we avoid the possibility of out-of-stock situation, which means lost sales and damaged goodwill. In addition, we do not want the inventory level to fluctuate for a long time. For that reason we have chosen our second response as the fluctuation time. Our primary goal in conducting this analysis is to help the managers, (or decision making process) in making flexible, frequent, and optimal decisions, by providing them with the optimal system settings (which we will find in this analysis). For both of the responses, the smallest numbers are

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[19] In its simplest form, the *S/N ratio* is the ratio of the mean to the standard deviation, commonly referred to as "Coefficient of variation". This ratio immediately causes the dimensions to cancel and we need not worry as to the actual dimensions of the performance measurement. While there are many different S/N formulas, three of them are considered standard and are generally applicable when the response can be classified as "larger-the-better," "smaller-the-better," and "nominal-the-best." Regardless of the type of characteristic, the transformations are such that the S/N ratio is always interpreted the same way: the larger the S/N ratio, the better. For more detailed information see Ref. 20, and Ref. 21.

associated with the best results. Therefore, they are evaluated using *smaller-the-better* criterion.

The formula used to calculate the mean $\overline{X}$ for each run is $\overline{X} = \frac{(X_1 + X_2 + ... + X_n)}{n}$,

where "n" is the number of tests in a run. Since the responses are a smaller-the-better criterion, their signal-to-noise ratios are calculated according to the formula:

$$S/N = -10 \log \left[\frac{X_1^2 + X_2^2 + ... + X_n^2}{n} \right]$$ [Ref. 15:p.172]

The results for both responses (DIF and TIME) for each run of the L_{16} array and the results of calculations for $\overline{X}$ and S/N for all runs are shown in Table 7.2. Since there is only one test[20] in a run in our experiment "n" is equal to one. Therefore, X_i and $\overline{X}$ are the same.

One way to draw conclusions from this experiment at this point is to select the conditions of the run which has produced the lowest $\overline{X}$ or the highest S/N ratio. However, only 16 of the possible 128 (2^7) treatment combinations were considered. To improve our probability of finding the best combination, we will next calculate the $\overline{\overline{X}}$ and $\overline{S/N}$ ratio for each main effect and interaction.

20 Each run with the same parameter values produces the same behavior or results in our model. Therefore, there is no need for several test or data points for the same response in a single run.

Run no	DIF X	DIF $\overline{X}$	DIF S/N	TIME X	TIME $\overline{X}$	TIME S/N
1	130	130	-42.3	50	50	-34.0
2	100	100	-40.0	85	85	-38.6
3	50	50	-34.0	65	65	-36.3
4	300	300	-49.5	250	250	-48.0
5	50	50	-34.0	65	65	-36.3
6	330	330	-50.4	120	120	-41.6
7	130	130	-42.3	82	82	-38.3
8	165	165	-44.3	84	84	-38.5
9	175	175	-44.9	70	70	-36.9
10	75	75	-37.5	75	75	-37.5
11	40	40	-32.0	60	60	-35.6
12	880	880	-58.9	300	300	-49.5
13	70	70	-36.9	68	68	-36.7
14	450	450	-53.1	145	145	-43.2
15	250	250	-48.0	95	95	-39.6
16	280	280	-48.9	115	115	-41.2

Table 7.2 Response results, $\overline{X}$ and S/N ratios for each run

For the two-level factor A, inventory coverage, there are eight runs at level one, and eight runs at level two. $\overline{\overline{X}}$ for A_1 is then the average of all the $\overline{X}$'s of the runs in which parameter A was at level one. Similarly, $\overline{S/N}$ for A_1 is the average of all the S/N ratios of the runs in which parameter A was at level one. Sample calculations are shown below.

Response A1: $\overline{\overline{X}}$ =average of $\overline{X}$'s for all runs in which response A is at level 1

$$= (130+100+50+300+50+330+130+165)/8 = 156.9$$

Response A1: $\overline{S/N}$ = average of S/N's for all runs in which response A is at level 1

$$= (-34.0-38.6-36.3-48.0-36.3-41.6-38.3-38.5)/8 = -39.0$$

The rule for interactions is: if both main effects participating in the interaction are at the same level, the interaction is at level one; if the main effects are at different levels, the interaction is at level two [Ref. 14:p. 91]. The subscripts of the interactions are the levels of the interaction, e.g., $(A*B)_1$ indicates level one of the interaction, not either of the main effects participating in it. Table 7.3 shows $\overline{\overline{X}}$ and $\overline{S/N}$ ratios for each main effect and interaction for all runs.

We can now draw some conclusions about the results of the experiment. Significant variation in the empty columns, e1 and e2, would indicate that we did not account for all the important factors when we set up the experiment. Since the differences in levels for both e1 and e2 appear to be small we can say that there is no significant factor operating in either of these columns.

If we arbitrarily assume that a difference of 3 in the signal-to-noise ratio is significant, we see that three main effects (A, D, G) for DIF response, and two main effects (D, G) for TIME response are significant. No interactions are significant for both responses.

Now, we will conduct an analysis of variance by using the $\overline{X}$ results. Tables VII.4 and 7.5 are completed ANOVA tables. The first column, labeled "Factor level," is a listing of the factors and levels from the Table 7.3.

		DIF		TIME	
Parameter	**Level**	$\bar{\bar{X}}$	$\overline{S/N}$	$\bar{\bar{X}}$	$\overline{S/N}$
Inventory Coverage	**A_1**	156.9	-31.5	100.1	-39.0
	A_2	277.5	-45.0	116	-40.0
Processing Delay	**B_1**	218.8	-42.4	119.4	-39.6
	B_2	215.6	-44.7	96.8	-39.4
	$(A*B)_1$	203.8	-44.1	109.1	-39.7
	$(A*B)_2$	230.6	-43.0	107	-39.3
Out-stock Delay	**C_1**	172.5	-42.4	84.8	-38.1
	C_2	261.9	-44.7	131.4	-40.9
	$(A*C)_1$	275.5	-44.3	111.3	-39.6
	$(A*C)_2$	176.9	-42.8	104.9	-39.4
	$(B*C)_1$	163.1	-43.5	82.0	-38.1
	$(B*C)_2$	271.3	-43.6	134.1	-40.9
	$e1_1$	245.6	-43.7	109.3	-39.3
	$e1_2$	188.8	-43.4	106.9	-39.7
Handling Delay	**D_1**	111.9	-39.3	69.4	-36.7
	D_2	322.5	-47.8	146.8	-42.3
	$(A*D)_1$	255.6	-43.9	112.1	-39.5
	$(A*D)_2$	178.8	-43.3	104.0	-39.4
	$(B*D)_1$	202.5	-43.7	88.6	-38.4
	$(B*D)_2$	231.9	-43.4	127.5	-40.6
Mailing Delay	**E_1**	243.8	-44.0	107.1	-39.2
	E_2	190.6	-43.1	109.0	-39.8
	$(C*D)_1$	256.3	-45.0	125.3	-40.1
	$(C*D)_2$	178.1	-42.2	90.9	-38.8
Transport Delay	**F_1**	182.5	-42.6	103.0	-39.1
	F_2	251.9	-44.5	113.1	-39.9
Inventory Adjust.	**G_1**	330.6	-48.7	139.0	-41.4
	G_2	103.8	-38.5	77.1	-37.6
	$e2_1$	169.4	-42.5	102.5	-39.1
	$e2_2$	265.0	-44.7	113.6	-39.9

Table 7.3 Complete response table

2. Total variation

The next column in Tables 7.4 and 7.5, labeled "$\overline{X}$ total," is the sum of all the $\overline{X}$'s for each level of each factor. For example, the $\overline{X}$ total for row A_1 is the sum of all the $\overline{X}$'s for which parameter "A" is at level one;

$A_1 = 130+100+50+300+50+330+130+165 = 1255$

As we go down this column, we see that the sum of the $\overline{X}$ totals for each factor is the same. This is because we are using the same data for each factor: we are just grouping the runs differently.

3. Degrees of freedom

The next column, labeled "dF," is the degrees of freedom. For a Taguchi experiment, the number of degrees of freedom of a parameter is always equal to the number of levels of that parameter, minus one. All the two-level parameters of this experiment have one degree of freedom.

4. Calculation of the source variation

Condra defines source variation as,

> The source variation of a factor is the quantitative measure of the magnitude of its effect due to changes in its level. [Ref. 14:p. 94]

The source variation can be calculated by the following formula [Ref. 15:p.34]:

$$Sx = \left[\frac{\left(X_1^2 + X_2^2\right)}{n/2}\right] - \left[\frac{T^2}{n}\right]$$

where X_1 = sum of data for parameter X at level one

X_2 = sum of data for parameter X at level two

n = total number of data points

T = total of all the data.

For example, for parameter A: A_1=1255, A_2=2220, n=16, T=A_1+A_2=3475 and $S_A=[(1255^2+2220^2)/(16/2)]-3475^2/16 = \mathit{58177.4}$.

5. Pooling

In the next column, we list whether or not the variation of the parameter is pooled. Our purpose to conduct an ANOVA is to determine if individual parameters are significant by comparing their variation with the overall variation (error variation) of the data from the experiment. To estimate error variance we used columns which have been assigned factors which were suspected to be significant, but which are shown by the results to be insignificant. In general, as Condra explains, if the variation of a factor is less than that of an error column (e1 and e2) or if it is significantly lower than that of some other columns with factors in them, it can be considered random, and it can be *pooled* (combined) with other insignificant factors and error columns to provide a data base for estimating the random variation of the experiment [Ref. 14:p. 95]. The combining of column effects to better estimate error variance is referred to as *pooling*.

The decision of whether or not to pool data from a particular parameter can be subjective. In this experiment, all the S_x's were compared with those of the larger of the source variations of the two error columns. The source variations of the two error columns are 12,905.0 (e1) and 36,557.4 (e2). If a given S_x is less than the S_x for the error column, it was pooled. In this experiment, all parameters with S_x less than 36557.4 are pooled. There are ten such factors:

B, A*D, C, e1, A*D, B*D, E, C*D, F, e2

These factors are designated by a "Yes" in the column labeled "Pool?" in Tables 7.4 and 7.5. Their values are then transferred to the columns labeled "dF_e" for degrees of freedom of the error, and "S_e" for source variation of the error. The total degrees of freedom for the error terms is 10, and the total source variation of the error is 166443.2.

6. Variance of the source

The variance of the source, V_x, is the variation of the source corrected for the number of degrees of freedom, according to the formula [Ref. 15, pp.29]: $V_x = \frac{S_x}{dF_x}$

Since we are dealing in this experiment only with two-level factors, all variances of the sources are equal to their source variations, e.g., V_A=58177.4/1=58177.4. The V_x values are shown for all factors in Tables 7.4 and 7.5, but the V_e values are shown only for the pooled factors. It is important to note that the total error variation at the bottom of the V_e column is equal to S_e/10, or 16,644.3.

7. The F-Test

The F-ratio of the source is calculated for significant, or unpooled, factors only. It is used in the F-test, which is a statistical test for significance of variance. The formula is: $F_x = \frac{V_x}{V_e}$, where V_e is the total error variance, shown at the bottom of the V_e column in Table 7.4 and 7.5. For example, F_A = 58,177.4 / 16,644.3 = 3.495.

The F-ratios are then compared with the values from the F-distribution table. In this experiment, the number degrees of freedom in the numerator is 1, and that for the denominator is 10. The F value for the 95% confidence level is *4.9646*. From the column labeled "F" in Tables 7.4 and 7.5, we can see that the following factors are significant at this level: D (Handling delay), and G (Inventory adjustment time).

Parameter	Total $\overline{X}$	dF	S_x	Pool?	dF_e	S_e	V_x	V_e	F	S_x	ρ_x (%)
A_1	1255.2	1	58177.4	No			58177.4		3.495	41533.1	**6**
A_2	2220.0										
B_1	1750.4	1	41.0	Yes	1	41.0	41.0	41.0			
B_2	1724.8										
$(A*B)_1$	1630.4	1	2873.0	Yes	1	2873.0	2873.0	2873.0			
$(A*B)_2$	1844.8										
C_1	1380.0	1	31969.4	Yes	1	31969.4	31969.4	31969.4			
C_2	2095.2										
$(A*C)_1$	2204.0	1	38887.8	No			38887.8		2.336	22243.5	**3**
$(A*C)_2$	1415.2										
$(B*C)_1$	1304.8	1	46829.0	No			46829.0		2.814	30184.7	**4**
$(B*C)_2$	2170.4										
$e1_1$	1964.8	1	12905.0	Yes	1	12905.0	12905.0	12905.0			
$e1_2$	1510.4										
D_1	895.2	1	177409.4	No			177409.4		10.659	160765.1	**23**
D_2	2580.0										
$(A*D)_1$	2044.8	1	23593.0	Yes	1	23593.0	23593.0	23593.0			
$(A*D)_2$	1430.4										
$(B*D)_1$	1620.0	1	3457.4	Yes	1	3457.4	3457.4	3457.4			
$(B*D)_2$	1855.2										
E_1	1950.4	1	11321.0	Yes	1	11321.0	11321.0	11321.0			
E_2	1524.8										
$(C*D)_1$	2050.4	1	24461.0	Yes	1	24461.0	24461.0	24461.0			
$(C*D)_2$	1424.8										
F_1	1460.0	1	19265.0	Yes	1	19265.0	19265.0	19265.0			
F_2	2015.2										
G_1	2644.8	1	205753.0	No			205753.0		12.362	189108.7	**27**
G_2	830.4										
$e2_1$	1355.2	1	36557.4	Yes	1	36557.4	36557.4	36557.4			
$e2_2$	2120.0										
e total					10	166443.2		16644.3			
TOTAL		15	693500.2				46233.3				**63**

Table 7.4 Complete ANOVA table for the response DIF

Parameter	Total $\overline{X}$	dF	S_x	Pool?	dF_e	S_e	V_x	V_e	F	S_x	ρ_x (%)
A_1	801.0	1	1008.0	No			1008.0		5.1		
A_2	928.0										
B_1	955.0	1	2047.6	No			2047.6		10.3	1849.5	**2.5**
B_2	774.0										
$(A*B)_1$	873.0	1	18.1	Yes	1	18.1	18.1	18.1			
$(A*B)_2$	856.0										
C_1	678.0	1	8695.6	No			8695.6		43.9	8497.5	**11.5**
C_2	1051.0										
$(A*C)_1$	890.0	1	162.6	Yes	1	162.6	162.6	162.6			
$(A*C)_2$	839.0										
$(B*C)_1$	656.0	1	10868.1	No			10868.1		54.9	10670	**14.4**
$(B*C)_2$	1073.0										
$e1_1$	874.0	1	22.6	Yes	1	22.6	22.6	22.6			
$e1_2$	855.0										
D_1	555.0	1	23947.6	No			23947.6		120.9	23749.5	**32.1**
D_2	1174.0										
$(A*D)_1$	897.0	1	264.1	Yes	1	264.1	264.1	264.1			
$(A*D)_2$	832.0										
$(B*D)_1$	709.0	1	6045.1	No			6045.1		30.5	5847	**7.9**
$(B*D)_2$	1020.0										
E_1	857.0	1	14.1	Yes	1	14.1	14.1	14.1			
E_2	872.0										
$(C*D)_1$	1002.0	1	4726.6	No			4726.6		23.9	4528.5	**6.1**
$(C*D)_2$	727.0										
F_1	824.0	1	410.1	Yes	1	410.1	410.1	410.1			
F_2	905.0										
G_1	1112.0	1	15314.1	No			15314.1		77.3	15116.0	**20.4**
G_2	617.0										
$e2_1$	820.0	1	495.1	Yes	1	495.1	495.1	495.1			
$e2_2$	909.0										
e total					7	1386.4		198.1			
TOTAL		15	74038.9				74038.9				**94.9**

Table 7.5 Complete ANOVA table for the response TIME

8. **Pure variation of the source**

The pure variation of the source is calculated only for unpooled factors. It is the variation of a factor with the portion due to error variance removed, and is calculated by the formula [Ref. 14:p.97]: $S_X = S_x - (dF * V_e)$

For example, S_A= 58177.4–(1)*(16644.3)= 41533.1.

9. **Percent contribution of the source to total variation**

The percent contribution of the source to the total variation is also calculated only for unpooled factors. It is designated by "ρ_x", and is calculated by the formula [Ref. 14:p. 97]: $\rho_x = \left[\frac{S_X}{S_T}\right](100\%)$, where S_T is the total of all S_x at the bottom of the S_x column.

For this experiment, ρ_A= 41533.1 / 693500.2= 6%. This means that 6% of the total variation in response DIF is due to parameter "A".

E. CONCLUSIONS OF THE EXPERIMENT

Tables 7.4 and 7.5 are the completed ANOVA tables for both responses DIF (inventory fluctuation magnitude) and TIME (inventory fluctuation stabilization time) in the experiment. Upon completion of the analysis of variance, we now have four different quantitative measures of the responses of the various factors:

1. The means, or $\overline{\overline{X}}$ of DIF and TIME
2. The signal-to-noise ratios of DIF and TIME
3. The F-ratios of DIF and TIME
4. The percent contributions of factors to the total variation

1. Magnitude of inventory fluctuation (DIF)

For the magnitude of inventory fluctuation, the best levels of all factors are chosen by selecting the level of each factor that gave the minimum absolute difference between the maximum and minimum inventory levels.

Mean *($\bar{\bar{X}}$)*

The smaller the mean of response the better it is. In terms of means following are the optimum values of the factors, which can be seen in Table 7.3: A_1, B_2, $(A*B)_1$, C_1, $(A*C)_2$, $(B*C)_1$, D_1, $(A*D)_2$, $(B*D)_1$, E_2, $(C*D)_2$, F_1, G_2.

Signal-to-noise ratio

As stated earlier, the larger the S/N ratio, the better. According to signal-to-noise ratio three main effects are important: A, D, and G.

F-ratio

The F value for 95% confidence is *4.9646* for this experiment. As can be seen from Table 7.4 only two main effects are significant at this level: D, and G.

Percent contribution to total variance

It can be seen from the "ρ" column of Table 7.4 that 27% of the total variation in the experiment was due to parameter G (Inventory adjustment time), and parameter D (Handling delay) and A (Inventory coverage) were the next two largest contributors with 23% and 6% respectively. Overall, 63% of the variation was accounted for by five factors.

By looking at the signal-to-noise ratios, F-ratios, and percent contributions there are three parameters, which are responsible for most of the variation: A, D, and G. To find the optimum levels of these parameters we have to look at the mean effects. It can be seen that the optimum levels of the parameters for DIF (magnitude of inventory fluctuation) response are:

- A_1: Inventory coverage ratio 7 weeks
- D_1: Handling delay 1 day
- G_2: Inventory adjustment time 7 days

2. Inventory fluctuation stabilization time (TIME)

For the inventory fluctuation stabilization time, the best levels of all factors are chosen by selecting the level of each factor that gave the shortest inventory fluctuation stabilization time.

Mean ($\overline{\overline{X}}$)

The smaller the mean of the stabilization time the better it is. In terms of means following are the optimum values of the factors, which can be seen in Table 7.3: A_1, B_2, $(A*B)_2$, C_1, $(A*C)_2$, $(B*C)_1$, D_1, $(A*D)_2$, $(B*D)_1$, E_1, $(C*D)_2$, F_1, G_2.

Signal-to-noise ratio

As stated earlier, the larger the S/N ratio, the better. According to signal-to-noise ratio two main effects are important: D, and G.

F-ratio

The F value for 95% confidence is *5.5914* for this experiment. As can be seen from Table 7.5 seven factors are significant at this level: D, G, C, B, (B*C), (B*D), and (C*D).

Percent contribution to total variance

It can be seen from the "ρ" column of Table 7.5 that 32.1% of the total variation in the experiment was due to parameter D (Handling delay), and parameter G (Inventory adjustment time) was the second largest contributor with 20.4%. Parameter B, C, and interactions (B,C), (B,D), and (C*D) are the next largest contributors. Overall, 94.9% of the variation was accounted for by the factors investigated.

By looking at the signal-to-noise ratios, F-ratios, and percent contributions there are two parameters, which are responsible for most of the variation: D, and G. To find the optimum levels of these parameters we have to look at the mean effects. It can be seen that the optimum levels of the parameters for TIME (inventory stabilization time) response are:

- D_1: Handling delay 1 day
- G_2: Inventory adjustment time 7 days

However they are not significant for DIF response factors B, C, (B,C), (B,D), and (C*D) are significant for TIME response (because of their percent contributions). Therefore, we need to look at their optimum levels. Optimum levels can be easily found from the mean effects. They are: B_2, C_1, $(B*C)_1$, $(B*D)_1$, and $(C*D)_2$.

3. Optimum values of the parameters

Table 7.6 and 7.7 show the preferred levels of all factors with regard to two different responses have been chosen.

	MAIN EFFECTS						
DIF	A_1	B_2	C_1	D_1	E_2	F_1	G_2
TIME	A_1	B_2	C_1	D_1	E_1	F_1	G_2

Table 7.6 Optimum levels of parameters

	INTERACTIONS					
DIF	$(A*B)_1$	$(A*C)_2$	$(B*C)_1$	$(A*D)_2$	$(B*D)_1$	$(C*D)_2$
TIME	$(A*B)_2$	$(A*C)_2$	$(B*C)_1$	$(A*D)_2$	$(B*D)_1$	$(C*D)_2$

Table 7.7 Optimum levels of interactions

Here the two responses produce almost similar results. There are only two differences, one is parameter E and the other is interaction (A*B). We need to investigate the effects of these factors on responses to select their optimum level. If we look at the Table 7.4 and 7.5, we can see that both factors are not significant for either of the responses. Therefore, a management judgement must be made to select a level for them. For parameter E, a value midway between level 1 and level 2 was chosen.

It is important to note that if the preferred levels of main effects are used, the only interaction which will be optimized is (A*B) (assuming that we select $(A*B)_2$). This is true because of the rule for interaction. The rule is (as stated earlier in this chapter): if both main effects participating in the interaction are at the same level, the interaction is t level 1; if the main effects are at different levels, the interaction is at level 2. Since in this experiment we will attach more significance to main effects, the other interactions will not be optimized. Table 7.8 shows the optimized parameters and their levels.

	PARAMETER	LEVEL
A	Inventory coverage	7 weeks
B	Processing delay	4 days
C	Out-of-stock delay	0.2 day
D	Handling delay	1 day
E	Mailing delay	1.15 day
F	Transportation delay	0.5 day
G	Inventory adjustment time	7 days

Table 7.8 Optimized parameters

F. CONFIRMATION RUN

The last task in the experiment is to conduct a confirmation run, in which all parameters are put their chosen levels, and one final run is made to confirm that we can indeed produce an optimized product. The result of the confirmation run can be seen in Figure 7.1.

The maximum level of inventory is 7,710 units, and the minimum level is 7,660 units. The inventory level stabilizes at 7,670 units. The difference between the maximum and the minimum levels is only 50 units. If we investigate the stabilization time we can see that after the 26th week the inventory stabilizes. In addition the biggest fluctuation in inventory (50 units) is not even 1% of the stabilization level (7,670 units). The best results in the experiment were in the 1st run for the magnitude of the biggest fluctuation (40 units), and in the 11th run for the stabilization time (50 weeks). However, in the 1st run the stabilization time was 60 weeks, and in the 11th run the magnitude of the difference was 130 units. Therefore, it can be seen that the fluctuation magnitude and the stabilization time results are significantly better than those of any of the experimental run.

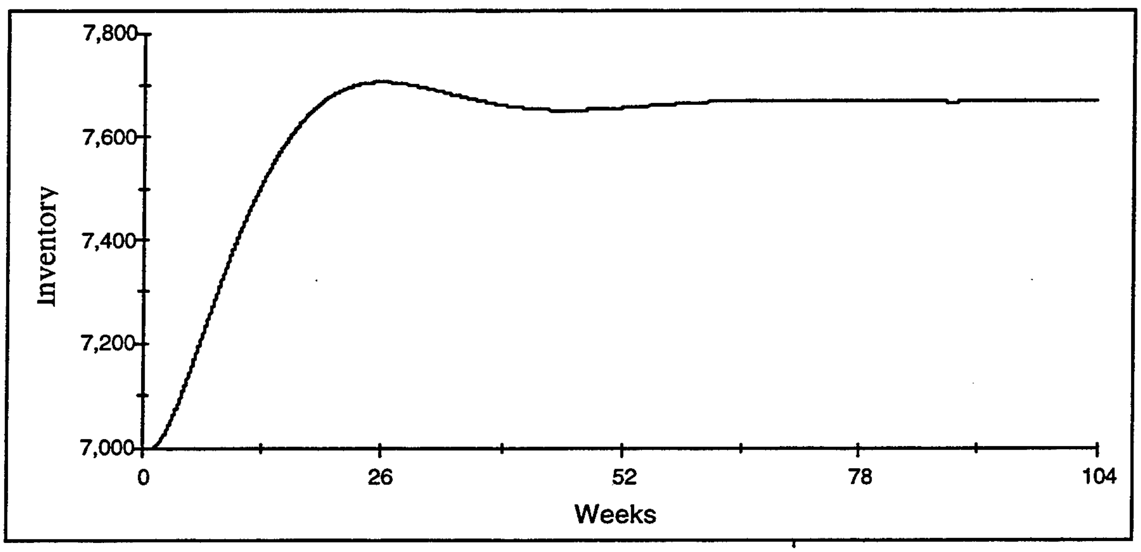

Figure 7.1 Inventory level in the confirmation run

VIII CASE STUDY

This case study has been developed to show the use of the simulation model build in this thesis to explore many important problems which are included in the regular business life and to supplement the material presented in the previous chapters.

A. COMPANY HISTORY

The Star Electronics Company[21] was a retailer of high technology T.V. sets in California area. Star had grown from a small start-up operation to a $10 million per year business in a span of ten years. The growth of its dollar volume was based on an excellent reputation for good service and rapid delivery coupled with the general expansion of industry in California. From its inception Star had been a profitable business in good financial condition.

In spite of the continued growth of profits in absolute terms, however, Star found that profits as a percentage of sales declined to well below the level that the company had enjoyed in the past. When management became aware of the seriousness of the problem, it was decided to undertake a thorough review of policies and procedures in the areas that could have significant influence on costs and profits—namely, stock handling and storage methods, billing and record keeping, and inventory management. The last area was included as a major area for study because the company had been experiencing increasing difficulty with unbalanced inventories, out-of-stock situations, and inventory level fluctuations.

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[21] This case is adapted from earlier versions of several different cases written in: [Ref. 20:p. 19], [Ref. 26:p. 315], [Ref. 27:p. 51, 123, 217].

Up until the time that the review of the inventory management policies and procedures was begun, there had been no formal study of this phase of the company's operations. Since maintaining inventories was one of the company's major functions, Star had always used experienced personnel to control the placing, handling and processing of orders and relied on inventory manager's judgement to make correct decisions. Because no formal study had been made previously of the inventory management operations, it was decided as a first step to get some general information about order processing, and inventory carrying and handling costs.

Analysis of the company records indicated that the following were reasonable estimates of the variable costs: The T.V. sets were purchased for $250 from a distributor and sold for $750. The cost of carrying inventory, including handling and processing costs, amounted to $50 per set. For this particular item, there were other retailers in Star's immediate vicinity that could supply a comparable T.V. set made by another manufacturer. Because of this, orders that Star could not fill immediately were lost, and Star's sales manager has determined that for all "lost sales" there should be a charge for damage to customers' goodwill of $100 per unit.

It has taken 0.3 to two days to ship and hand in the T.V. sets to the customers. An analysis of the delay in processing orders at the company indicated that this delay varied between two and four days. Further analysis of the historical records showed that there was a delay of minimum handling time between one and two days. The T.V. sets ordered from the distributor located about 500 miles away and shipped to Star by truck, which have generally taken half a day to two days. In addition, the out-of-stock items caused a delay of 0.2 day to two days. It is also found that the review of the inventory levels occurred once every four days, therefore, the inventory manager turned in his purchase requisitions only once in every four days (namely inventory adjustment time). Finally, the number of weeks of average sales, which could be supplied out of the inventory (inventory coverage) at the company was four weeks, since the day the company was started.

B. NEW CONTRACT

The Star Electronics Company contracted to deliver 10,400 units of T.V. sets at the rate of 100 units per week. A further contractual requirement was to deliver 200 units per week for the first 52 weeks, in order to receive a non-recurring payment of $500,000.

In both scenarios below the president and his staff believe that the demand rate in the new year will be the same as the demand rate in the year 1999.

C. SCENARIO 1

1. First meeting

Knowing that the company had already some inventory management problems before the new contract, the president called a management meeting to bring the key people of the company together and discussed the inventory problem. The president believed that this new contract might cause the inventory fluctuations to get bigger and lead more out-of-stock conditions. This would be a really serious problem for the company because profits had already declined and more out-of-stock situations would cause to loose customers and goodwill, which would lead to less profit. To emphasize the seriousness of the company's situation, the president distribute two charts, seen in

Figures 8.1 and 8.2, to the people at the meeting showing the inventory level of the company for the last two years. The president said, "As could be seen in Figure 8.1 customers' demand for our product was almost constant at 1,000 T.V. sets per week in 1997. Therefore, we had no out-of-stock situations, no significant inventory fluctuation, and our profits were increasing. Figure 8.2 showed the data of year 1998. In 1998 the demand from the customers began to show some randomness and seasonality. For example the demand peaked to 1,600 units per week around the 10^{th} week and dropped to 400 units per week around the 34^{th} week. In addition, in the first half of the year average sales were approximately 1,300 units per week, whereas in the second half it dropped to 700 units per week. This new fluctuating demand rate caused some out-of-stock conditions, which leaded to lower sales and decreasing goodwill and revenues. In addition, our inventory policy could not be able to keep the inventory level stabilized. We sometimes carried more than we need, which increased our inventory costs or sometimes carried less than we needed, which caused out-of-stock conditions. We believed that the demand pattern in 1998 will continue in 1999."

In discussing the situation, the president was assured that, at least for the foreseeable future, there would be no limitations on purchasing capacity. The company could purchase as many T.V. sets as it wanted from the distributor. The inventory manager also stated that inventory space was not a critical problem. The warehouse had been designed with space for expansion into new products or purchasing more products should the company desire.

The most important issue that bothered both the president and the inventory manager was the question of inventory coverage. When the company received an order, they would want to have enough on hand to take care of the demand plus some protection against higher than expected demand until the next time the inventory manager reordered. In 1998 the inventory coverage of four times the average sales leaded to some out-of-stock situations. In 1999 the president did not want to face any such situations. Besides, they already knew that the average demand in 1999 would at least be 200 units per week more than the average sales in 1998, because of the new contract. Therefore, they decided—guessed—to increase in the inventory coverage from 4 times to 6,000 times the average sales (six weeks of average sales could be supplied out of inventory).

Furthermore, they assumed that if they could decrease the time required to process and handle the orders they could decrease or might prevent the inventory fluctuations. Hence they decided to process the orders at most three days and handle the orders at one day.

At the end of the meeting they decided to meet every three months to review the efficiency of inventory management during the past three months and make some changes if necessary.

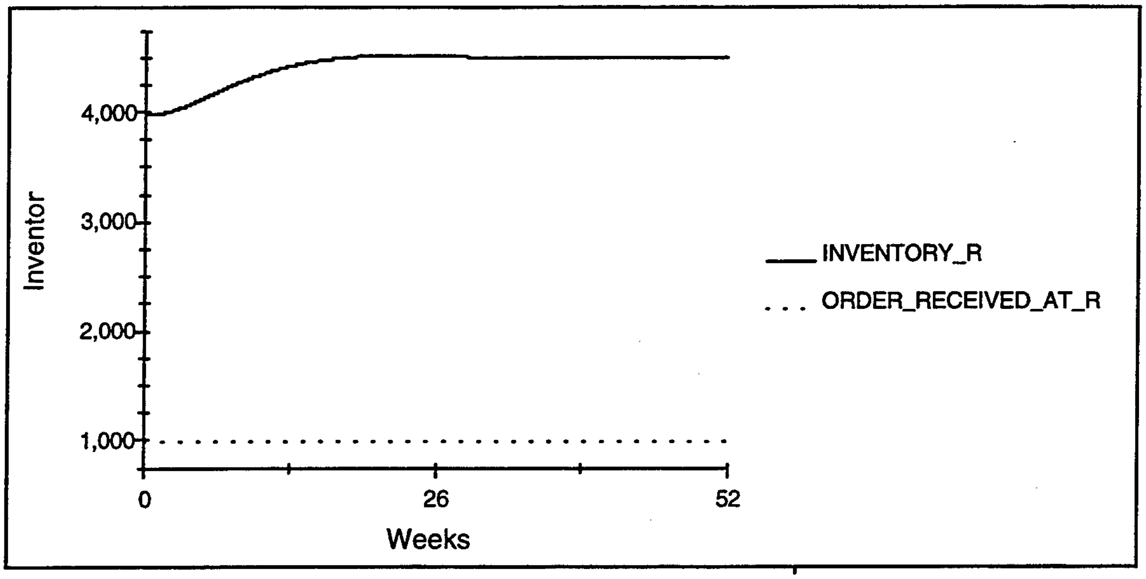

Figure 8.1 Inventory level and demand for T.V. sets in 1997

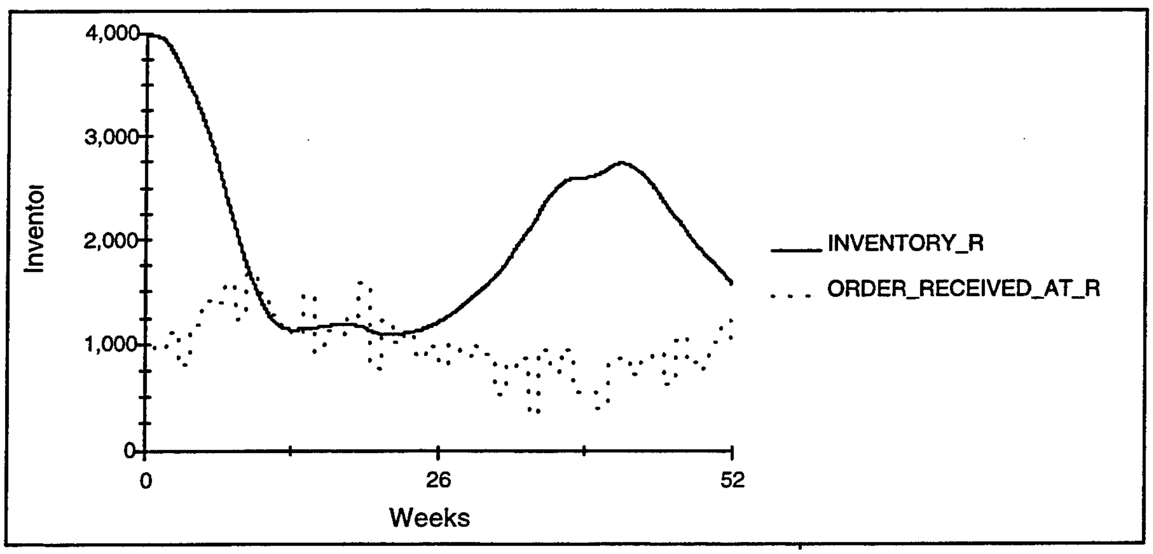

Figure 8.2 Inventory level and demand for T.V. sets in 1998

2. Second meeting

The president of the Star distributed the chart seen in Figure 8.3 at the beginning of the second meeting and said, "The chart shows that we have not faced any difficulty to meet the demand. There was no out-of-stock situation. However, we can see that our inventory level decreasing rapidly. We know that in 1998 customer demands peaked in the first six months. If the inventory continue to diminish at this rate we may not be able to satisfy all the demand."

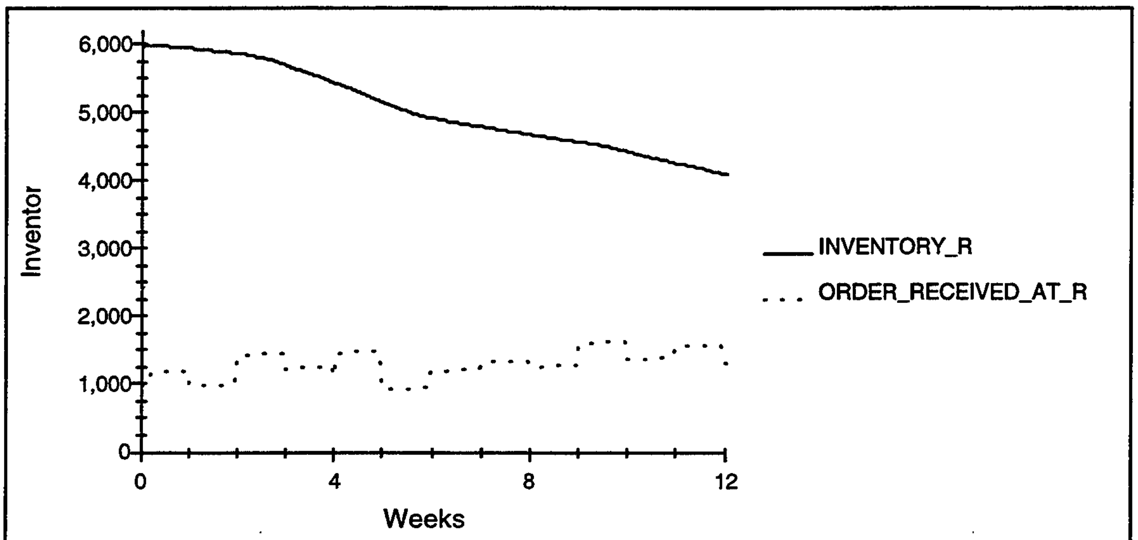

Figure 8.3 Inventory level and demand for T.V. sets in the first three months of 1999

Inventory manager continued, "I believe we can process and deliver the orders more quickly and decrease the time to satisfy out-of-stock demand." At the end of the meeting they decided to make the following changes: Inventory coverage ratio would be seven times the average sales. All orders would be processed in two days. Out-of-stock orders would be satisfied in one day. The orders would be delivered to the customers in one day.

3. Third meeting

The president said at the beginning of the meeting, "The chart (Figure 8.4), I sent to all of you yesterday, shows that we are still doing good in terms of out-of-stock situations. We gained our good service and rapid delivery reputation back. However, our inventory level is too high. We have had much more inventory than we needed during the last six months. This situation increased our inventory holding and handling costs too much and leaded to a low profit margin. Briefly, our stock holders are not pleased with the current situation of the company."

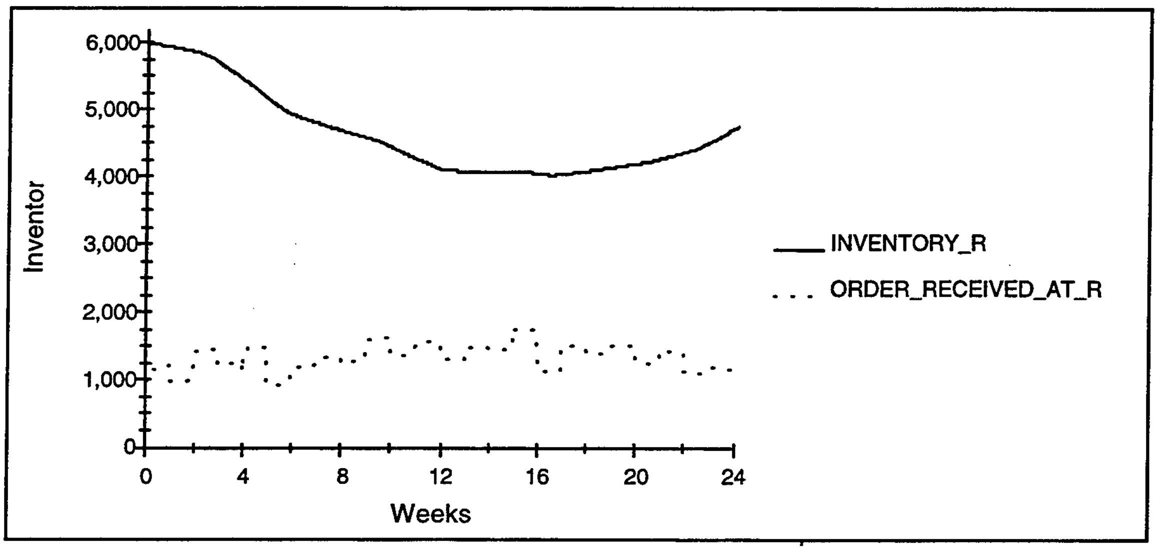

Figure 8.4 Inventory level and demand for T.V. sets in the first six months of 1999

The inventory manager said, "In the last six months of 1998, average sales was lower than the sales of the first six months. Assuming the same demand rate will continue in this year, we can decrease our inventory coverage ratio." They decided to hold five weeks average sales in the inventory to decrease the inventory level. In addition, they determined the following adjustments: The inventory manager would turn in his purchase requisitions once in every five days. The T.V. sets would be transported from the distributor in one day. Orders would be delivered in 18 hours and out-of-stock situations would be resolved in 12 hours.

4. Fourth meeting

The president started the meeting by saying, "We decreased our inventory coverage ratio in the last three months, but the average sales decreased too. As you can see in the chart (Figure 8.5), in fact the inventory level continued to increase two months as the average sales started to decrease. For that reason we could not achieved to lower the inventory costs. We closed the last three months with a loss because of the low sales rate and high inventory costs.

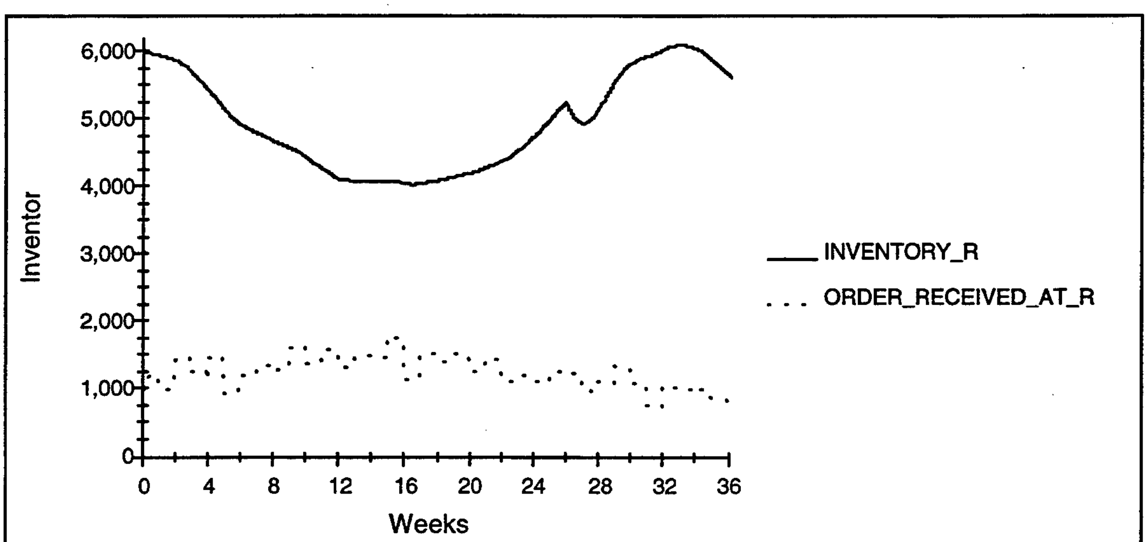

Figure 8.5 Inventory level and demand for T.V. sets in the first nine months of 1999

They concluded the meeting with the following decisions: Inventory coverage ratio would be four times the average sales. The T.V. sets would be transported from the distributor in 12 hours. The inventory manager would turn in his purchase requisitions once in every week.

5. End-of-the-year meeting

The president concluded the end of the year meeting as follows: "At the beginning of 1999, we established three main goals for our company: (1) keep the inventory level as low as possible, (2) prevent inventory level fluctuations, and (3) avoid out-of-stock situations. It is clear that we achieved the third objective and it is the only one we achieved. We achieved it at the expense of the other two goals, as can be seen in Figure 8.6. In fact, we made all shipments on time, and received the non-recurring payment of $500,000. However, we kept a very high level of inventory during all year to satisfy our demand. Only in the last three months, we finally managed to decrease our inventory level without causing any out-of-stock situations."

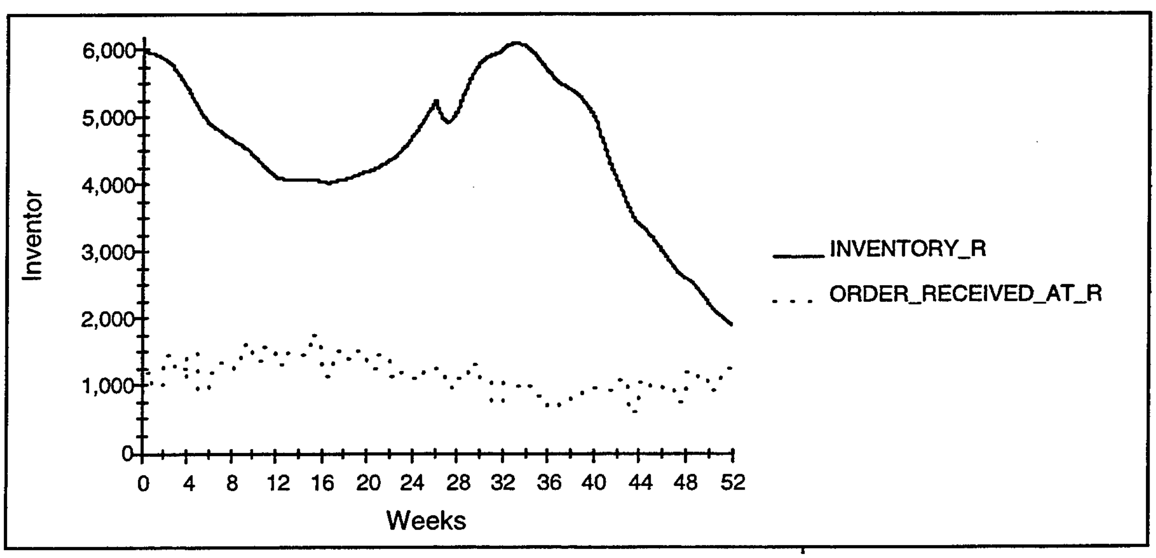

Figure 8.6 Inventory level and demand for T.V. sets in 1999

Furthermore, we could not keep our inventory at a stabilized level. The inventory level was "6,000 units per week" at the beginning of the year. It dropped to 4,000 units in April, increased to 6,000 units again in September and dropped to 2,000 units at the end of the year. These inventory problems created a huge inventory cost, which leaded to a year with a huge loss."

D. SCENARIO 2

In the winter of 1998, Star hired its first industrial engineer as the inventory manager. Several factors contributed to the decision to hire him. There had been a significant decrease in profits. This was due mostly to the inventory costs, which were higher than necessary and this made it difficult for the company to compete effectively. The new inventory manager's first assignment was to see if he could improve the efficiency of the inventory management.

Knowing that the company had already some inventory management problems before the new contract, the president called a management meeting to bring the key people of the company together and discussed the inventory problem. The new inventory manager attended the meeting, too. The president explained the inventory and the results of the review of the inventory management policies and procedures. He also stated his concerns about the new contract. The new manager listened to all discussions through the end of the meeting.

As soon as the meeting was over, the new inventory manager decided to investigate alternative methods for managing inventories. His objective was to determine whether worthwhile cost reductions could be made. In order to establish a point of reference, he took a detailed report of the review of the inventory management from the president. As he studied the report he noticed that there were seven distinct major operations and parameters; inventory coverage ratio, processing delay, out-of-stock delay, handling delay, mailing delay, transportation delay, and inventory adjustment time. He felt that if he studied carefully these operations and ratios and adjusted their values, he could gain some efficiency. After considerable experimentation he established a reasonable range for the time required for each major operation and a range for the value of each parameter.

He was somewhat uneasy about the high degree of variation in demand—especially the seasonal pattern and randomness—and about the optimal values of the time required for each major operation and the optimal value for each parameter. He felt that he should test the inventory management policies and procedures with a simulation before recommending that the changes be made. He assumed that, if his simulations achieved his anticipated increased efficiency, he would recommend the installation of the new inventory management policies.

As a result of his studies, he gathered sufficient data to conduct a simulation to determine the optimal values for the operations and parameters in order to minimize the inventory costs. After analyzing this data, the inventory manager became convinced that a system dynamics simulation model would help him in preparing the optimal inventory management policies and procedures. Although this technique is by no means a "crystal ball", its use would provide good estimations for parameter values to serve as a guide in planning inventory levels at the company. He developed a simulation model—the model we developed in this thesis— so that he could test each operation and parameter using the same demand sequence (demand rate in 1998).

To start his evaluation of the operations and parameters he chose the values that were the closest to the present inventory policy. Then, he found the following optimal values—using the same techniques we studied in the "Design of Experiments" chapter—for the operations and parameters based on the demand rate in 1998: The incoming orders would be processed in two days. Out-of-stock orders would be satisfied in five hours (by buying the product from a different distributor or retailer, if necessary). Orders would be handled in one day and shipped to customers in 10 hours. The T.V. sets would be transported from the distributor the company in twelve hours. The purchase requisitions would be turned in once in every week.

He found that the key element to control the inventory level was the inventory coverage ratio. After setting all other parameters and operations to their optimal values, he found the optimal inventory coverage ratios for each week as follows:

- The first week; three weeks (three weeks of average sales can be supplied out of the inventory)
- The second week: four weeks
- The third week; three weeks
- The fourth week; two weeks
- The fifth week; one week
- Between the sixth and fortieth weeks; 0.5 week
- Between the fortieth and fiftieth weeks; one week
- Between the fiftieth and fifty second weeks; two weeks.

The simulation results convinced him that the anticipated gain in efficiency could be realized with the optimal settings he found for the parameters and operations. He, then, discussed his new inventory management policy with the president at a meeting. During this meeting, the inventory manager presented the analysis that he had prepared using his simulation model. Ultimately, he proposed to revise the current inventory management policy with the new policy he developed. The president agreed to let the inventory manager use his simulation model for managing inventories.

E. VALUE OF THE SIMULATION MODEL

After an hour of evaluation of the year 1999, the president concluded the end-of-the-year meeting (of scenario 2) by saying,

Inventory management, in every company, deals with the problem of keeping correct amount of items in the inventory so that neither too much capital is tied up in the form of unused inventory nor too few items are kept in inventory so that customers are lost. In the year 1998 our inventories were always either excessive or insufficient. Due to this problem, we could only manage to be break-even in that year.

However, in the year 1999 the simulation model, which was developed by our inventory manager, provided the management with a rational and traceable, yet flexible, means to analyze and establish inventory management policies. It served as a central storage for a large amount of data, and integrated a variety of models that represented inventory policies. The simulation model made a very powerful decision-making tool directly and readily accessible to the management. The management team is unanimous it its praise of the simulation model. It let us keep the inventory as low as possible so that *capital could circulate while still maintaining an adequate supply to meet the customers' orders as can be seen in Figure 8.7.*

The simulation model was not used just operationally to set inventory levels, but also at a strategic level. It was used to forecast or project future values, design new inventory policies to satisfy unpredictable changes in the demand rate, assess the impact of policy changes, and perform sensitivity analyses.

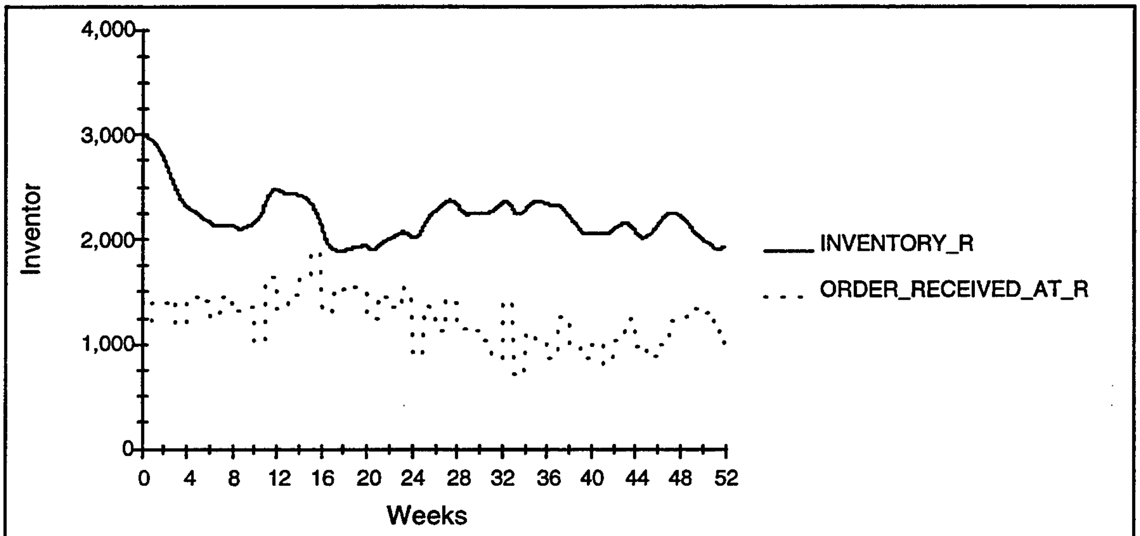

Figure 8.7 Inventory level and demand for T.V. sets in 1999

F. COMPARISON

We need not tell much to show the superiority of the simulation model (Scenario 2) over arbitrary judgement (Scenario 1). It is enough to investigate the tables and figures below to understand the effect and the use of the simulation model in a real business environment.

First objective of the management at the beginning of the year 1999 was to stabilize the inventory level (to minimize the inventory level fluctuations) and to keep this level as low as possible. Table 8.1 shows how efficient the management was in achieving this objective in each of the scenarios. It shows the maximum, minimum, and average level of inventory, and the difference between the two extreme levels as a percentage of the average sales for each scenario. It is clear from the table that the inventory values for scenario two (with the simulation model) are much better than those for scenario one.

	Scenario 1	Scenario 2
Maximum level of inventory (units)	6100	2500
Minimum level of inventory (units)	2200	1900
Average level of inventory (units)	4750	2200
Difference between max. and min. levels	3900	600
Maximum difference as a % of average sales	82% (3900/4750)	27% (600/2200)

Table 8.1 Comparison of the scenarios

The second objective of the management was to lower the inventory carrying costs, thus, to increase profits. Figure 8.8 shows the exact and smoothed (polynomial curve with degrees of freedom three) profits for each scenario in the year 1999. It is assumed that profits equal to total revenue minus total inventory costs (all other costs are disregarded for simplicity). It is obvious that the profits gained by using the simulation model are much higher and stabilized than the profits earned by the arbitrary judgement of the management.

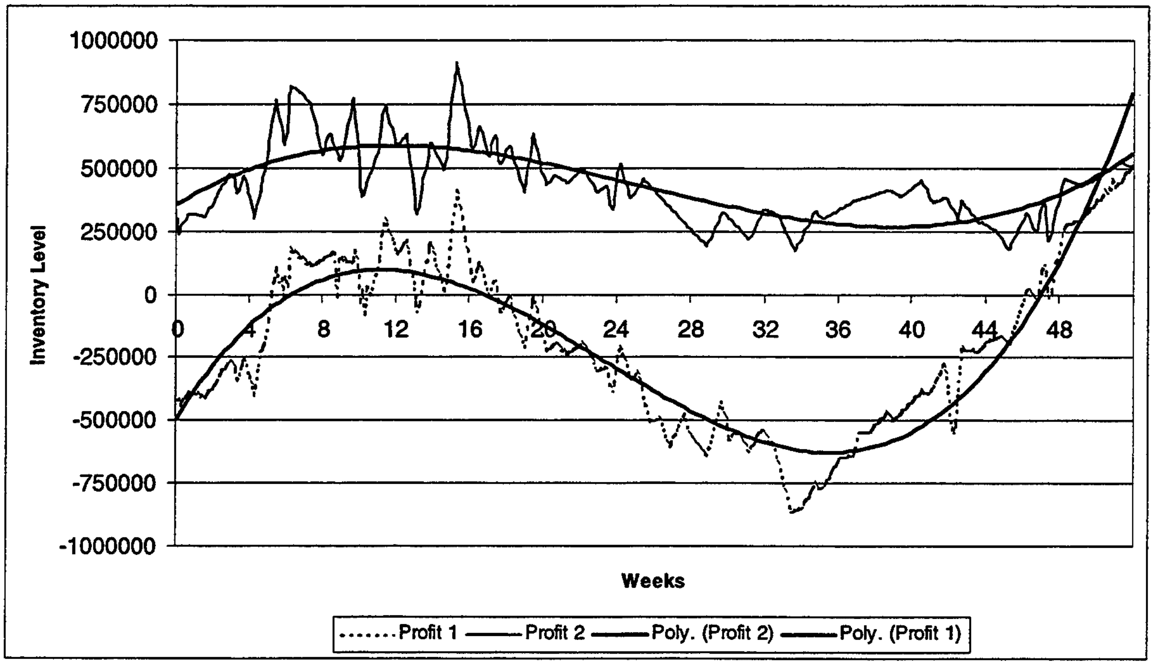

Figure 8.8 Profits for each scenario in 1999

IX CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

System dynamics and simulation gaming share many common characteristics. As Mohapatra and Saha point out, both are dynamic situations; both are simulation exercises; both evaluate effects of decision functions and often use computers to carry out this evaluation; and both aspire to enhance understanding of the real-life situation modeled. Therefore, it is appropriate and beneficial to combine them in a single model or simulation [Ref. 23: pp. 238].

In this thesis, we discussed how Forrester's "Industrial Dynamics" model was converted into a computer network game by using Powersim® software package. Our purpose was to provide hypothetical business scenarios in which players or managers can practice decision making in their companies.

At the beginning we have provided enough background about system dynamics and its methodology. We have explained the necessary elements to build a system dynamics model. Then, we have introduced Forrester's "Industrial Dynamics" model, and explained the general characteristics of this model. While examining the model, we have realized that this model presented a good organizational setting and provided good background material for a business game.

After deciding that the "Industrial Dynamic" model is appropriate for a business game, we have described the principles to formulate dynamic systems for simulation. We have converted the model into a computer network game by using the Powersim® software package to improve managers' decision-making processes. Then, we have showed how managers or players can use the network game. The game was very user-friendly and easy to use and understand. The players (maximum of seven players) could play the game by just using the mouse and clicking on the buttons and slide bars. The graph in the game interface provided simultaneous feedback by showing the current levels of the interested variables—inventory and unfilled orders levels.

We have tested and validated the simulation model. To do this, we have used several different patterns of customer purchases as input to the model. We have (1) increased the customer purchases suddenly; (2) introduced an unexpected seasonality; and (3) inserted a random variation into the customer purchases. Then, we have tested the model's behavior to all these changes. In addition, we have limited the manufacturing capacity of the factory, adjust some parameter values in the model to make the test situations more realistic. In all these tests satisfactory results were obtained and therefore we have established sufficient confidence in the model to use it for our purposes.

We have stated that the primary purpose of the system dynamics is to develop policies, which improve the dynamic behavior of a system and to aid in the design of improved industrial and economic systems. To achieve this objective we have conducted a design of experiment in which we tried to design the best possible robust behavior into the system. We have used Taguchi methods to conduct our experiment since these methods collect data quickly and efficiently. In this experiment we have found the optimum parameter levels, by conducting an ANOVA and by examining the signal-to-noise ratios, that minimize the inventory oscillations and the inventory stabilization time at the retail sector. Finally, we have conducted a confirmation run, in which all parameters were put their optimum levels. We have seen that the fluctuation magnitude and the stabilization time of the inventory were significantly better (with the optimum levels) than those of any of the previous runs.

At the end, we have used the network game in a case study to show the use and benefits of the simulation model to explore many significant real life problems. In the first scenario the inventories of the company were managed with the conventional methods—by guessing. Hence, the company experienced a huge loss and diminished goodwill. In the second scenario, the company used the simulation model, and found the optimum parameter levels for the business environment that they faced. The company kept much less inventory than it kept in the previous years and yet managed to satisfy the demand. Inventory fluctuations also were much less than the fluctuations in scenario one. Therefore, the company concluded the year with a profit and increased goodwill.

The simulation model provided the management with a rational and flexible means to analyze and establish inventory management policies. It served as a very powerful decision-making tool directly and readily accessible to the management. Furthermore, it was used to design new inventory policies, assess the impact of policy changes, and perform sensitivity analyses.

We concluded that the simulation model, as a decision support tool, supports planning, decision-making, and policy-setting processes by providing a way to readily analyze the effect of changes in the operations and resources that impact inventory levels and costs. In addition, it provides a means to test, present and proposed policies under different scenarios. The game creates a "dynamic business environment" in which the players—managers—can practice decision making in their companies.

Ultimately, the network game developed in this thesis is a tool for managers to understand the complex structure of manufacturing-distribution systems. It equips such systems with a desktop, system dynamics based decision support tool to integrate and rationalize the functional areas of management, and to improve the design of their systems. This tool will help managers acquire the necessary experience and system-wide view of the effect of "local" changes to the whole system without "field" work.

B. RECOMMENDATIONS

There are six interacting flow networks in an industrial system—materials, orders, money, personnel, capital equipment, and information. The simulation model developed in this thesis includes only the materials, the orders, and the information flow networks. It could be modified so that money, personnel and capital equipment networks took into consideration and their effects on the behavior of organization could be examined.

Another approach could be to extend the simulation model developed in this thesis to include the market-advertisement interaction of the industry. This model could determine how consumer deferrability of purchase might be influenced by advertising. The model in this thesis could be developed to include multiple products and can be used to improve the inventory management of more than one products.

APPENDIX SYSTEM OF EQUATIONS

In the model, the equations for the three sectors—retailer, distributor, and factory—are formulated. Forrester's original mathematical notation[22] is rewritten to keep the notation close to the vocabulary of business and to keep the formulation easy enough for any user who will run the simulation model. Below is the summary of the equations that are copied from the "Equations view" of Powersim©.

1. init Average_Sales = Initial_Orders_Received

flow Average_Sales = +dt*Order_Sum

2. init Goods_InTransit = Initial_Goods_Intransit

flow Goods_InTransit = -dt*Shipment_In+dt*Shipment_Out

3. init Inventory = Initial_Inventory

flow Inventory = -dt*Shipment_Out+dt*Shipment_In

4. init Orders_InMail = Initial_Orders_InMail

flow Orders_InMail = +dt*Orders_Sent1-dt*Purchase_Orders

5. init Orders_InProcess = Initial_Orders_InProcess

flow Orders_InProcess = +dt*Purchasing_Rate1-dt*Orders_Sent

6. init Unfilled_Orders = Initial_Unfilled_Orders

flow Unfilled_Orders = +dt*Orders_Received-dt*Shipment_Out

7. aux Order_Sum = (Orders_Received-Average_Sales)/Averaging_Time

---

22 Original equations can be seen in [Ref. 1:p. 141].

8. auxOrders_Received=Customer_Orders WHEN p=FIRST(p) BUT Purchase_Orders (p-1) OTHERWISE

9. auxOrders_Sent = DELAYINF(Purchasing_Rate1(p), Delay_In_Processing,3)

10. auxOrders_Sent1 = Orders_Sent

11. auxPurchase_Orders = DELAYINF(Orders_Sent1(p), Delay_In_Mailing, 3)

12. auxPurchasing_Rate= Customer_Orders+(1/Inventory_Adjustment)*((Inventory_Desired-Inventory)+(Desired_Pipeline_Orders-Pipeline_Orders)+(Unfilled_Orders-Normal_Unfilled_Orders)) WHEN p=FIRST(p) BUT Customer_Orders +(1/Inventory_Adjustment)*((Inventory_Desired-Inventory)+(Desired_Pipeline_Orders-Pipeline_Orders)+(Unfilled_Orders-Normal_Unfilled_Orders)) OTHERWISE

13. auxShipment_In = DELAYMTR(Purchasing_Rate(p), Lead_Time, 3, Purchasing_Rate(p)) WHEN p=LAST(p) BUT DELAYMTR(Shipment_Out(p+1), Delay_In_Delivery, 3) OTHERWISE

14. auxShipment_Out = IF(Neg_Inventory_Limit>=Desired_Shipping, Desired_Shipping, Neg_Inventory_Limit)

15. auxCustomer_Order= (ORDER_SWITCH=1) *CNS_1000+(ORDER_SWITCH=2) *RND_INPUT+(ORDER_SWITCH=3)*CYCLE_INPUT+(ORDER_SWITCH=4)* STEP_INPUT

16. auxCustomer_Orders = Customer_Order

17. auxCYCLE_INPUT = 1000+SINWAVE(100,52)

18. auxDelay_In_Delivery = SELECTDECISION(INDEX(p), Delivery_Decided, Delivery_Simulated, Delivery_Simulated, Delivery_Dummy)

19. auxDelay_In_Filling= Min_Handling_Time + (OutofStock_Delay *(Inventory_Desired /Inventory))

20. auxDelay_In_Mailing = SELECTDECISION(INDEX(p), Mail_Decided, Mail_Simulated, Mail_Simulated, Mail_Dummy)

21. auxDelay_In_Processing = SELECTDECISION(INDEX(p), Process_Decided, Process_Simulated, Process_Simulated, Process_Dummy)

22. auxDesired_Pipeline_Orders = Average_Sales*(Delay_In_Processing+Delay_In_Mailing+Delay_In_Filling(p+1)+Delay_In_Delivery) WHEN p<LAST(p) BUT Average_Sales*(Delay_In_Processing+Lead_Time) OTHERWISE

23. auxDesired_Shipping = Unfilled_Orders/Delay_In_Filling

24. auxInitial_Goods_Intransit = Delay_In_Delivery*Initial_Orders_Received

25. auxInitial_Inventory = Initial_Orders_Received*Inventory_Coverage

26. auxInitial_Orders_InMail = Delay_In_Mailing*Initial_Orders_Received

27. auxInitial_Orders_InProcess = Delay_In_Processing*Initial_Orders_Received

28. auxInitial_Unfilled_Orders = Initial_Orders_Received*(Min_Handling_Time +OutofStock_Delay)

29. auxInventory_Adjustment = SELECTDECISION(INDEX(p), Inventory_Adj_Decided, Inventory_Adj_Simulated, Inventory_Adj_Simulated, Inventory_Adj_Dummy)

30. auxInventory_Coverage = SELECTDECISION(INDEX(p) , Coverage_Decided, Coverage_Simulated, Coverage_Simulated, Coverage_Dummy)

31. auxInventory_Desired = Inventory_Coverage*Average_Sales

32. auxMin_Handling_Time = SELECTDECISION(INDEX(p), MinHandling_Decided, MinHandling_Simulated, MinHandling_Simulated, MinHandling_Dummy)

33. auxNeg_Inventory_Limit = Inventory/TIMESTEP

34. auxNormal_Unfilled_Orders = Average_Sales*(Min_Handling_Time+ OutofStock_Delay)

35. auxOutofStock_Delay = SELECTDECISION(INDEX(p), OutofStock_Decided, OutofStock_Simulated, OutofStock_Simulated, OutofStock_Dummy)

36. auxPipeline_Orders = Orders_InProcess+Orders_InMail+Unfilled_Orders(p+1)+ Goods_InTransit WHEN p<LAST(p) BUT (Orders_InProcess+Orders_InMail) OTHERWISE

37. auxRANDOM_INPUT = NORMAL(1100,100)

38. auxRND_INPUT = SAMPLE(RANDOM_INPUT, 1,1,1100)

39. auxSTEP_INPUT = 1000+STEP(100,1)

40. const Averaging_Time = [24,24,24,24,24]

41. const CNS_1000 = 1000

42. const Initial_Orders_Received = 1000

43. const Lead_Time = 7

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