A System Dynamics Model for Operations Management Improvement in Multi-plant Enterprise

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Executive Summary

Decision making in multi-plant setups has to strive towards reconciling several manufacturing plants activities in such a way that they align their tasks towards improving overall performance of the enterprise. Each plant's internal function is as important as it's relation with other plants since each plant is part of the network. The main objective of this study is to identify important issues that managers and researchers must address so that operational decisions of multi-plant setups can be determined for all plants of an enterprise form the enterprise perspective.

The approach adopted started by identifying important tasks of operations management. Identification of the important tasks of operations management in multi-plant enterprise is carried out by studying an already developed agent based model and literature. Scheduling, inventory management (procurement and storage) and production operations have been identified as key tasks of operations management in multi-plant enterprise. Moreover, criteria were set to determine the effectiveness of the operational functions from the perspective of the enterprise. The most widely used performance indicator from the enterprise perspective, the delivery lead time also used in this study as the performance indicator.

Then the system dynamics modeling is used for modeling. System dynamics perceives processes in the world in terms of stocks, flows between those stocks, and information that determines the values of the flows. Single events are less relevant than behavior; events are abstracted to an aggregated view on feedback loops and delay structures. This integrated view of a system as a unified whole as promoted by this method was used to investigate contribution of this modeling paradigm to the operations management problem in multi-plant set ups.

The process of system dynamic modeling was started by conceptualization. During conceptualization, the different factors that influence operations management functions in multi-plant enterprise were developed from literatures and an existing agent based model. These factors have been also crossed check with experts for their dependability.

Before interpreting and using the results of the model, the model has to be verified and validate. Although there was no actual data for validation, some of the simulated results of an agent based model for the same problem were used to validate the model. The result of the verification and validation test shows viability of the model for the intended purpose.

Plausible improvement tactics are defined in relation to the outcome of the sensitivity analysis. It is revealed that tactics originated from sensitivity analysis are appealing to be combined further as strategy since this tactics generates desirable results. The strategy used the four tactics to improve the performance of the enterprises operations management. These tactics includes increase safety stock, reduce the raw material delivery lead time, increase raw material inventor capacity, and increase plant production capacity. Combination of these tactics results in a more aggressive impact on the performance indicator as compared to the individual impacts of each tactics.

Of the two strategies constructed the first brings a considerable improvement in the enterprises delivery lead time without changing any physical conditions, whereas the other strategy also brings a considerable improvement by considering some physical changes.

Within the limitation of the model assumption and simplification, the first strategy lowers the delivery lead time of the enterprise by 20%. Second strategy also reduces the enterprises delivery lead time by 23%.

Furthermore, the robustness of these strategies in dealing with the uncertain future has been explored under three different future scenarios. Both strategies are robust with all the three scenarios except ‘the capacity change’ strategy under the scenario ‘demand fall’ is unreasonable. Because this strategy is includes increasing the plant capacity and if the demand actually falls then is it unwise to have an enlarged capacity for a reduced demand.

And finally, the modeling approach of this study has been compared with that of an existing agent based model developed for the same problem. The two paradigms performance is evaluated based on the efficiency, robustness and flexibility.

Considering efficiency some of the important factors used to describe the problem are easily captured by agent based modeling where as it is very difficult, if not impossible, to incorporate in the system dynamics model. Considering robustness, both models can easily include new parametric change. In case of introducing a new factor, agent based model is much more robust. This is because system dynamic model is based on a predefined structure of the problem which makes it very difficult to easily include new factor without adjusting the predefined structure. Flexibility is the strength of both modeling paradigms. One can easily use part or all of a model which is built using these two paradigms. System dynamic model and its behavior can easily and understandable be explained and communicated with. But that is not the case with agent based model.

A future work in the operations management in multi-plant enterprise is to combine the two modeling paradigms (Agent Based modeling and System Dynamics modeling) which can be very useful to exploit the potential strength of each paradigm and overcome the limitations of each approach.

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This thesis is possible due to the contribution of some people. It is my pleasure to thank those who made this thesis possible.

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Part I: Problem Exploration and Research Framework

1. Introduction

1.1. Research Context

Faced with dynamic market changes and competitive threats, manufacturers are broadening their focus from execution within a single plant to a global network of plants to preserve their competitive advantage. Extended enterprise employs geographically dispersed manufacturing plants for more reasons such as saving on transportation cost/time, and/or to improve the customer service by locating the plant close to the customer and/or to have a strategic advantage to a unique resource.

When the manufacturing network is composed of plants that are able to make different products, the enterprise can respond more quickly to dynamic market events. Unfortunately, this brings a challenge to decision makers due to the added complexity within and around the enterprise. The decision making process have to take into consideration important issues of these complexities to manage the enterprise effectively.

Behdani et al (Behdani et al, 2007) developed an Agent-based model of a multi-plant enterprise with geographically dispersed plants to demonstrate the contribution of such model to operations management in a multi-plant enterprise. Presently, as extension to this earlier work, they continue their research work on "Abnormal Situation Management in Industrial Networks and Supply Chain" at the Faculty of Technology, Policy and Management.

This research work focusing on the same objective, but uses a different modeling paradigm, namely system dynamics. Using system dynamics, this study further explore the important issues that managers and researchers must address so that operational decisions can be determined for all plants in such a way that the organization as a whole performs better. Furthermore; the implication of the outcomes of the two modeling paradigms will be analyzed.

1.2. Background

In order to remain competitive in today's ever-changing markets, companies have to examine alternative solutions for their logistics network. One of these solutions may be shifting from one-plant manufacturing facilities to multi-plant enterprise. Such shifting can bring many advantages, i.e. being close to low cost raw materials, proximity to market, flexibility in producing many products and specialization in activities (Maritan, *et al.*, 2004).

At the same time, decision making in multi-plant setups has to strive towards reconciling several manufacturing plants activities in such a way that they align their tasks towards improving overall performance of the enterprise. Each plant's internal function is as important as it's relation with other plants since each plant is part of the network.

Although overall objectives are often not defined in detail and concerned with a longer time horizon, the local objectives are generally more detailed, concerned with a shorter time horizon and often with the specific interests of individual plant. To facilitate an overall optimization of the performance of the system as a whole, a kind of coordinator may be required to supervise local decision making in its relation to the overall goal. Such a complex network of production plants needs a special form of operations management in order to coordinate the plant dependant activities and attain an optimal performance of the system form the enterprise perspective (Bhatnagar *et al,* 1993).

This operations management involves decision making on how to best operate a multi-plant enterprise and at the same time how to operate the separate plants, too. These decisions can be categorized into long, medium, and short-term decisions. The long-term decisions basically deal with plant strategies, product planning, and the design of facilities and processes. The medium- and short-term decisions are concerned with planning and control of production activities; more precisely, procurement and inventory management, sequencing and scheduling, quality management and maintenance management (Lee-Post and Chung, 2008).

Although some of those decisions can be made by an individual company, in a multi-plant enterprise each plant is a part of a corporate network and its relation with other plants is as important as its internal model. With an appropriate operations management, the enterprise can respond more quickly to dynamic market events, reduce its operating costs and increase customer satisfaction.

Different literature has focused on the different scenarios of the multi-plant operation management. Bhatnagar et al (Bhatnagar et al, 1993) discussed the multi-plant coordination problem in two levels. The first level, called General coordination, can be seen as integrating decisions of different functions like inventory planning and production planning inside one plant. At another level, called multi-plant coordination, the coordination of decisions of same functions at different plants, for example production planning at different plants, was considered. In order to get the benefits of multi-plant coordination, the critical issue of demand fluctuation, lot sizing and safety stock need to be integrated as these has a considerable impact on a firm’s performance.

Jolayemi and Olorunniwo (Jolayemi and Olorunniwo, 2003) tried to determine an optimal production and transportation quantity using a mathematical model for multi-plant, multi-warehouse setups. Their model integrates three different means of satisfying customer’s demands namely production, subcontracting, and use of inventory. The mixed integer linear programming model maximizes total profit over finite planning horizon.

Moreover, some works was mainly focused on planning and scheduling decisions in multi-plant enterprise. Kanyalkar et al (Kanyalkar et al, 2005) proposed a linear programming model to integrate planning at the top level considering multiple plants capacity, demand from several selling location, and the capacity at each plant levels of the enterprise as opposed to the hierarchical production planning procedure to improve the production and distribution decision. Factors such as the limitations of storage space, raw material availability and production capacity at plants as well as a requirement of maintaining a minimum level of inventory buffer have been modeled. The capacity of the manufacturing locations and the periodical demand from the selling locations was used to handle the time varying demand.

Many of the models developed in the literature for solving the challenge of operations management in multi-plant enterprise used a mathematical method. Many of these models consider the problem form specific functional point of view like inventory management, planning, scheduling etc (Jolayemi et al, 2004). These studies are concerned with part of a bigger problem within the context of large enterprises. This unduly focus has not provided a conceptual framework needed to identify the inter-relationship and impact of operations management on the total enterprise.

System dynamics is a methodology that is capable of studying and modeling complex system as it is the case for a multi-plant enterprise. Despite their diversity, multi-plant enterprise setup has many structural and functional features in common that can be effectively simulated. This research is designed in view of getting an additional insight of a multi-plant enterprise system from the perspective of a system dynamic modeling approach.

1.3. Research Goal and Question

The main objective of this research is to identify important issues that managers and researchers must address so that operational decisions can be determined for all plants of an enterprise as a whole using a system dynamic modeling approach.

The main question for the research is:

How can operations management in Multi-plant enterprise be improved using a System Dynamic simulation model?

The following research questions will lead to answering the main question.

1. What are the tasks of operation management in Multi-plant enterprise and what are their possible relations?
2. With what proper criteria can the improvement of these tasks be assessed?
3. Using system dynamic modeling approach, what must be included in the simulation?
4. Based on the improvement criterion, what can be concluded from the model?
5. By comparing the result of the SD model with that of an existing Agent based model, what can be concluded?

1.4. Scope and Outcome

Research Scope

The main focus of this research is on operations management decisions at different level (which includes, enterprise, plant and departments within a plant) of a Multi-plant enterprise. The decisions considered in this study are mainly concerned with the short to medium-term horizons. The long-term decision or strategic behavior of the enterprise is assumed to be given and stable. The different operational decisions at different levels of the enterprise will be examined in order to find their implication to the performance of the overall enterprise. As an assumption, cost and cost implications of any decision process are not considered due to the added complexity.

The study is designed to achieve the following two goals. The first goal, the model has to provide an insight on the operations management decision in a multi-plant enterprise. Another goal is to help compare and contrast the results of a different modeling paradigm (namely agent based modeling) used in solving operations management problem with that of the System dynamic model built in this study.

Within this scope, it cannot be expected that a complete and finished answer is given to the problem under consideration. This research is of an explorative nature, because of the complexity of the system and the limited literature that is available on the focus used in this thesis.

Research Outcome

The expected result of this research is a system dynamic model that helps enterprise managers make operations management related decisions in multi-plant enterprise efficiently. The model also helps researchers and managers identify important issues that must be addressed in order to align the different operational functions of the enterprise in the pursuit of their long term strategy. Furthermore, the implication of the system dynamic model developed in comparison with an already developed agent based model will be presented.

1.5. Research Approach

The research approach is designed in such a way that it will answer the research questions defined in section 1.3. The following steps show the research approach;

1. Capturing the concept of operation management in multi-plant enterprise

The different factors that influence operation management in multi-plant enterprise will be determined after a closer look at the literatures and an already built agent based model. The identified factors will be reviewed by experts to minimize the risk of neglecting important variables.

2. Model Building

The next step is to build the model for analysis. The model has to include the relevant variables and the relation among them and also performance indicators.

Before starting to use the model for the intended purpose it has to be verified and validated. At this stage the expert opinion and the consistency of the model with that of the expected behavior is significant.

3. Model Usage

At this stage of the research, a plausible tactics and strategies will be developed using the model and modeling process. These alternatives will be evaluated based on the performance indicator to illustrate their contribution to the operations management in multi-plant enterprise.

4. Result comparison

Finally, the results of this research finding will be compared with that of Agent based model to reflect how to start on comparing and/or translating one modeling paradigm to another. A model benchmarking approach will be used to facilitate this cross comparison.

1.6. Report Structure

The thesis consists of three parts. Part I gives a thorough background on the problem and some theoretical background on the modeling approach. Part II presents the modeling process that follows this approach. Part III presents the results of simulation runs of the model and reflects on the approach and the modeling choices. Figure1 summarizes the structure of the thesis.

The first part, which includes this section, explores the problem area and the revised literatures including the theoretical backgrounds for the study which will be useful for further analysis in later stage.

The second part details on the development of the model by first explaining the case study. The model conceptualization in Chapter four, basically, is a thorough overview of the models' main components together with a discussion of the system boundaries for which the model holds. Chapter five contains the model specification which includes the verification and validation as well.

The third part is dedicated to the result and reflection on the research. In chapter six the model output and its usage to tackle the problem is addressed by developing strategies and tactics. The comparison of the modeling approaches will be dealt in chapter seven followed by the overall modeling process experience in chapter eight. Finally, chapter nine discusses the major conclusion and recommendations of the study.

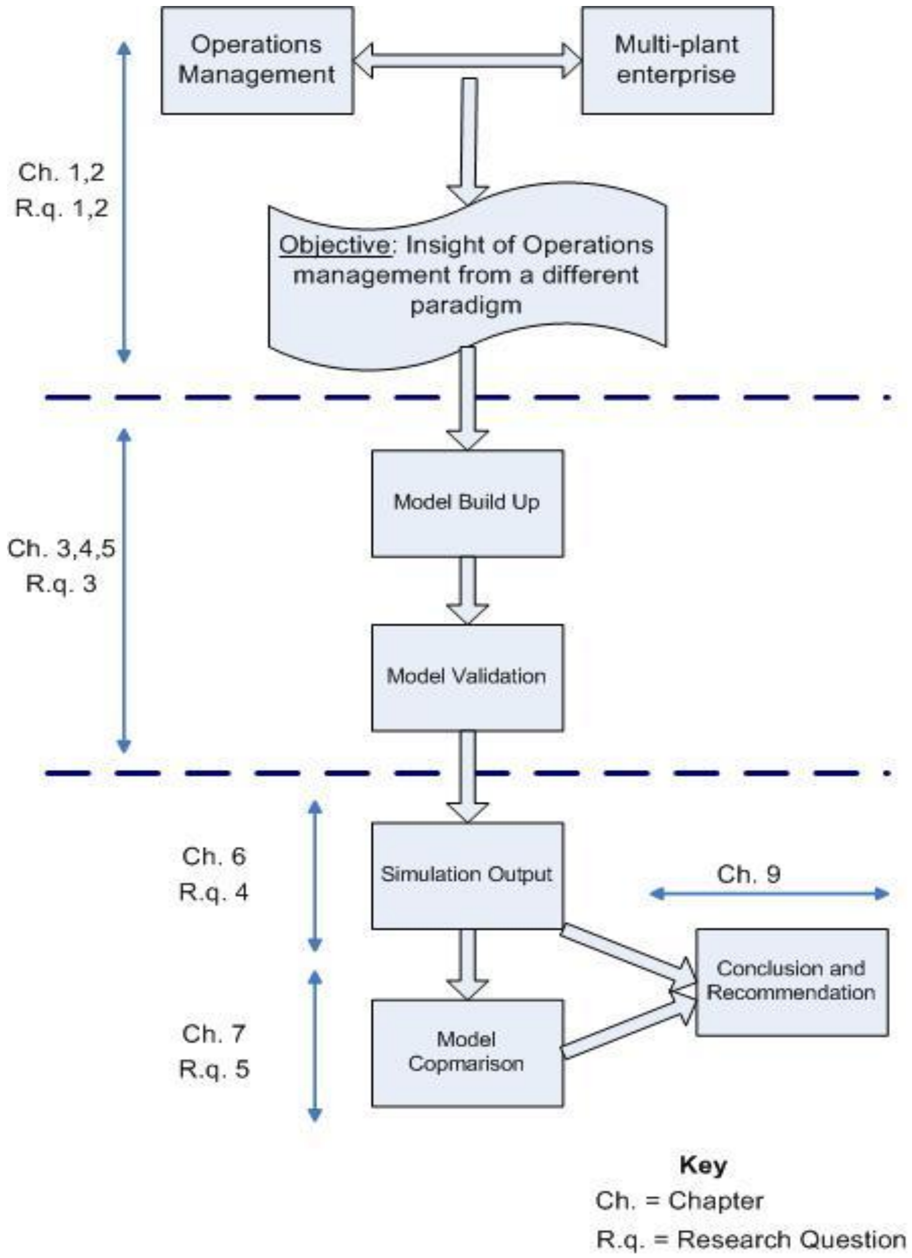

Figure 1. Thesis structure

2. Theoretical Background

2.1. Multi-plant Enterprise

Multi-plant enterprise uses geographically dispersed location for one or more of the following reasons. Plant can be located to a low cost production input such as raw material or human resources. This may bring considerable cost reduction for enterprise. Plant can also be located in geographically dispersed location to be in a close proximity to new or special market. Accordingly, multi-plant enterprises follow different types of plant arrangements to achieve these objectives.

In general, a multi-site production setup can be arranged in parallel (each producing the end products and supply to the market) or serial (some plants producing intermediate products supplying other plants, which convert them into finished product) as can be seen in figure 2 (Kanyalkar and Adil, 2005).

Efficient operations of these geographically dispersed plants depend on the effective coordination of all the local plants and make their objective align to that of the enterprise. But effective coordination is a challenge that needs to overcome the different limitations of the existing networked relation in the enterprise. This limitation arises due to the complex interdependencies of the decision making process in managing the enterprise network. Hence, the enterprise has to be better equipped to manage the different function of the network towards achieving its goal.

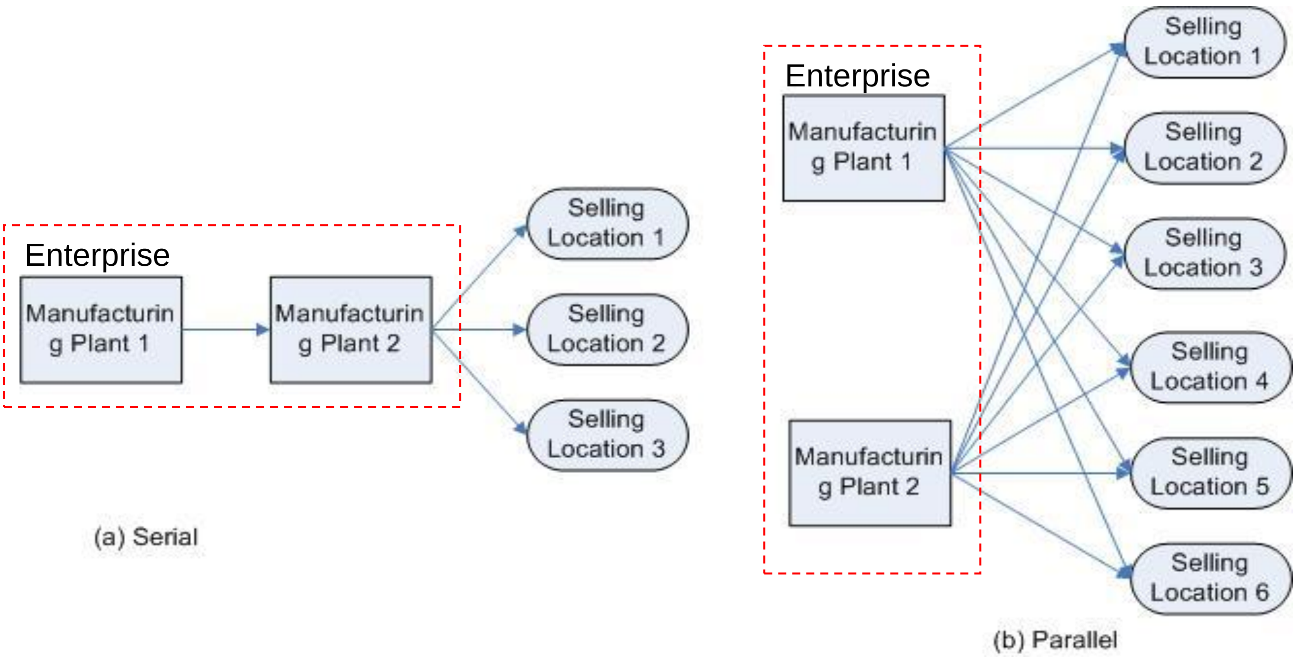

Figure 2. Multi-plant setups *(Source: Kanyalkar et al, 2005)*

2.2. Operations Management

The long term survival of an enterprise is linked to the ability of managing its operations to achieve its task. Operations management is the management of resources, the distribution of goods and services to customers. It focuses on carefully managing the processes to produce and distribute products and services. Generally, the importance of operation management is embedded in every aspect of the enterprises activities and therefore has critical role to play in ensuring organization's survival and achievement of its objectives and goals.

Survival is dependent on an organization's ability to shape and focus its operational resources to meet its stakeholders' expectations (its customers, employees and shareholders), expressed through the organizational strategy. The ability of operations managers to fulfill those tasks is dependent on understanding that they have to make trade-offs. They cannot avoid working under constraints and in each situation there will be some things that they can do well and some they can do less well. In order to tackle such constraints, it requires understanding of the ranges of areas where operations management can contribute.

The areas of Operations Management range from strategic to tactical and operational levels. Representative strategic issues include determining the size and location of manufacturing plants, deciding the structure and means of communication. Tactical issues include plant layout and structure, project management methods, and equipment selection and replacement. Operational issues include production scheduling and control, inventory management, quality control and inspection, materials handling, and equipment maintenance policies (Russsell et al, 2004).

Operational issues which are important in the medium to short time horizons, play important role in the effective management of the transformation of input resource into output (end products of the organization). Overall activities of operations management in this horizon include plant and machinery loading, deployment of man power, purchasing policy, inventory policy, production scheduling, logistics and evaluations among other. As a great deal of focus is on efficiency and effectiveness of processes, operations management often includes substantial measurement and analysis of internal processes or internal supply chain associated with this activities. With this respect, information associated with some of the activities is more insightful as compared to other activities.

The next few sections will explore further into some of the activities that are important in operations management in the medium to short-term time horizon, namely production scheduling and inventory management.

Production Scheduling

Limited resources make scheduling an important decision in the manufacturing industry, if not for every human activity. It is important for proper functioning of manufacturing enterprise, where it can have a major impact on the productivity of process. Well-organized and carefully executed work is necessary to produce in the required quantity, of the required quality, at the required time, and at the most reasonable cost.

Production scheduling deals with the allocation and sequencing of jobs to manufacturing resources over a certain time interval. Its output is a production plan, which specifies start and finish times for every job. Jobs are scheduled according to some criteria and the quality of schedules is evaluated through some performance measures related to costs, resource utilization and due date fulfillment (Alvarez, 2007).

Manufacturing operations can be faced with a wide range of uncertainties and production scheduling is incorporated with accommodating these in advance. There may be relatively little uncertainty, or a plant may experience rampant orders. In such case, an efficient production scheduling and follow up is important to deal with such uncertainties.

Moreover, without effective production scheduling, it might become impossible to meet delivery commitments by the organization. Scheduling facilitates the controlled release of order for execution by reconciling the production with the delivery commitments. Poor production scheduling also increases costs as when plant capacity utilization goes below optimum levels. For example, machines can remain idle because materials or operators were not available in time.

At the shop floor level where the actual productions activities undergo, production schedule gives the shop floor personnel an explicit statement of what should be done so that supervisors and managers can measure their performance accordingly. This is an important role played by production scheduling for operations managers in controlling what is going on in the actual production environment. If there is any resource conflict, production schedule helps identify this and initiates a possible mitigating measures.

The ultimate responsibility of a production scheduling activity is to balance the demand with the output of the enterprise. The different factors of production (man, machine and material) have to be coordinated to increase productivity and minimize operating costs. In doing so there are number of criteria used for scheduling which can be used by an enterprise as per their existing condition and preference which could help in pursuing their competitive advantage. Such criteria can be of;

- Minimizing WIP(work-in-progress) inventory
- Minimizing average flow time through the system
- Maximizing machine and/or worker utilization
- Minimizing setup times, waiting time, etc.

Inventory Management

Inventory constitutes one of the most important elements of any system dealing with the supply, manufacture and distribution of goods and services. Inventory in wider sense is defined as any idle resource of an enterprise-raw, in process, finished, packaging, spare and other- stocked in order to meet an expected demand or distribution in the future. Even though inventory of materials is an idle resource in the sense it is not meant for immediate use, it is a necessary to maintain some inventories for the smooth functioning of an organization.

Inventory management includes policies, procedures, and techniques employed in maintaining the optimum number or amount of each inventory item. The objective of inventory management is to provide uninterrupted production, sales, and/or customer-service levels at the minimum cost.

The high cost of inventory has motivated companies to focus on efficient inventory management. They believe that inventory can be significantly reduced by reducing uncertainty at various points along the supply chain. In many cases uncertainty is created by poor quality on the part of the company or its suppliers or both. This can be in the form of variation in delivery times, uncertain production schedule and/or fluctuation in customer demand (Russell et al, 2004).

The success of an inventory management can be measured by several parameters. But the most suggested parameters are the inventory turns and inventory age as inventory performance indicator. Inventory turn is defined as the ratio of total material consumption per time period to the average inventory level of that period. Inventory age is the average time goods are residing in stock. High inventory turn is a good implication that it requires less cost for keeping it.

2.3. Operations Performance

The performance indicator of any operations management is used to help organizations define and evaluate how successful it is in terms of making progress towards its long-term organizational goals. These indicators can be specified by answering the question, "what is really important to different stakeholders?"

The three important objectives of performance of the operations management system are customer satisfaction, effectiveness and efficiency. The case of efficiency or productive utilization of resource is clear. For any kind of enterprises, the productive or optimal utilization of resource input is always a desired objective. However effectiveness has more dimensions to it which incorporates the fulfillment of multiple objectives with possible prioritization of objectives. This is not difficult to imagine since operations management activities involves different stake holders. This effectiveness has to be viewed in terms of the short and long time horizons because what may seem now an effective solution may not be all that effective in the future. In order to survive, the operations management system, has not only be profitable and/or efficient but also satisfy customer also.

The effectiveness of the operations management system may depend on not only on a satisfying multiple objective but on its flexibility or adaptability to change situations in the future so that it continues to fulfill the desired objective set while maintaining optimal efficiency.

The conflicting attributes of operations management to fulfill its predefined operational objective is important to take into consideration while defining its performance indicators. Ganeshan et al, (Ganeshan et al, 2001) put forward one alternative ways of seeing the most important factors in choosing the performance indicator of any enterprise. These can be put into three main categories: customer service metrics, asset metrics and time/speed/flexibility metrics.

The customer service measures how satisfied are both the internal and external customers of the enterprise. Asset metrics related with the capacity utilization. The most widely used performance indicator from the enterprise perspective includes delivery lead-time and inventory turns (the number of times that a company's inventory cycles or turns over per year) while traditional lean floor plant measures, such as cost per unit and manufacturing cycle time, too shortsighted to address the interests of the different actors.

2.4. Modeling[1]

Sometimes it is necessary to perform experiments with a system in order to understand its behavior, test and compare different scenarios, or find optimal solutions. However, there are systems with which cannot be experimented in the real world because it would be too expensive or sometimes even impossible. This is the case with operations management in multi-plant enterprise where it is very expensive for the enterprise to experiment the different alternative solutions for its problems in the long or short-term.

In such cases it is wise to move from the real world to virtual world of models, perform experiments with the model of the system in a risk-free environment, and map the solution back to the real world. Figure 3 summarizes how modeling works in solving the real world problems by capturing the defining structure of the problem under investigation.

"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. Modeling and Simulation is a discipline for developing a level of understanding of the interaction of the parts of a system, and of the system as a whole. A simulation generally refers to a computerized version of the model which is run over time to study the implications of the defined interactions. Simulations are generally iterative in there development" (Vernadat, 2002). One develops a model, simulates it, learns from the simulation, revises the model, and continues the iterations until an adequate level of understanding is developed.

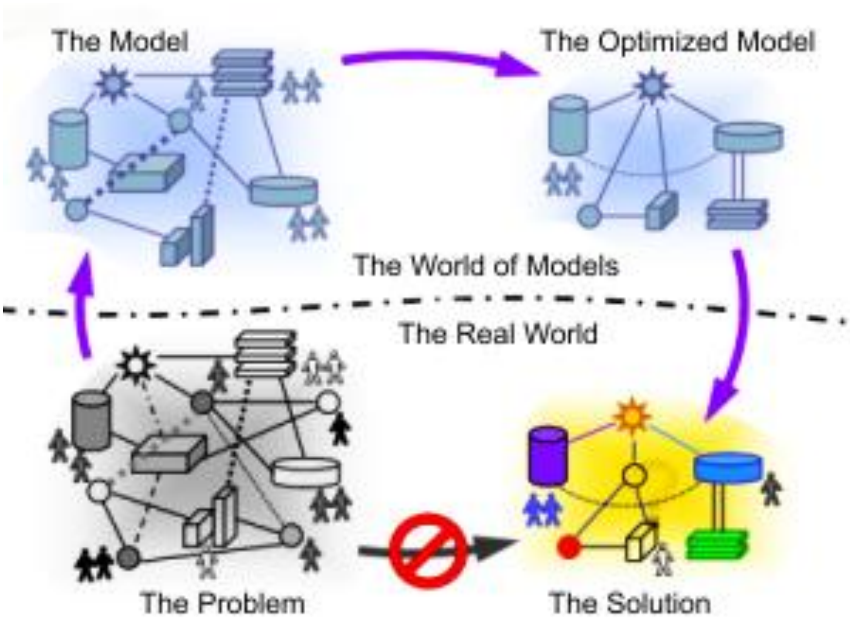

Figure 3. The model vs. real world ()

Considering simulation modeling, there are three major methodologies of model development: System Dynamics (SD) modeling, Discrete Event (DE) modeling, and Agent Based modeling (AB). While the first two were suggested in 1950s and 1960s, agent based modeling has been adopted by simulation practitioners after year 1990. Both SD and DE modeling employ system-level (top-down) view on things while AB approach is a bottom-up one: here the modeler focuses on behavior of the individual objects.

[1] The majority of this theory section is adopted from XJ Technology

Theoretically it is possible for anyone to consider a problem from any given modeling paradigm. But it is sensible to have a great grasp at the problem under consideration and chose a paradigm which gives the most insight. The next three sections explores the three modeling paradigm with respect to the problem of operations management in a multi-plant enterprise.

Discrete events (DE)

The greater majority of processes around us appear to be consisting of continuous changes. However, when analyzing those processes, in many cases it makes sense to abstract from their continuous nature and consider only some important event and moments in the system lifetime. The modeling paradigm that suggests approximating the real-world processes with such events is called Discrete Event Modeling.

This type of modeling is useful in finding an optimal combination of redundant activities by taking a representative case for the problem under study. Before deciding to use this approach, it is suggested to verify that the system is indeed naturally described as a sequence of activities.

Discrete event modeling can be used to find the best possibility of the different operational tasks of the enterprise rather than the enterprise's operations as a whole. Some of the operational activities of a multi-plant enterprise are hierarchical like the production activity in a given plant. For such activities of an enterprise, discrete event modeling is an important tool of analysis to find a better combination of the different activities of the production operation. But to have an overall insight in multi-plants operations management, discrete event modeling is of less importance. This is due to the complex interdependencies of the different operational functions of the enterprise which is difficult to capture in detail using this approach.

Agent based Modeling (AB)

Agent Based Modeling can be defined as essentially decentralized, individual-centric (as opposed to system level) approach to model designs. When designing an agent based model the modeler identifies the active entities, the agents (which can be people, companies, projects, assets, vehicles, cities, animals, ships, products, etc.), defines their behavior (main drivers, reactions, memory, states, ...) and also their interactions, puts them in a certain environment, and runs the simulation. The global (system-level) behavior then emerges as a result of interactions of agents and their individual behaviors.

Agent Base modeling has been used to model operations management in multi-plant enterprise (Behdani et al, 2007). In this model the different plants and their departments, such as procurement and operation, are considered like agents who perform certain tasks with some degree of autonomy. In addition there is a central coordinating agent which coordinates the behavior of the different plants in different geographical location. The model is constructed with the assumption that the plants and departments within a given plant interact through the information and material flow giving rise to the overall dynamics of the enterprise.

The application of Agent-Based modeling approach for a multi-plant enterprise problem has given a number of insights to improve the operations management in multi-plant enterprise. It is used to perform many experiments in studying the important factors that influence the performance of the enterprise as a whole. This research will further explore this model in chapter 7 in comparison with the model developed in this research using the System dynamic model.

System Dynamics (SD)

As chosen modeling paradigm for this research is system dynamics, the next section explores the system dynamic modeling approach.

2.5. System Dynamics

System dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems. System dynamics is also a rigorous modeling method that enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations. Together, these tools allow us to create management flight simulators-micro worlds where space and time can be compressed and slowed so we can experience the long-term side effects of decisions, speed learning, and develop our understanding of complex systems, and design structures and strategies for greater success (Sterman, 2000)

It uses the principles and techniques of controls systems to organizational and socio economic problems (Daalen et al, 2007). A system can be considered a control system if it has some common features. A control system senses the effect of external environment to the actual condition of the system compares the actual condition with the desired situation and then employs policies to determine what to do in given circumstances to reach the desired states. Control system also involves delays (there is always some time needed to feel the effect of the action) and information feedback (to know whether the desired condition achieved or not and what to do next). This is also why the control can be said to have a "dynamic" characteristic.

In more practical term, the perception of system dynamics is that processes in the world are represented in terms of stocks (e.g. of material, energy, knowledge, people, money), flows between those stocks, and information that determines the values of the flows (Forrester 1958). Single events do not exist; events are abstracted to an aggregated view on feedback loops and delay structures.

System dynamic address some of the issues like what policies a firm should use as circumstance changes with time. Moreover, it can help organization design its information feedback structure to ensure that effective policies become possible.

If the system is significantly dynamic, i.e. if its state changes over time, it has causal and time dependencies, time-related constraints, etc., and is complex (so that it cannot be represented by analytical calculations, by formulas), the only way to explore the system behavior is to simulate its model – build a trajectory of the system in time. The model in this case is a set of rules telling how to obtain the next state of the system from the current state. Its essential idea is that the model takes a number of simulation steps along the time axis. At the end of each step, some system variables, which denote states of the system, are brought up to date for representing consequences ensued from previous simulation step. Initial conditions are needed to get the simulation to start the first time step.

At enterprise level of a multi-plant enterprise setup, a complex network of plants and their corporate head quarter gives rise to the emergence of a dynamic behavior due to the interdependence and feedback from the different plants. The interdependence may rise due to the direct influence of one plant decision in pursuing its local objective. This dynamic relation creates some feedback structures which needs to be address if the enterprise to investigate the implication for its decision making process.

At the plant level, the different operational functions at each plant which includes inventory management, production scheduling, and production operation are also another source of dynamic relationship. There is also a feedback structure between different decisions of the plant. For example, scheduling constrains the amount of production operation in a give day and production operation affects the raw material inventory management which in turn constrains the scheduling process. Hence, the performance of one function will have an implication for the performance of the other function thereby for the plant too.

An insight on the effect of these two levels of interaction on the operations of the enterprise can be obtained by using the system dynamic modeling which is well equipped to deal with such problem. The basic modeling process of system dynamics that will be followed in part two of this research is summarized in the next section.

System dynamic modeling process

The system dynamic methodology (model cycle) consists of the following steps (Daalen et al, 2007).

1. Problem Identification
2. Conceptualization
3. Specification
4. Model testing and,
5. Model use.

Problem Identification involves the clearly identifying the issue of concern to management. In this step the system has to be clearly demarcated and collect some primary data. Then follows the conceptualization step, which is important to capture the feedback structures for endogenous explanation of the problem. This step involves identifying main variables, developing a causal diagram, identifying system archetype, and identifying key leverage point.

During specification or quantitative system dynamics quantitative data are entered into the system dynamics diagram. That means the relation between the variables is specified. Then the last step before using the model is to test the model. This will be helpful in determining whether the actual translation from conceptualization to a formal model is conducted properly and weather the model is suitable for the intended purpose. The final step of the modeling process is to use the model and come up with the alternate solution that is helpful in solving the problem under consideration.

Powersim: A software tool for system dynamic

The operation of a powersim and the explanation of each building block is taken from literature (Christina, 2004). The basic building block for system diagram in powersim is illustrated in Figure 4. There are four building blocks in powersim: stock (representing the system rate), flow (representing rate, filling or depleting the stocks), auxiliary (as converters), and the connectors (connecting the different blocks).

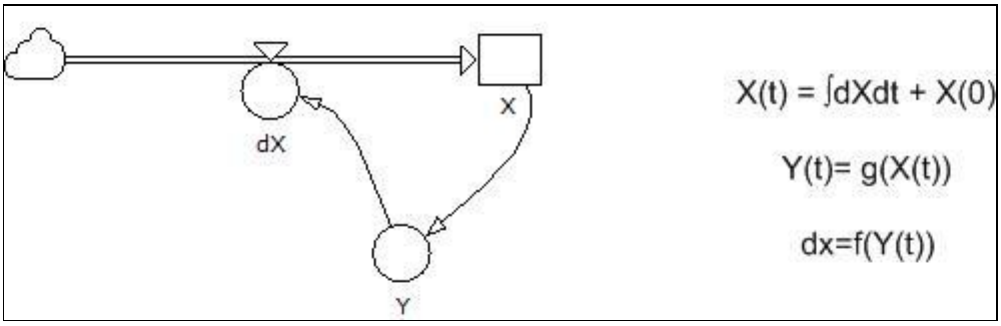

Figure 4. Basic building block of in Powersim

Stock is represented as a box. Flow as a double arrow line with valve flow into (or out of) the stock, auxiliary as a circle, and connectors as arrow line connecting different system components. All of these variables can be time dependent or not. X(0) mean the initial state of the stock value. The stock level X(t) accumulates by integrating the flow rate (dx). Auxiliary variable (Y) control or convert other entities (g(X(t))).

Part II: Modeling Process

3. Case study

Application of agent-based modeling for operation management in multi-plant enterprise has been discussed in Behdani et al (2007). In their work, they have presented a numerical case study for a multi-plant lubricant enterprise with three local blending production plants. This chapter presents the base case for the system dynamic model for similar multi-plant enterprise retaining the basic structure but with two plants, two product types and two raw material requirements for each product type.

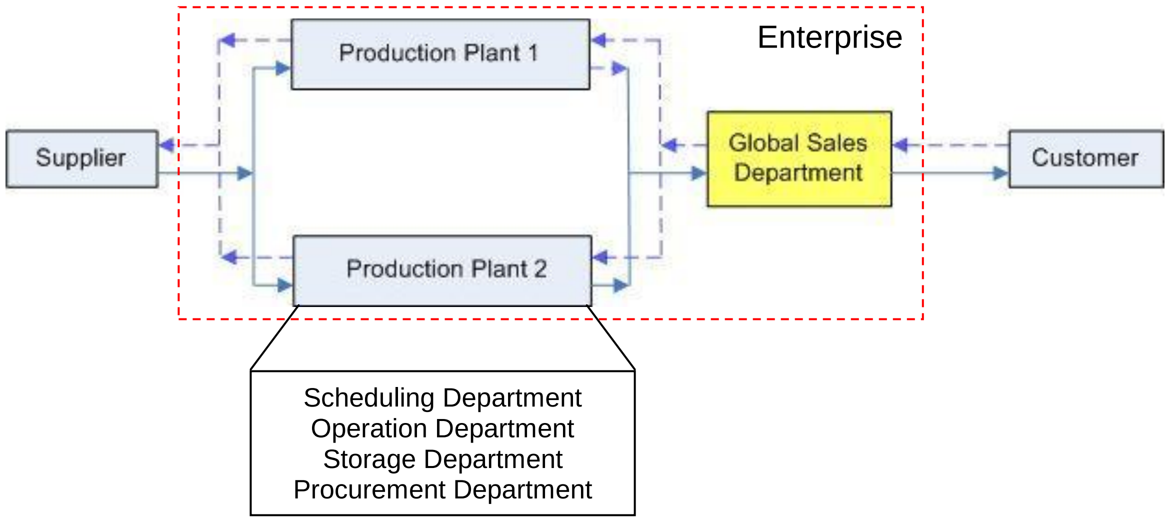

Figure 5: A Schematic representation of an enterprise with two plants (after Behdani et al, 2007)

More specifically, there is a multi-plant enterprise that consists of a global sale department which directly interacts with customers and two production plants at different geographical locations (figure 5). The customer sends its orders to the global sales department. The order received from customer will automatically be assigned to a production plant by the global sales department based on a predefined order allocation criteria and monitors the time it took to process an order.
Schematic
Each production plant manages its internal supply chain. It has some departments and its function is distributed across these departments. Each of these departments has a specific role and performs certain tasks.

Scheduling Department: the scheduling department after receiving the order from the global sales department will schedule which product to produce based on some criteria. Moreover, scheduling department sends the possible expected completion time of a new order to the global sales department.

Operation Department: Based on the product scheduled to be produced the operation department will process raw materials into products following a unique recipe. The operation department is constrained by the available raw material for a given order.

Storage Department: The storage department provides raw materials for the operation department provides raw materials for the operation department and also manages the raw material inventory level. Raw material procurement is performed based on a predefined reorder point policy. Reaching the reorder level, the storage department reports to the procurement department to place an order for the desired raw material.

Procurement Department: The procurement department calculates the required raw material and places an order to a supplier.

Each day, customers send their orders to global sales department and global sales department assigns them to one of the production plants based on their first possible completion time of each order. After assigning the orders, each plant should manage its production by scheduling the orders, process it and ship it to the customers. In addition they should manage their inventory based on the schedule and their actual production operation.

Moreover, there is no finished goods inventory where customer orders can be fulfilled directly. Every order will be processed after receiving it form the customer. The customer orders one of the two types of products the enterprise produce. Each plants can produces these two types of products and each product is produced by blending two different raw materials. The goal is to fulfill a set of customer orders in the first possible time through assigning them to different production plants and coordinate the different departments in each plant towards this goal.

4. Model Conceptualization

A progressive development of dynamic models proceeds by an initial qualitative phase of formalization of the causal relation in the systems, starting with system demarcation. This chapter first explores demarcating our system in the following section, and then follows the causal loop diagram that plays an important role as a preliminary sketch of the causal hypothesis.

4.1. System Boundary

A clear definition of the boundaries between the system under study and its external environment is an essential step of system dynamics modeling. A broad definition of systems runs the risk of leaving out important details involved in the functioning of the system. The model and its analysis must be kept as simple as possible while capturing all necessary elements for the analysis of the system under study.

System dynamics includes a variety of tools to communicate the boundary of the model and its structure. Subsystem diagram is one of these tools. Subsystem diagram helps to show the overall architecture of a model. Each major subsystem is shown along with the flows of material, money, goods, information and so on coupling the subsystem to one another. It is useful to convey information on the boundary and level of aggregation in the model by showing the number and type of different agents represented (Sterman, 2000).

Figure 6 shows the detailed subsystem diagram. It includes the different operational functions that are similar to each plant and the interlinking point of the enterprise which is the global sales department located at the upper left corner. In other words, the Scheduling, Production, Inventory management, Procurement, Inbound and Outbound logistics are all activities that are conducted at the plant level. The global sales department interacts with the local plants via scheduling department and feedbacks from the customer.

Since the purpose of the model is to obtain insight into the operation management activities in a multi-plant enterprise, the model boundary set by the subsystem diagram in Figure 6 can sufficiently capture the problem variables. Besides to the usual subsystem of inventory management the model has to include factors that play important role in the local plant internal supply chain which includes scheduling, procurement and production processes as it is shown in the figure.

The inventory management (storage and procurement process), scheduling and production are placed within the boundary of the local plants, since the local plant can fully influence these functions by itself. In fact these are the major functional areas of operations management as discussed in section 2.2. The subsystem sales which represent the process of allocating customer orders from the global sales department to local plant are within the boundary of the extended enterprise. On the other hand, the logistics function of the organization, inbound and outbound, is at the border of the organization boundary. This is because both subsystems include factors which can be determined both endogenously and exogenously. For example, the inbound logistics is determined by the amount of order placed for a new raw material deliver and time it takes supplier to process the order.

The customer subsystem which is basically the order arrival process from the customer is considered to be exogenous, as it is the supplier subsystem too. For graphical conveniences figure 6 shows two customer boxes but these two are same because an order received form customer has to be shipped back to the same customer. The model only includes material and information flows. Cash flow is not considered in this work due to the added complexity.

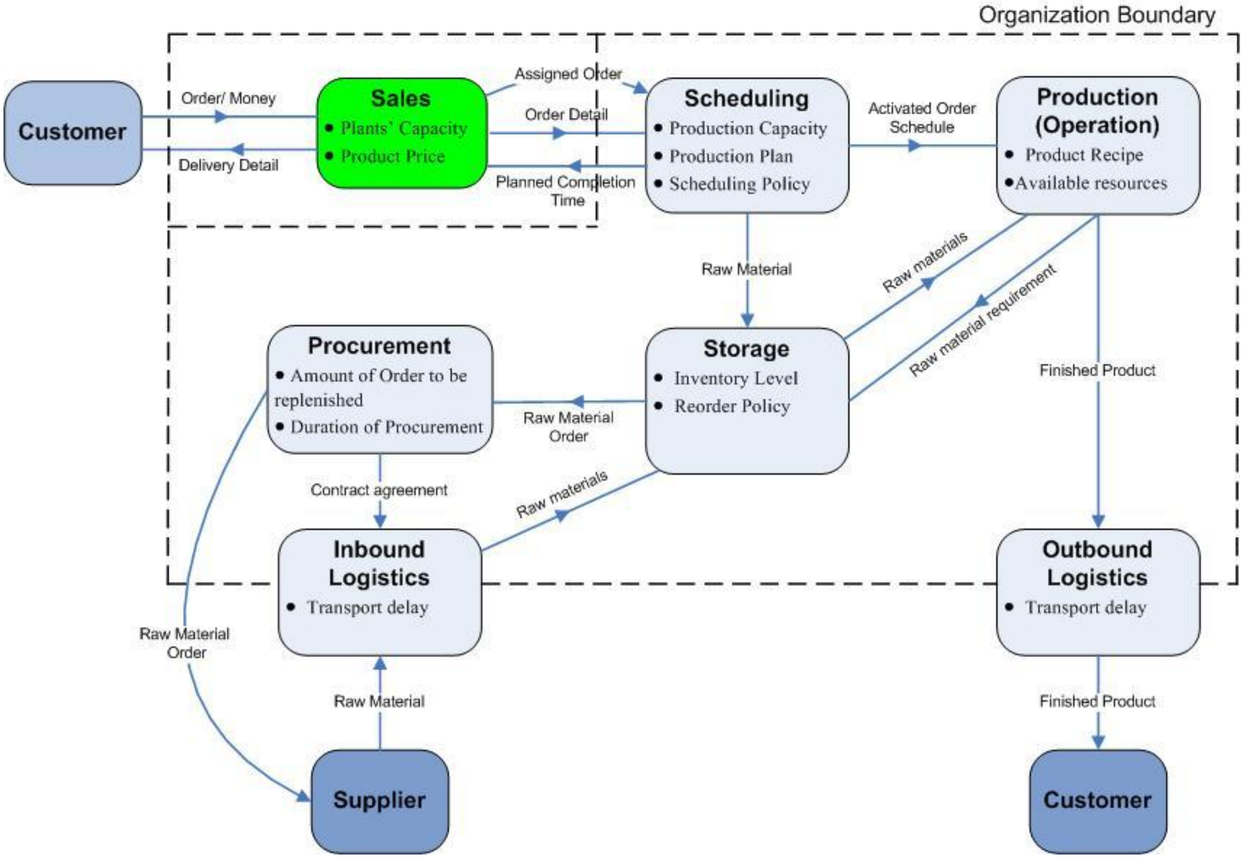

Figure 6. Sub-system diagram

4.2. Causal Diagram

Causal diagram is an important tool used to capture the (feedback) structure of a system. It shows variables and their interaction so that arrows point out of the cause (the arrow's origin) and its direct effect (the arrow's point) (Minegishi and Thiel, 2000).

For ease of understanding the structure of the problem, the causal diagram is used to show the problem from two levels. The first level is the interaction of plants at the enterprise level with the global sale function which is represented in figure 7. From figure 7 we can clearly see the variables that are used to link the internal process with that of another with in and around the enterprise. Local plants (plant 1 and plant 2) will influence the decision making process at the global sales department level through their information about the expected completion time of an already allocated order and the number of orders shipped to the customer. At the same time, based on a predefined order allocation criterion, the global sales department will send order detail to the local plants for production.

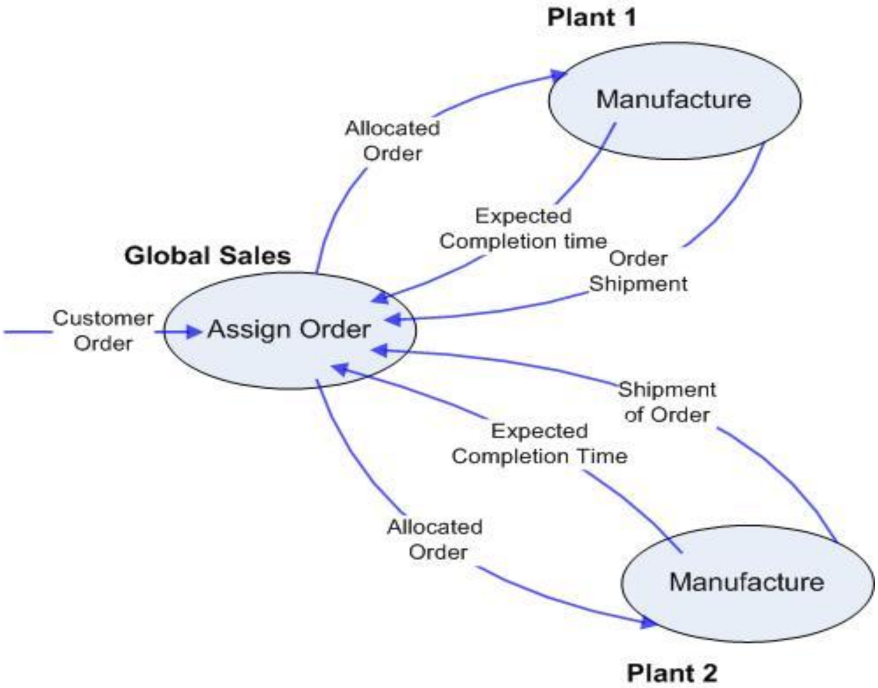

Figure 7. Generic Causal diagram of two plants

The second level of interaction is within a given plant internal functions which will influence the decision process within the plant. The structure of this problem at this level is shown in figure 8. According to a well known causal links representations, arrows are indexed and show how they influence variables: a minus (-) sign means that a change in variable's value consequently induces a change in the variable of the destination in the opposite direction. Conversely, a plus (+) sign means that the two variables are directed in the same way (Minegishi and Thiel, 2000).

Moreover, a causal diagram captures the major feedback mechanisms. These mechanisms are either negative (balancing) or positive feedback (reinforcing) loops. A negative feedback loop exhibits a goal seeking behavior: after a disturbance, the system seeks to return to an equilibrium situation. In a positive feedback loop, an initial disturbance leads to further change (Georgiadis et al, 2005).

At this level, the causal diagram of the global sales department with that of one of the plants will be discussed thoroughly in the following sections. The definition of each variable within the context of this study can be found in appendix 2. Further, the variables have been categorized into two major categories, global and local. A variable with numbered prefix indicates a local variable whereas a variable without numbered prefix indicates a global variable. For example, a variable with prefix 1(one) means it is applicable to plant one only. The variable with no prefix is either determined by the enterprise or the variable is independent of plant location.

Order Allocation and Scheduling

The balancing loop number one (B1) is defined by the sequence of variables '*Allocation to plant'—'1 Allocated order'—'1 Planned completion time' —'Allocation to plant'.* Any order placed at the global sales department will be allocated to a given production plant based on the planned (expected) completion time. Allocation to a specific plant will increase the number of orders allocated to the specific plant in this case plant1. As the number of orders allocated to a given plant increase so do its completion time which in turn reduces the number of order to be allocated to the plant, assuming all other factor to remain constant. Therefore, allocated order will stabilize at a finite level and eventually the system reach an equilibrium (steady) state if the order allocation continues to plant 1 only.

The reinforcing loop number one (R1) is defined by the sequence of variables '*Allocation to plant'—'1 Allocated order'—'1 Production Rate'—'1 Planned completion time' —'Allocation to plant'.* Allocation to a specific plant will increase the number of orders allocated to the specific plant in this case plant1. Increased number of orders allocated to plant 1 will lead the plant to increase its production rate. An increased production rate means the planed completion time of a given order in plant 1 will decrease which eventually lead to the increase in the number of orders allocated to the plant.

Production and Raw Material Management

The balancing loop number three (B3) is defined by the sequence of variables '*Production rate*'—*'1 Material B2 usage'— '1 Material B2 inventory level'— '1 Feasible production form material B2'—'Production rate'.* An increase in the production rate of a plant will result in an increase of the actual raw material usage of any component raw materials used in the production (in this case raw material B1 or raw material B2), of course according to the proportion of the raw material usage in the production process. An increased raw material usage, in this case raw material B2, will lead to a reduction in the actual inventory level of the raw material. Decreased inventory level of a raw material means the feasible production from the available raw material will be reduced which in turn reduces the production rate. The same causal explanation applies to the balancing loop number seven (B7). The only difference is the constraining raw material type which is raw material B1 in case of loop B7.

The balancing loop number four (B4) ,which is defined by the sequence of variables '*1Material B2 inventory level'— '1Desired inventory of material B2'— '1Reorder quantity of material B2'— '1Material B2 delivery' — '1Material B2 inventory level',* is responsible to stabilize the inventory levels of a given raw material, in this case raw material B2. As the desired inventory of material B2 increases, the quantity of raw material to be replenished will also increase. The increased reorder quantity after some time delay (raw material suppliers order processing time) will increase the delivery rate of the material which in turn increases the actual inventory level of the raw material B2. An increased inventory level of raw material B2 means the desired inventory will ultimately decreases. The same causal explanation applies to the balancing loop number seven (B6). The only difference is the raw material type which is raw material B1 in case of loop B6.

To develop the causal loop diagram, there are some assumptions that are considered. The first one is there will be no order rejection. The order will be in the system until it is processed and delivered. But in reality no order will be placed without any constraint of time. The second assumption was the shipment of the end product is not bounded by the quantity of order executed. That is to say, whatever portion of the actual order size is ready, will be shipped as soon as it is ready.

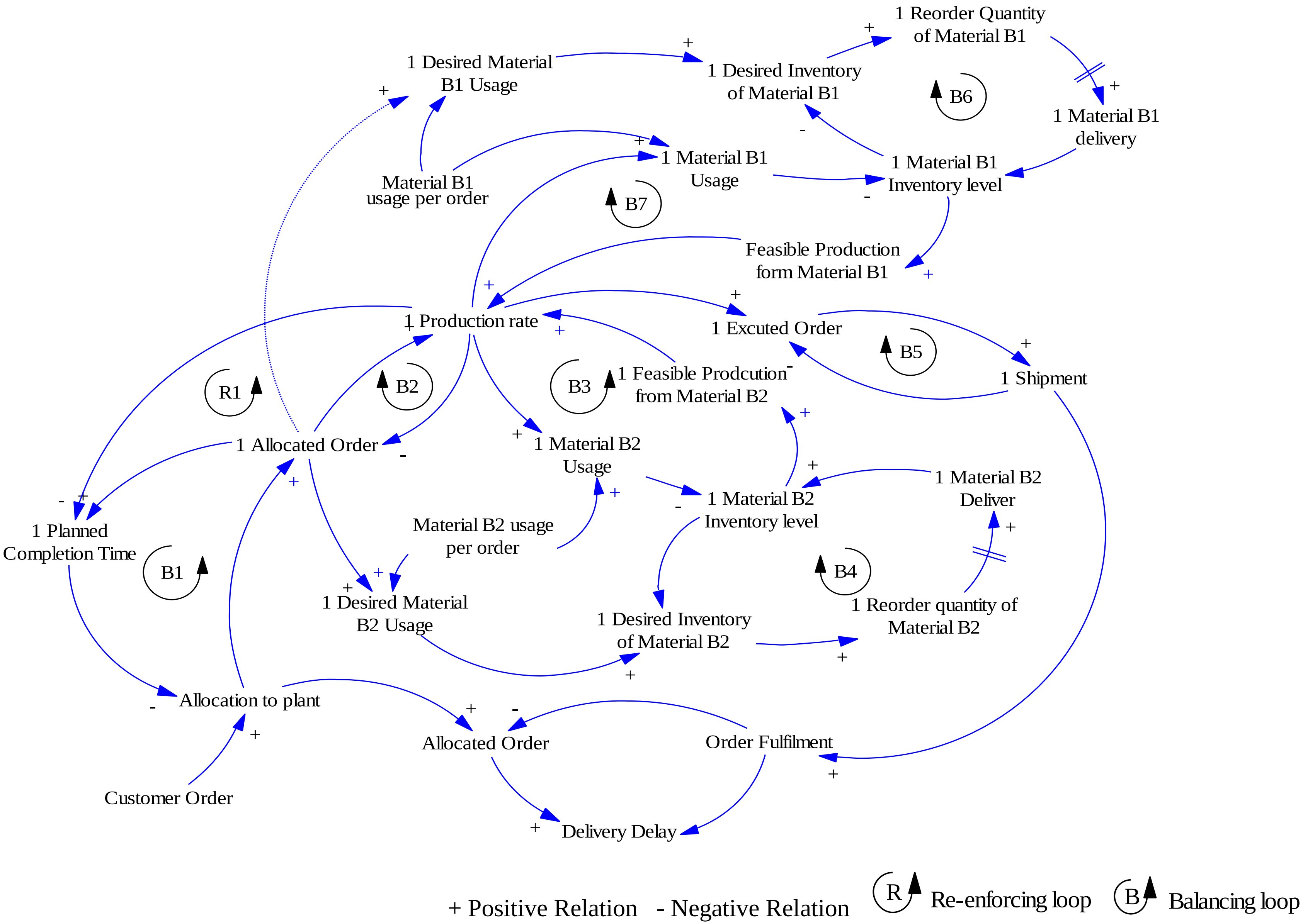

Figure 8. Causal relation diagram for the single plant and single product

5. Model Formulation

Causal loop diagrams are interesting method to summarize and communicate the structure of the model. The conceptual phase results in one or more conceptual models like the one in figure 9. These conceptual models are the basis for a quantitative specification of a system. The next step of the system dynamic methodology involves the mapping of the causal diagram into a dynamic simulation model using specialized software. The formulation phase results in a quantitative model. Formulation means that a conceptual model is transformed into a formal quantitative representation. The quantitative model is the starting point for a more detailed analysis of the system behavior (Daalen et al, 2007).

This chapter discusses the formulation of the system dynamic model using *Powersim Studio 7 Academic service release 4* software. The choice for this software package was made because it was readily available for use by TUDelft students.

5.1. Overall model picture

An overview of the portion of the model with a single plant is shown in figure 9. Clearly there are five inter related sections identified using five different color, namely global sales department in green, scheduling process in light green, production and delivery process in rose, raw material storage process in pale blue, and procurement decision in light yellow. The two plants interact through the global sales department. There is no direct information or material from between the local plants. The customer will place an order to the global sales department and the plant which is responsible for processing it will ship the end product to the customer. Each section will be detailed in the subsequent sections.

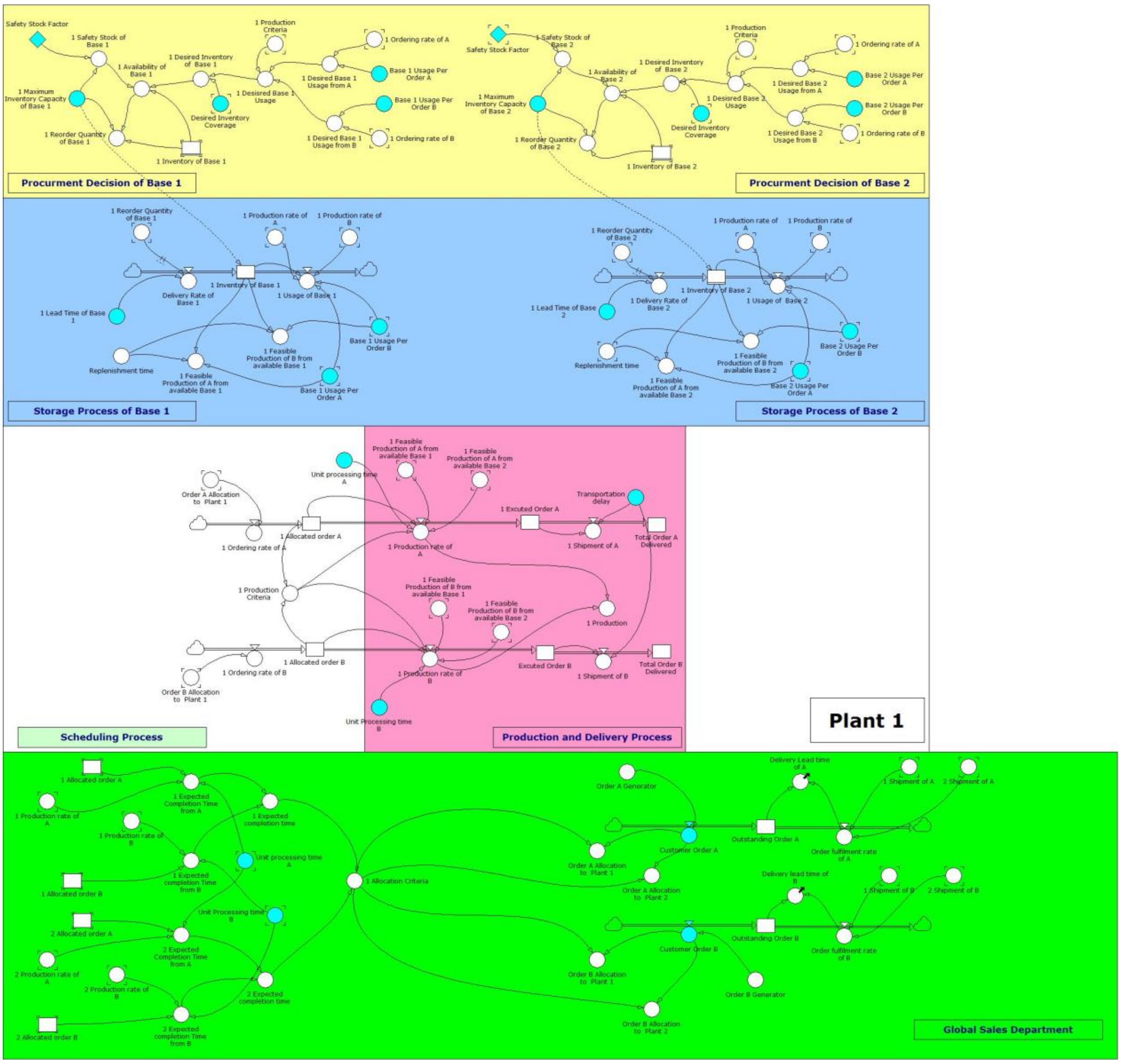

Figure 9. Single-plant model

5.2. Formulation of sales Process

The main task of the global sales department is to allocate the customer orders to a local plant based on predefined criterion (in this case expected completion time in each plant). The expected completion time is the time a given order will wait before the start of production. It depends on the active production rate (which will be explained in production and delivery process), the amount of order allocated and the unit processing time of each product. The unit processing time is the time it takes to process a unit order of a given order type. Figure 10 depicts the process to determine the expected completion time from Plant 1. The same process applies to determine the expected completion time from Plant 2 using the respective information for each variables in the plant.

The formulation for expected completion form one order type is:

1 Expected completion time from A = IF ('1 Production rate of A'<>0<<Order/da>>,'1 Allocated order A'/'1 Production rate of A','1 Allocated order A'*'Unit processing time A')

The expected completion time from the allocated order type A is determined based on the actual production rate. The actual production rate is determined based on production criteria (which will be explained in scheduling section). In case there is no order allocated to the plant, the expected completion time will be the unit processing time of the order to be assigned to the plant.

The same explanation applies to the expected completion time from allocated order type B. The only difference here is the unit processing time which is dependent of the product type. The combined expected completion time from allocated order A and B in Plant-1 will give the total expected completion time of the plant.

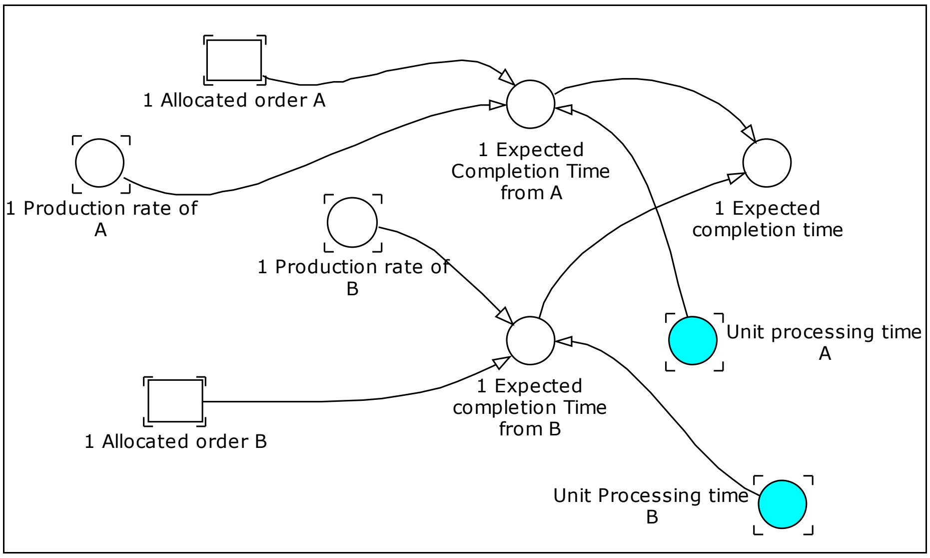

Figure 10. Expected completion time

5.3. Formulation of Scheduling Process

The ultimate responsibility of a production scheduling activity in a given plant is to balance the demand with the output of the enterprise. Here the criteria of scheduling is minimizing the waiting time of an already allocated order to the plant. Based on the number of orders of each product type in a given plant, the production start criteria is used to determine when to start production of a given product type, hence scheduling.

If the allocated order of product type-A is higher than that of product type B, the production will go ahead with the product type which has got the higher amount of allocated orders, which is product type A. The formulation of the production criteria is as follows:

1 Production criteria = IF ('1 Allocated order A'>='1 Allocated order B',TRUE,FALSE)
Where,

‘1 Allocated order A’ and ‘1 Allocated order B’ detail can be seen in the formulation of production department.

Here the production starts based on the amount of orders in plant-1 order portfolio. If the amount of allocated order A is higher than that of allocated order B, then the plant will process plant A, this is the ‘TRUE’ condition in the conditional specification. Otherwise, the plant has to process allocated product B since the amount of order B will be higher than that of A, this is the ‘FALSE’ condition in the conditional specification.

5.4. Formulation of Storage Process

The storage department, which handles the raw material inventory, is shown in Figure 11. The raw material delivery and consumption process of one raw material (Base 1) in plant-1 is explained here. This explanation applies to the other raw material within the same plant too.

The formulation of the actual inventory of the raw material and related variables is:

1 Inventory of Base 1(t) = 1 Inventory of Base 1(0) + ∫ (Delivery rate of Base 1 – 1Usage of Base 1)*dt
Where:

Deliver rate of Base 1 = DELAYPPL ('1 Reorder Quantity of Base 1','1 Lead Time of Base 1') /'1 Lead Time of Base 1'

1 Usage of Base 1 = IF ('1 Inventory of Base 1'>0<<kg>>,'Base 1 Usage Per Order A'*'1 Production rate of A' + 'Base 1 Usage Per Order B'*'1 Production rate of B', 0<<kg/da>>)

The delivery rate of base is a delayed function. Already placed order needs duration (reorder time) before receiving any raw material ordered. This is the order processing time in the supplier side. This is included in the model as lead time of the raw material delivery, in this case '1 Lead time of Base 1' read as the delivery lead time of raw material Base-1 to deliver to plant-1.

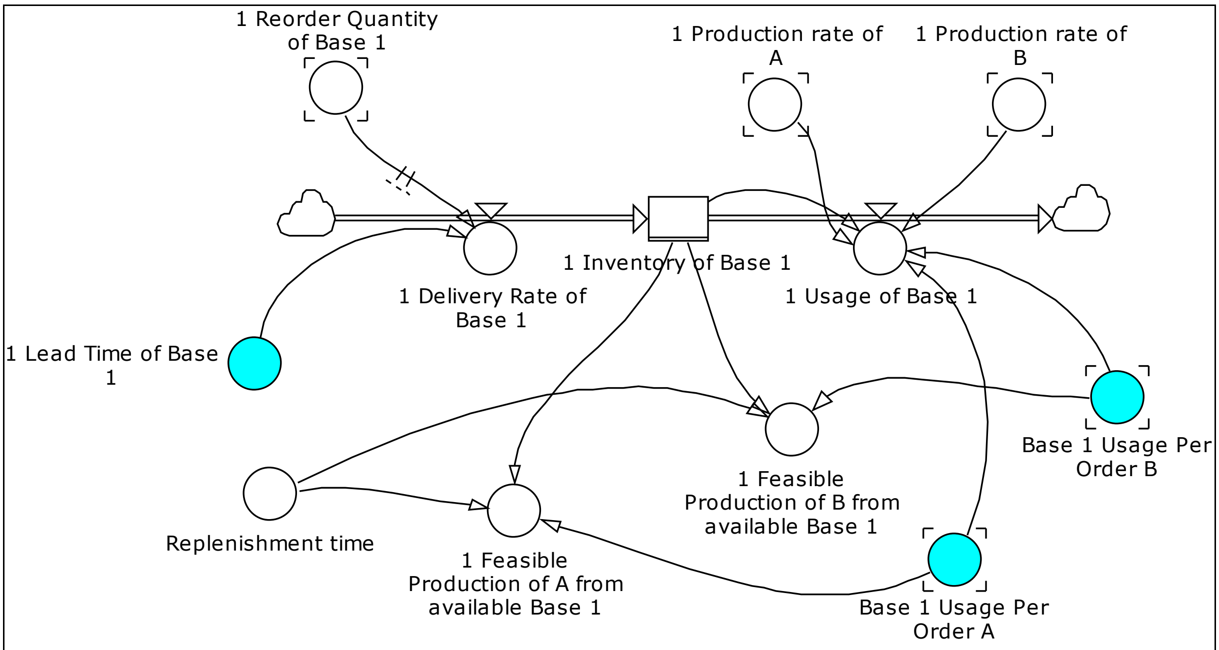

Figure 11. Storage department

The feasible production form available material also formulated as follows. The feasible production from available material depends on the actual amount of available raw material inventory and the time we need to replenish the raw material inventory which is the replenishment time. The formulation is;

1 Feasible production of A from available Base 1(t) = 1 inventory of base/(Base 1 usage per order type A * Replenishment time)

1 Feasible production of B from available Base 1(t) = 1 inventory of base/(Base 1 usage per order type B * Replenishment time)

Where:

The raw material usage (Base 1 in this case) is the amount of raw material required to produce a unit quantity of product type A or B

5.5. Formulation of Procurement Process

The formulation of the procurement decision process starts by formulating the desired raw material usage based of the ordering rate of each product type (see the detail in the next section) and the unit raw material usage of each order. Figure 12 shows one of the four formulations in the model. To determine the desired material usage the formulation is as follows;

1 Desired Base 1 usage from A = 1 Ordering rate of A / Base 1 usage per order type A

The desired raw material usage will be determined based on the production criteria. The amount of raw material needed must meet the amount needed to accomplish the planed production of an order. The mathematical formulation is;

1 Desired Base 1 usage = If (production criteria 1=TRUE, 1 Desired Base 1 usage from A, 1 Desired Base 1 usage from B)

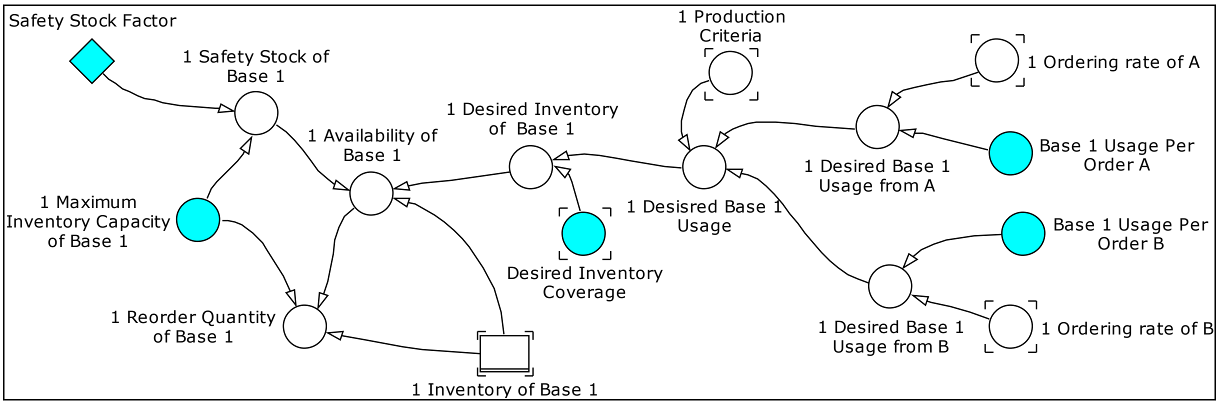

Figure 12. Procurement process

The desired inventory of the raw material (Base 1) will be counter checked with the actual inventory level of the raw material. Here the reorder policy is to replenish it to the maximum capacity of the inventory whenever the amount of raw material required is less than the actual inventory level. The complete formulation of the reorder quantity is as follows:

1 Reorder quantity of Base 1= If (1 Availability of Base 1 = FALSE, 1 Maximum Inventory capacity of Base 1 – 1 Inventory of Base 1, 0<<kg>>)

Where;

1 Availability of Base 1 = IF (('1 Desired Inventory of Base 1'+'Safety Stock factor ')>'1 Inventory of Base 1', FALSE, TRUE)

5.6. Formulation of Production Process

The amount of order types allocated to a given plant accumulates with the increase in the allocation of orders to the plant and is reduced by the production rate of the product type. One of the four formulations is shown in Figure 13 and explained below for one of the product type.

1 Allocated order A (t) = 1 Allocated order A (0) + ∫ (1 Ordering rate of A – 1Procution rate of A)*dt

Where:

1 Ordering rate of A = Order allocation to plant 1

The order allocation is formulated in the global sales section. The production rate is constrained by three constraints, namely the feasible production from available material, the allocated order and production criteria. The combined formulation is as follows;

1 Production rate of A = IF ('1 Production Criteria'=TRUE AND '1 Allocated order A'>0<<Order>>,MIN ('1 Feasible Production of A from available Base 1','1 Feasible Production of A from available Base 2',1/'Unit processing time A'),0<<Order/da>>)

Where:

Feasible production from Base 1 and Base 2 formulation can be seen in the storage section formulation and the production criteria in the scheduling section formulation.

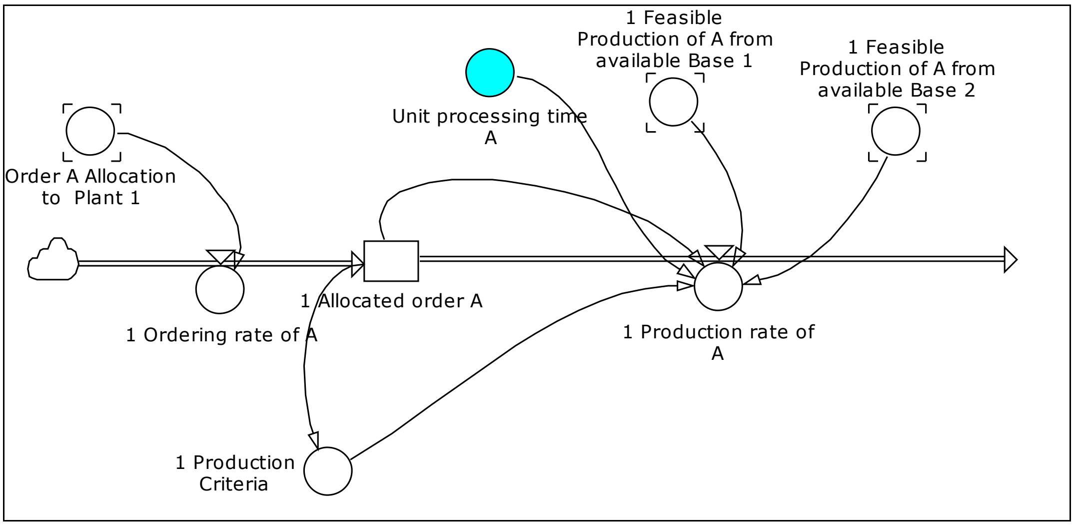

Figure 13. Production rate

The overall formulation in Appendix 2 includes all the variables used in the model with their respective formulation.

5.7. Model Verification

The next step of the system dynamic modeling approach, after finalizing the formulation, is verification. Verification is the term used to refer to consistency check of the model, to ensure that no errors have been made in representing the model in the computer (Daalen et al, 2007).

Verification uses dimensional consistency check, integration method and step size methods. The dimensional consistency check is used to verify the consistency of all related variable unit. For example, the formulation of procurement department dimensional consistency check is as follows;

1 Desired Base 1 usage from A = 1 Ordering rate of A / Base 1 usage per order type A
[Kg / day] = [Number of order /day] / [Kg / order]
[Kg / day] = [Kg / day]

The desired base usage is measured in kilograms of base required per unit time (in this case day). The ordering rate is the amount of order received by the local plant which is measured in number of orders per unit time (still in this case day) and base usage is measured in kilograms of base required to produce a unit order, hence the consistency of the dimensions in the right and left side of the equal sign. Moreover, this test is automatically carried out by the software (Powersim Studio). If there is any dimensional inconsistency the model will not run in the Powersim environment.

Almost all the time, the behavior of a system dynamic model must be computed numerically a process known as numerical integration. This method uses a finite time step and average the resulting approximation in the interval. This in turn introduces an error known as integration error.

The primary consideration in selecting the time step is the accuracy of the numerical integration process. The smaller the value, the more accurate the assumption that the rate of change remains constant between time step and the closer to the true continuous time solution will be. The smaller the time steps the greater the round-off and the truncation error. Round offs and truncation errors arise because computers operate with finite precision arithmetic. The total numerical error in a simulation consists of the integration error and the round off error (Sterman, 2000).

The effect of integration method can easily be seen by considering Euler and other higher order integration methods for the same time step. If there is no significant change in the results, then Euler integration is fine.

The integration method of the model is second order Runge- Kutta with a time step of 0.125 day and the model is run for one year since one year is way more than enough time span to see the effect of operational decisions.

5.8. Model Validation[2]

Validation is used to refer to the model usability. During the validation phase first the model structure has to be studied and only after this, if the structure is deemed to be adequate, the model behavior is to be tested. There are two types of validation tests; direct structure test and structure oriented behavior test. Both tests have been applied in this model.

Direct Structural test

In this test the model is tested without running any simulation rather each relation in the model is studied. Direct structural test can be conducted in 6 different ways. Three of these will be discussed below.

Theoretical structure and parameter confirmation

Both of the model structure and structure and the parameters must correspond to the relevant descriptive knowledge of the system. The parameters must also be checked on the basis of any numerical knowledge. No quantitative literature is available with the focus of this thesis other than what is used to build the model. There are no studies to compare with the simulation outputs of the model. However, comparison is possible for parts of the model. Part of the model (the decision process in inventory management) is modified from the model developed by Sterman (Sterman, 2000). This validates the relevant structural descriptions used in the model with reference to a previous model.

Direct extreme condition

In this test, the model equation is tested individually under extreme conditions. Every equation can be checked this way by entering extreme values for the input variables and comparing the output variable to the expectations in the real situations. This test has been done resulting in minimum-maximum function of several variables. An examples is shown as follows;

[2] Theory in this section is adapted from Daalen et al, 2007, Chapter six.

For the equation;

1 Feasible production of A from available Base 1(t) = 1 inventory of base 1/(Base 1 usage per order type A * Replenishment time)

Which is the feasible production of order type A in Plant-1 from available raw material Base-1 is define by the actual inventory of the raw material (Base-1), the raw material usage per order type and the replenishment time of the raw material.

The two extreme conditions tested here is very high actual inventory of the raw material (Base-1) in the plant (plant-1) and very high Base-1 usage per order type A. Evaluating a very high number to the raw material inventory and base-1 usage per order type-A in the above equation results very high number (∞) and very low (~ zero) for the feasible production of A from available Base-1 respectively.

In reality, if the actual inventory of a given raw material goes very high so does its feasibility to produce a given product from this raw material. That is to say, we can produce as much as we want to produce if there is no raw material constraint. On the other hand, if the raw material usage of a given product gets higher, the feasible production from it gets very low.

Boundary adequacy of structure

This test is used to check whether the model has contained the most important concepts required to analyze the problem. The major concepts identified in the theoretical build ups like inventory management, production scheduling, and production processes are sufficiently captured by the model.

Structure-Oriented test

In this test, the model is evaluated indirectly by running the model. The next two sections evaluate two of such kind test; Extreme condition test and Sensitivity analysis.

Extreme condition test

The extreme condition test is conducted by considering two extreme conditions; no customer demand and very high customer demand. The model simulation result under this condition is compared with the expected behavior of some of the variables like actual inventory level, expected completion time and production rate at each plant. Table 1 summarizes the expected and actual results of this test. The full extreme condition test can be found in Appendix 3.

Table 1. Extreme condition test

Extreme Condition	Expected actual inventory behavior	Expected Expected completion time behavior	Expected production rate behavior	Simulated behavior
No customer order	The inventory level will sustain the initial amount of inventory in stock.	The expected completion time will be zero since there is no order allocated to any of the plants.	Constant production rate of zero since there is no order to engage in production.	The simulated behavior coincides with what is expected.
Very high customer demand	The inventory cycle will considerably increases.	There will be a considerable increase in the expected completion time.	Maximum capacity of the production plants will be utilized.	The simulated result coincides with what is expected.

Sensitivity analysis

A sensitivity analysis is designed to determine the element in the model to which the model is sensitive (and that have a major influence on the behavior when they are changed). Sensitivity analysis is not only a tool of validation but it is also helpful in identifying the policy leverage point for further analysis.

Sensitivity analysis is conducted by varying all the input parameters where the decision maker have a control over within 10% of the base value, with all other parameters held constant. The base case is used in this analysis. The variation of the output is measured under the 10% change in input. A change in the output of more than 10% means that the model is sensitive to the changed input parameter. Otherwise, the model is insensitive to that parameter. The change in the output is defined by two parameters, namely the delivery lead-time of product type-A and type-B. These parameters are also the performance indicator of the model.

Several types of input parameters are used in the analysis. There are parameters which are used globally (uniform throughout the enterprise) and there are parameters which are plant dependant. All this inputs sensitivity has been analyzed and appendix 4 includes the complete list of parameters tested and their respective outcomes. The results of this analysis which is useful in the tactical and strategic analysis will be discussed in section 6.2.

Part III: Results and Comparison

6. Model Usage

One of the main advantages of model development is, it allows experimentation without taking any form of risk in the real world. Nevertheless, before experimenting, the base case has to be understood. This chapter first covers the model behavior for the base case followed by the major findings of the sensitivity analysis. Then, tactics and strategies analyzed using the model and how it can be used to meet our research goal of improving the operations management at the enterprise level in reference to the base case will be presented. The final section includes the concluding remarks.

6.1. Base Case

To better understand how the model works, important parameters of the base case are explained in this subchapter. The time horizon of simulation is one year which is a reasonable time frame for the medium to short term decisions for planning and control of production activities. Results of the model are available in the form of time-graph but it is also possible to have it in the form of time-table.

6.1.1 Model Input

The customer demand for the two types of product, product type A and B, is the input to the model. The stochastic customer demand for the two type of product is shown in figure 14. The customer demand is approximated by using the demand data for one year considered as a normal distribution. Furthermore, these demands are filtered in order to consider negative demand like no demand (or Zero demand) since it is meaningless in this context to have a negative demand.

From the graph it is clear that the nature of demand is very erratic in each time frame. This is consistent with the original data which is obtained from the agent based model developed.

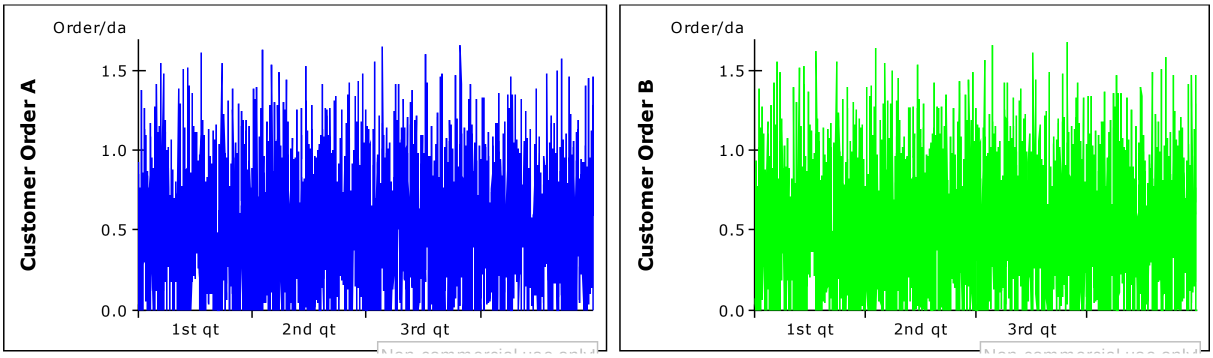

Figure 14. Customer order for Product type A and B

6.1.2 Internal model variables

The model uses a number of internal model variables which are useful in the operational decision making process. In this section the behavior of the two of them will be detailed.

Behavior of Raw material Inventory

Each product type uses two different types of raw materials, Base-1 and Base-2. These two raw materials are carried in different quantity at different time in each plant. Figure 15 shows the inventory of Base 1 and Base 2 in plant one. The cyclic behavior of this graph is due to the ordering strategy followed by the enterprise, that is, whenever an order for a raw material is placed it will be placed in such a way that the replenished quantity will fill the inventory to its maximum capacity. In addition to the ordering strategy, the type and quantity of order being processed in the production department may also affect on the inventory level of Base 1 and Base 2. This is because the two product types consume different quantity of the raw material (product type-A is produced by blending 350kg of Base-1 and 150kg of Base-2, whereas product type-B is produced by blending 200kg of Base-1 and 300kg of Base-2). So it is natural to see different degree of consumption of these raw materials.

The same behavior is observed in the inventory of Base-1 and Base-2 in plant two. And similar argument is applicable to the behavior of inventory of Base-1 and Base-2 in plant two which is shown if figure 16.

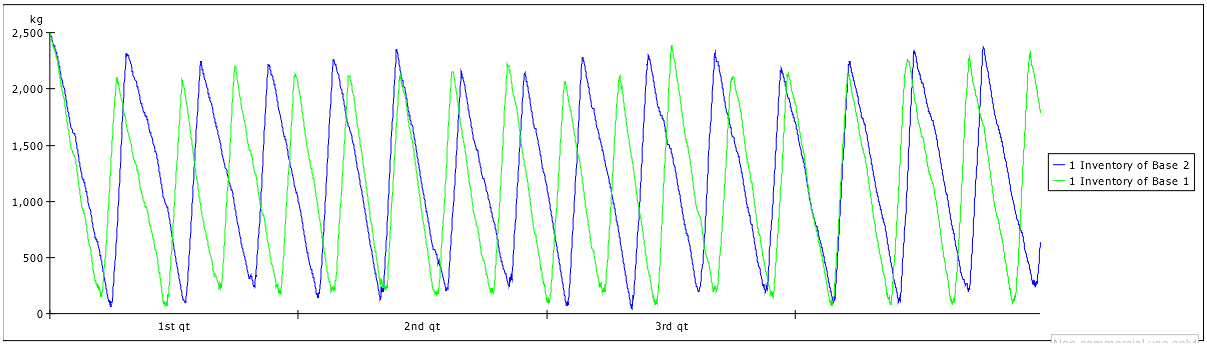

Figure 15. Inventory of Base-1 and Base-2 in plant 1

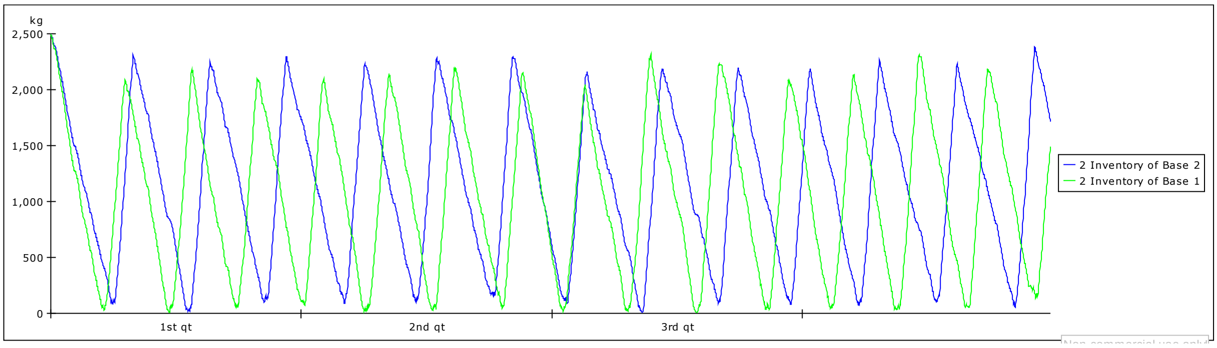

Figure 16. Inventory of Base-1 and Base-2 in plant 2

Behavior of Production Rate

Another important internal variable is the production rates of each plant which directly affects the performance of the other functions of the plant and the performance of the enterprise as a whole. Production represents the amount of order being processed at each moment in time in a given plant. The graphs in figure 17 and 18 show the irregular nature of production. This is consistent with the modeler's expectation due to the following reasons. First, each plant operates on the base of customer order assigned by global sales department, that is, it is a make to order plant. Unless there is a continues flow of demand, production have to wait sometime before they get the next order to produce. Secondly, the scheduling process continues to switch the production process in order to produce both types of products (Product type A and B) allocated to the plant.

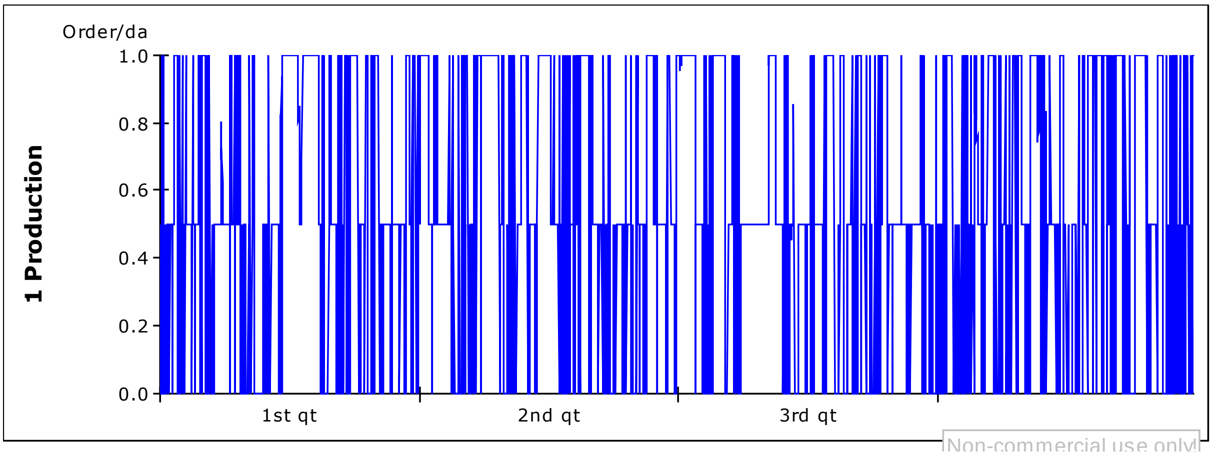

Figure 17. Production in Plant 1

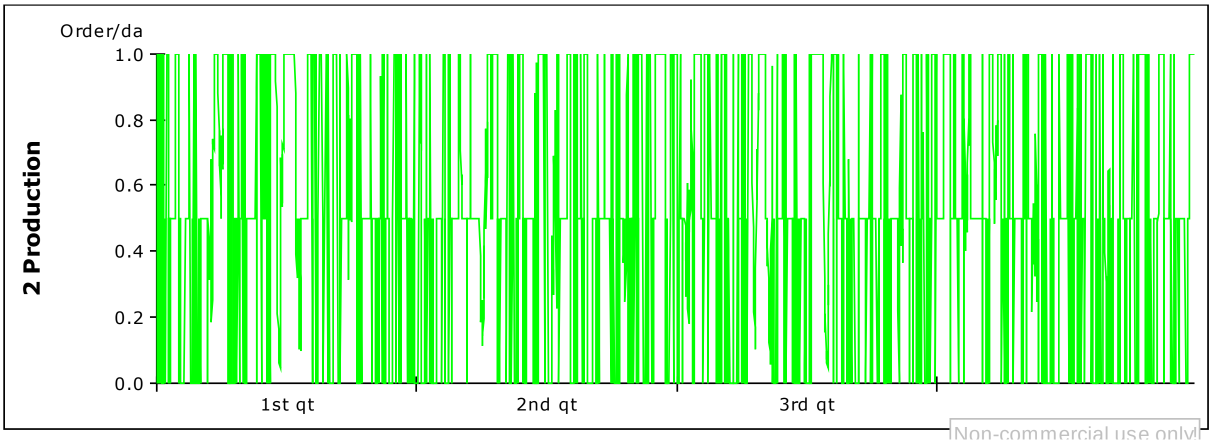

Figure 18. Production in Plant 2

6.1.3 Behavior of Delivery lead-time

The graph of delivery lead-time of each product type is shown in figure 19. The delivery lead-time of each product is used to show the performance of the enterprise. By definition, it is the time duration between receiving and fulfilling of orders. The customer orders increases the lead time while production decreases it. Moreover, the availability of raw material inventory also influences directly the production process hence it indirectly influences the delivery lead time of the enterprise.

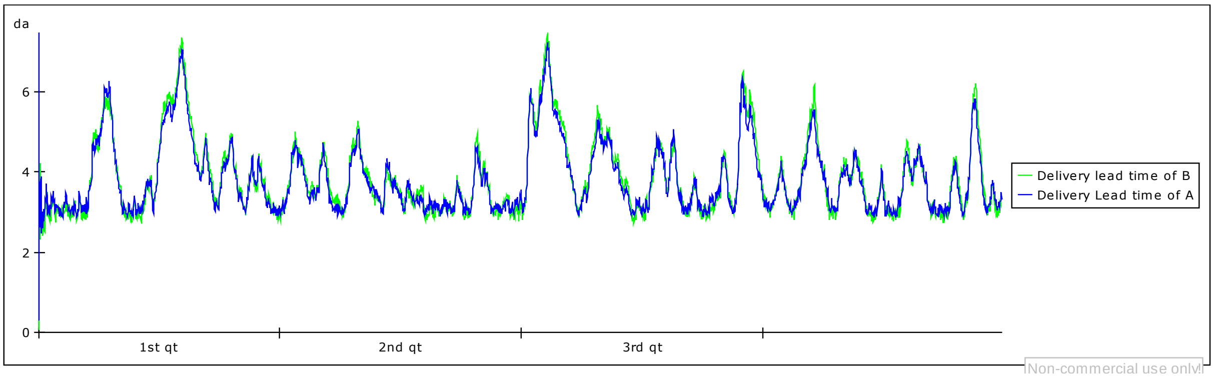

Figure 19. Delivery lead-time of Product type A and B

6.2. Sensitivity Results

The major finding of the sensitivity result will be summarized in this section. For each sensitivity analysis the variable has been varied from its base case value with 10% up and 10% down and observed the effect on the performance indicators. Some variable are very sensitive and some are less sensitive and some are not. In this study, I consider a variable is *very sensitive* if 10% variation in its base value can bring 10% and above change in the performance indicator. Furthermore, a variable is considered *slightly sensitive* if it can bring a change in the performance indictor between 5% and 10% for its 10% base value variation. And finally, a variable is *insensitive* if it can bring below 5% change in the performance indicator for a 10% variation of its base value. Appendix 5 summarizes the results of the sensitivity analysis and this section presents the findings of this sensitivity analysis.

Safety Stock Factor

The safety stock factors which is a level of extra stock that is maintained below the cycle stock to buffer against stock outs is very sensitive to the model. It is acceptable that the model is sensitive to safety stock factor because safety stock largely affects the delivery delays of a given order via production which can be disrupted by raw material stock out.

Raw material delivery Lead time

The model is slightly sensitive to the raw material delivery lead time of each type of raw material to each plant. For example, the model is sensitive to '2 lead time of Base 2' which is the delivery lead time of raw material Base-2 to plant-2. Even though the safety stock is used to absorb a variation in the raw material delivery lead time, the model's sensitivity to this variable is acceptable. This is because; under low levels of safety stock the model has to depend on the lead time variation.

Maximum Inventory Capacity

The model is slightly sensitive to an increase in the capacity of a plant's raw material inventory and a reduction in the maximum capacity of the raw material inventory. The models sensitivity to these variables can be justified by the direct influence of this variable on the safety stock factor of the plant which is the percentage of the maximum raw material inventory.

Unit processing time

The model is also very sensitive to the unit processing time of each product type which is the capacity indicator in the model. Even thought unit processing time is a capacity indicator in the model, the model's sensitivity to this variable indicates the junction point between the operational and strategic decisions of the enterprise which further validates the model.

As far as the rest of the input is concerned the model is not sensitive to variations in most of the input. Most parameters individually do not have a large influence because clearly the model has many input parameters that are relevant in the decisions of operations mangment.

6.3. Tactics and Strategies

To improve the mentioned base case and to study the effect of different parameters on the system performance, many experiments are done and presented here. These experiments are basically defining different tactics and strategies and analyzing them using the developed model. A tactic is a single purposeful intervention in the system; a strategy is a combination of different tactics which, together, form a solution alternative (Bolt, 2002). The following two sections will explore tactics and strategies that help improve the performance of the system.

6.3.1. Tactical Analysis

The tactical analysis in this section is based on the sensitivity analysis results. Sensitivity analysis in previous section has pointed out that the model is sensitive to the safety stock factor, each raw material delivery lead time, unit processing time of each product which is the capacity indicator and the maximum capacity of the raw material inventory.
Table 2 lists all the tactics analyzed which brings an improvement on the performance indicator and an interpretation of each tactics.

Table 2. Alternative tactics to improve the base case

Tactics	Interpretation of application	Change in the model
Tactic 1: Increase safety stock	Realizing this tactic can be of keeping a high level of safety stock as a percentage of the plant raw material capacity.	Increasing the percentage of the safety stock from X to Y
Tactic 2: Reducing the delivery lead time of each raw material	Realizing this tactic can be of finding a reliable and/or close supplier in the plant geographic location.	Decreasing the delivery lead time of each raw material from X days to Y days
Tactic 3: Increase raw material inventory capacity	This can be realized by physical expansion of the inventory	Increasing the maximum inventory capacity of each raw material inventory from X kg to Y kg
Tactic 4: Increase plant production capacity	This can be realized through improved technology or physical expansion of production plant	Decreasing the 'unit processing time of A' and 'unit processing time of B' from x day per order to Y day per order

All of the four tactics are chosen based on their effect on the performance of the enterprise (the desired delivery delay of each product). The effect of the different tactics on the performance indicator of the enterprise is summarized in table 3 below. The numerical output of these tactics alone is not enough. The reduction in variation of the delivery lead time of each product type is as important as the value of each products delivery lead time. We will further investigate the implication of the tactics to the behavior of the delivery lead time of each product type.

Table 3. Effect of each tactic on the performance indicators

Performance Indicator	*Tactic 1*	*Tactic 2*	*Tactic 3*	*Tactic 4*
Delivery Lead time of A in days	-15%	-16%	-12%	-18%
Delivery Lead time of B in days	-17%	-18%	-13%	-22%
Average Deliver lead time	***-16%***	***-17%***	***-12.50%***	***-20%***

*Effects are calculated based on average value relative to the average value of the base case

Tactic 1:
The result in figure 20 is a result of implementing tactic one which is obtained by changing the safety stock factor from 10% in the base case to 15% under this tactic. The green colored graph represents the behavior of the delivery lead time of product type A under the base case

scenario and the black represents after the implementation of this tactic. The average delivery lead time is reduced by 15% (from table 3) and there is a considerable decrease in the variation of the delivery lead time as can be seen in figure 20. Hence, this tactics reduces both the variation and the average value of delivery lead time of product type A. The same is true for product type B with respect to this tactic. It reduces the average delivery lead time of product type B by 17% (from table 3) and the behavior of the delivery lead time graph under this tactic which can be found in appendix 6 also shows an improvement on the variation of the performance indicator.

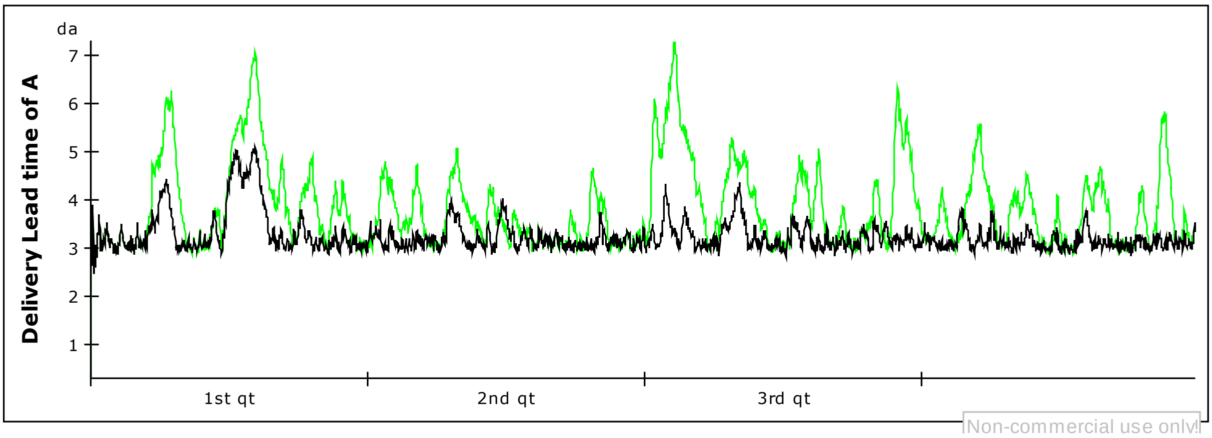

Figure 20. Results of Tactic 1 on the delivery lead time of product type A

Tactic 2:

The result in figure 21 is a result of implementing tactic two. Tactic two is implemented by reducing the delivery lead time of each raw material supply in each plant by one day from the base case value. The green colored graph represents the behavior of the delivery lead time of product type A under the base case scenario and the black represents after the implementation of this tactic. The average delivery lead time is reduced by 16% (from table 3) and there is a considerable decrease in the variation of the delivery lead time as can be seen in figure 21. Hence, this tactics reduces both the variation and the average value of the delivery lead time of product type A. The same is true for product type B with respect to this tactic. It reduces the average delivery lead time of product type B by 18% (from table 3) and the behavior of the delivery lead time graph under this tactic can be found in appendix 6. In comparison to the change made with that of the result obtained, it is a promising tactic also.

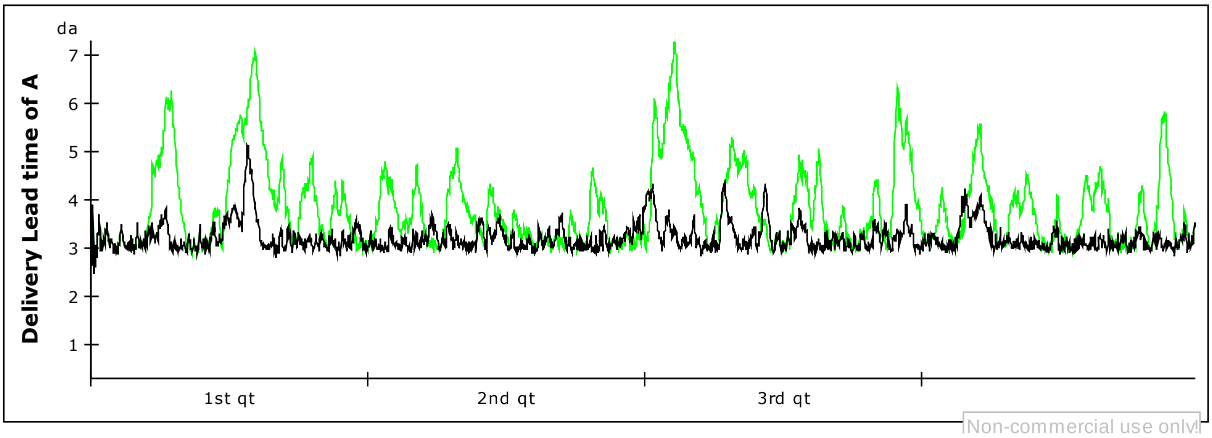

Figure 21. Results of Tactic 2 on the delivery lead time of product type A

Tactic 3:

The result in figure 22 is a result of implementing tactic three which is obtained by increasing the maximum inventory capacity by 500kg from the base case. The green colored graph represents the behavior of the delivery lead time of product type A under the base case scenario and the black represents after the implementation of this tactic. The average delivery lead time is reduced by 12% (from table 3). There is a moderate decrease in the variation of the delivery lead time as can be seen in figure 22. The decrease in the variation of the delivery delay is not as promising as it is in the previous two tactics but there is a reduction in the delivery delay variation. Hence, this tactics reduces both the variation and the average value of the delivery lead time of product type A moderately.

The same is true for product type B with respect to this tactic. It reduces the average delivery lead time of product type B by 13% (from table 3). The behavior of the delivery lead time graph under this tactic can be found in appendix 6.

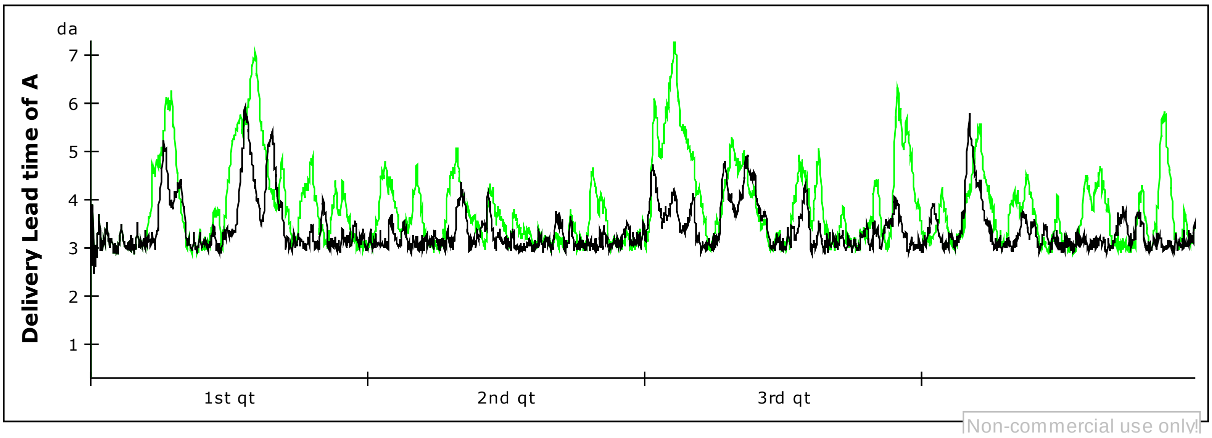

Figure 22. Results of Tactic 3 on the delivery lead time of product type A

Tactic 4:

The result in figure 23 is a result of implementing tactic four which is obtained by increasing the plant capacity by 25%. The green colored graph represents the behavior of the delivery lead time of product type A under the base case scenario and the black represents after the implementation of this tactic. The average delivery lead time is reduced by 18% (from table 3). The decrease in the variation of the delivery delay is not as promising as it is in the previous tactics. Even though the delivery lead-time variation has subdued in most of the horizon, there is a sporadic big variation in delivery lead time which needs to be addressed by some additional tactics (strategy). The same is true for product type B with respect to this tactic. It reduces the average delivery lead time of product type B by 22% (from table 3). The behavior of the delivery lead time graph under this tactic also exhibits the same behavior which can be seen in appendix 6.

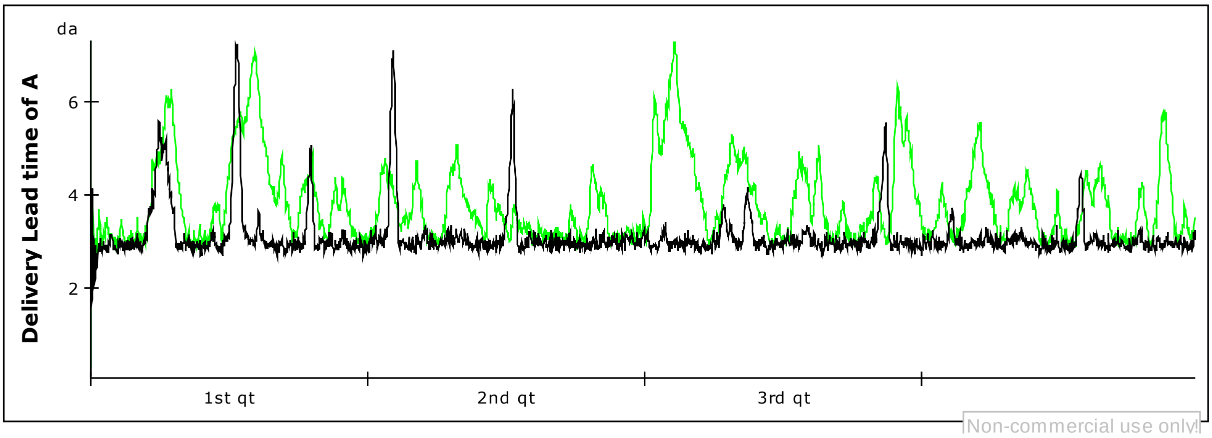

Figure 23. Results of Tactic 4 on the delivery lead time of product type A

6.3.2. Strategy Analysis

The different tactics identified in the previous section can improve the system independent of one another. Clearly, the cost for implementing these tactics is not similar and accordingly a detailed cost benefit analysis will be necessary for making a final decision. However, that is beyond the scope of this study. The possible approach that is feasible to be done in this study is strategy building, which is combining tactics to reach better improvement from the base case.

The objective of the enterprise is to improve the overall delivery lead time of each product type which is very important form the enterprise and customer point of view. All the tactics contribute significantly to the improvement of the delivery lead-time considerably as can be seen in the previous section. But a further combination of these tactics still produces a better improvement as can be seen in the following strategic analysis. Table 4 includes the two strategies that will be explored.

Table 4. Alternative strategies to improve the base case

Strategy	**Description**
Strategy 1: Avoid Material Constraint	This strategy can be realized by combining Tactic 1 and Tactic 2.
Strategy 2: Capacity Change	This strategy is the combination of tactic 3 and tactic 4.

Strategy 1:* *Avoid Material Constraint

The first strategy, 'Avoid material constraint', combines the first two tactics (tactic 1 and tactic 2). This strategy brings a considerable improvement in the plant delivery lead time without changing any physical condition. It needs to increase the safety stock to a level where it is economically feasible to hold on to, and have a material supplier which can reliably reduce the raw material deliver lead time through a facilitated logistics mechanism. The combined improvement of the safety stock level and the raw material delivery lead time as proposed in tactic 1 and tactic two brings 20% reduction the enterprises delivery lead time as can be seen in table 5. Moreover, the behavior of the graph of this strategy on the performance of the enterprise delivery lead time behavior can be seen in figure 24 and 25. The green graph represents the behavior under the base case and the black graph represents the after the implementation of strategy 1.

Table 5. Effect of each strategy on the performance indicators

Performance Indictor	*Strategy 1*	*Strategy 2*
Delivery Lead time of A in days	-19%	-21%
Delivery Lead time of B in days	-21%	-25%
Average Deliver lead time	***-20%***	***-23%***

*Effects are calculated based on average value relative to the average value of the base case

The implementation of this strategy brings both the required stability of the delivery lead time variation and a reduction in the actual delivery lead time value which is important from the enterprise point of view.

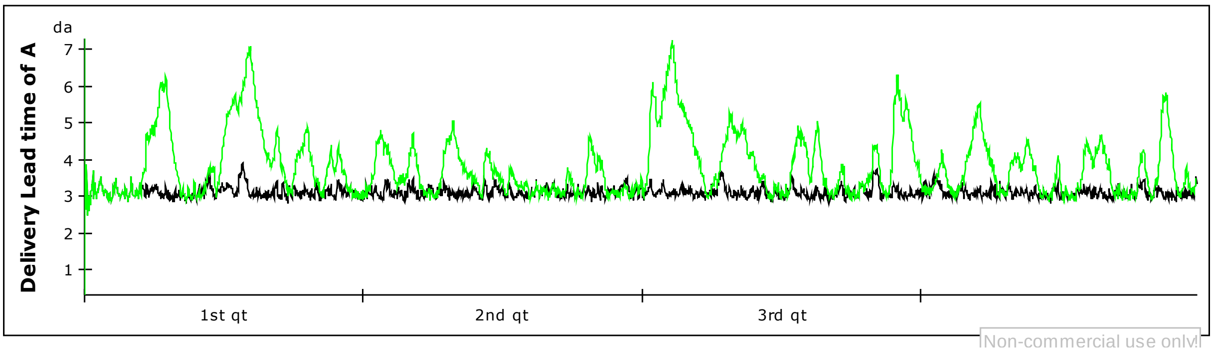

Figure 24. The results of Strategy-1 on delivery lead time of product type A

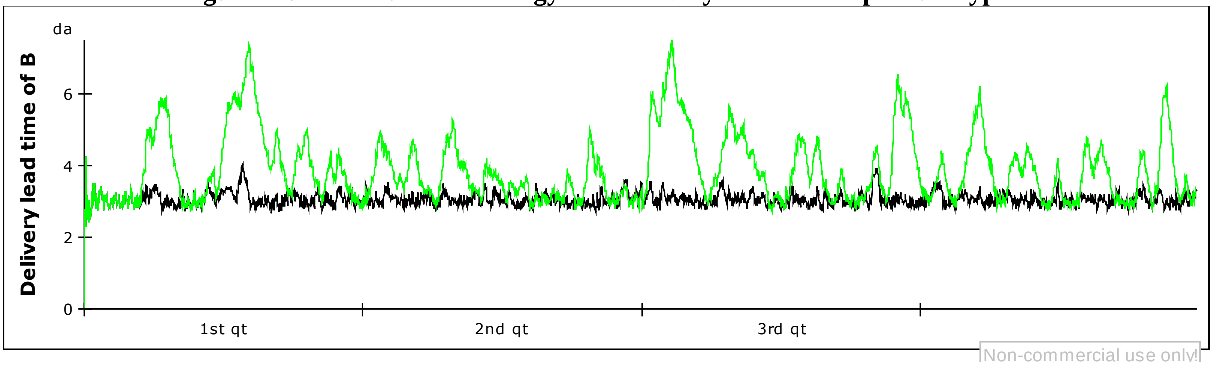

Figure 25. Results of Strategy-1 on the delivery lead time of product type B

<u>Strategy 1:</u> Capacity Change

The second strategy, 'the capacity change', uses tactic 3 and 4. In this strategy the physical and/or technological condition of each plant has to be changed in order to improve the capacity or process efficiency related factors so that the processing time of the plant will be reduced. In addition to this, the inventory capacity of each raw material has to be increased. The results of implementing this strategy will reduce the delivery lead time of the enterprise by 23% and brings a considerable stability to the delivery lead time of both product type as be seen in figure 26 and 27.

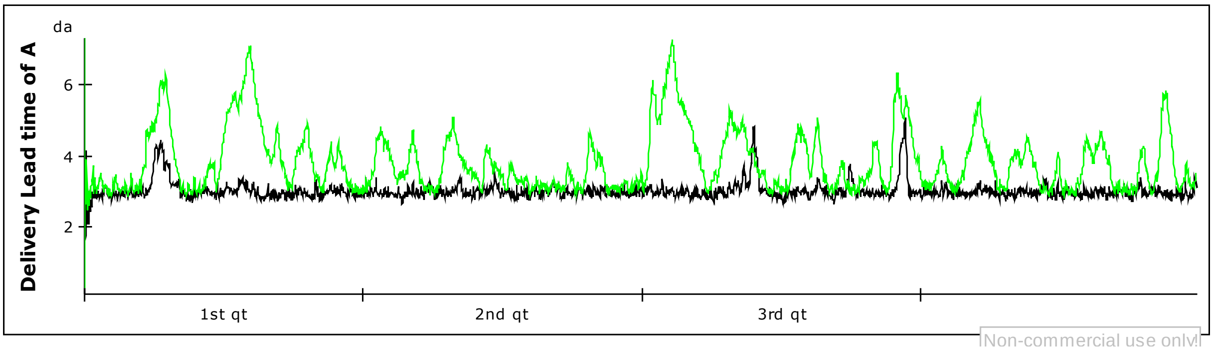

Figure 26. Results of Strategy 2 on the delivery lead time of product type A

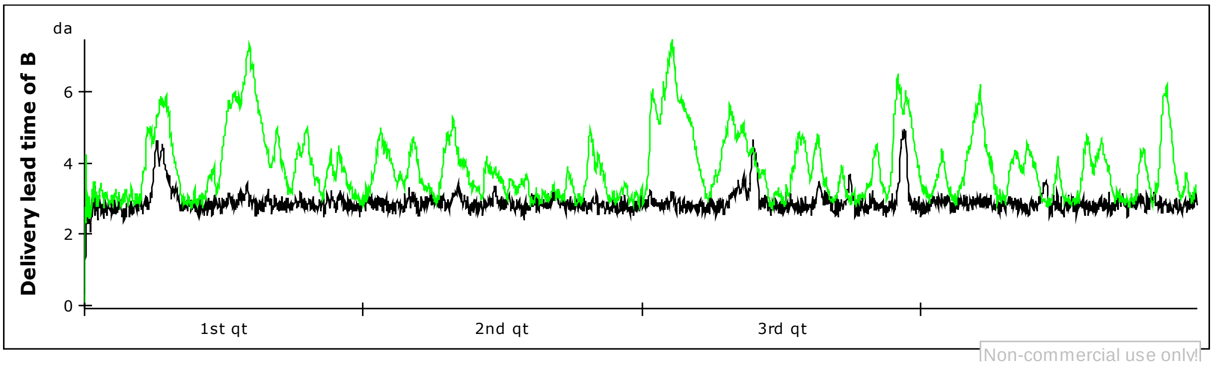

Figure 27. Results of Strategy 2 on the delivery lead time of prodcut type B

These two strategies are based on the underlying decision making process (structure of the model) both at the plant and enterprise level. This means, for example, the decision making process to allocate order to each plant at enterprise level and scheduling, procurement and production process at each plant level has to be consistent with what is considered in here. It is worth noting that the results of a model should not be taken as a 'hard' true prediction, but only in relative terms in the limits of all the model assumptions (Lim, 2002).

The two strategies are feasible as compared to the base case. But what would happen if some of the external variables which are beyond the control of the enterprise turn out to be different? For example, any improvement in the order processing capacity of the plants will considerably improve the delivery lead time. But this will be the case if the capacity increase is not faced with a falling demand or vice versa. With this respect, a necessary task in decision making process is to predict the consequences of each strategy that is being considered under the uncertain future. Uncertainty (the unpredictability in factors that affect the outcome of a course of action) are *sine qua non* of the analytic process; action can be taken to counter this presence, but they cannot be eliminated (Quade, 2000). Different methods have been developed to deal with uncertainty. These methods include forecasting, expert opinion and scenario analysis. In this study scenario analysis is chosen since it can be seen as a combination of the other methods of dealing with uncertainty.

Scenario analysis

A scenario is a description of what hypothetical future states of the world, including a consideration of the major uncertainties encountered in moving far into the future. The scenarios do not predict what will happen in the future; rather they are plausible descriptions of what can happen (Walker, 2000). The different methods used to deal with uncertainty use historical data, expert opinion and forecasting. Scenario analysis may use all (or one) of them.

The uncertainties of such enterprise mainly stems from the behavior of the customers which are beyond the direct control of the enterprise. In this study three plausible scenarios approach was developed to study the robustness of the proposed strategies under the uncertain future. In this research context, a strategy is robust if it can sustain between 50% to 100% of the proposed gain.

Scenario 1: Demand remain the same
In this scenario the demand for the product remains the same. Under this scenario, both strategies are robust. In fact, this scenario is the base case where the strategies are evaluated against and showed the result in of each strategy analysis in the previous sections.

Scenario 2: Demand growth
In this scenario, the demand for the product increases between 5% and 50%. Under this scenario, strategy one is robust to the point where demand growth is not higher than 15%. A demand growth higher than 15% considerably reduces the performance of the enterprise under this strategy. Strategy two is well organized to deal with situations like this. This strategy is robust unless the growth is higher than 30%.

Scenario 3: Demand Falls
In this scenario the demand for the product falls. Even though both strategies are robust with respect to this scenario, practically it is not wise to have a plenty of capacity (as it is in the case of strategy 2) and no demand. But this can be improved by combined effect of both strategies.

6.4. Conclusion

The behavior of the model developed in part two of this research is presented in this chapter. The behavior of the model described is observed with respect to the base case. The model uses order from customers as an input to the model.

The erratic demand from customer affects directly and indirectly much of the behaviors of the factors under consideration. For example, the behavior of production at each plant is presented which shows a very irregular behavior due to the variable input data. This irregular behavior has, indeed, induced an erratic variation in the behavior of the performance indicator of the model that is the delivery lead time of each product type.

Further in this chapter, the results of the sensitivity analysis were used to improve the models behavior by considering different tactics and strategies. By comparing the base case with that of the proposed tactics, it is learned that the safety stock factor in each plant and the raw materials suppliers' delivery lead time improvement will improve the performance of the enterprise by 16% and 17% respectively. Moreover, the raw material inventory capacity of a plant and the unit processing time of each product which is a capacity constraint in this model can also improve the performance of the enterprise by 12.5% and 20% respectively.

Even though some of the findings of the study are not confined to the short to medium operational decisions, such as inventory capacity and plant capacity, their effect on the performance of the enterprise clearly shows their implication on the short to medium operation of the enterprise.

7. Agent Based versus system Dynamics Modeling

This research is inspired by an already developed Agent Based model for the same problem of a multi-plant enterprise. In this chapter a comparison between the two modeling paradigms based on a clear outline of model comparison processes as disused in a literature will be presented. Although there is some difference between the base cases developed by the two models, the comparison is possible by taking that into consideration. This chapter uses the method of comparison as presented in the literature (van Dam et al, 2009) to compare the two modeling paradigms used in the same problem area.

Model Benchmarking

Model benchmarking is a systematic comparison of different modeling paradigms applied for similar problem areas in search of generalizable lessons. Comparison of two different modeling paradigms based on the fundamental conceptual description of the model is not possible. But this can be achieved through a clear outline of benchmarking process.

Van Dam et al (van Dam et al, 2009) developed a method which can be used to assess the performance of two modeling paradigms. They put forward the following points that must be addressed during the benchmarking process.

1. Definition of the objectives of the study
2. Identification of what is to be benchmarked
3. Determination and specification of performance measures
4. Description of scenarios and their simulation
5. Decision recommendations
6. Conclusion

Each of the above steps will be followed in this benchmarking of the two models used to comprehend the operations management in multi-plant enterprise.

1. Definition of the objectives of the study

The objective of the study has to be clear at the start of any benchmarking process. In this benchmarking process the objective is to find out the added value of the two modeling paradigms for operations management in a multi-plant enterprise.

2. Identification of what is to be benchmarked

This step is used to identify the objects of study. These objects have to be specific models that can be experimented with. The object of the study for this benchmarking process is an already developed Agent based model (Behdani et al) and the system dynamic model developed in this research for the same problem.

3. Determination and specification of performance measures

In benchmarking two different modeling paradigms, it is not sufficient to compare the results of the outcomes of each modeling paradigm. One has to be able to able to reflect on the whole modeling process to determine the performance measures of the different ways of modeling. In the same study (van Dam et al, 2009) they proposed set of performance measures which uses to evaluate the efficiency, robustness and flexibility of each modeling paradigms. These performance indicators are;

- Ease of expressing the problem
- Ease of extending the models

- Ease of re-use
- Ease of explaining

Ease of expressing the problem

The ease of the conceptualization of a system into a model through a paradigm is problem dependant. One should consider if all aspects can faithfully be included. Some aspects can be quickly implemented in one approach, but others may have to be left out or simplistic assumptions have to be made. In other words, there are some variables that can easily be used in Agent based model and are very difficult, if not impossible, to use in system dynamic model.

One example of such variable is the due date of an order from customer. Even though this variable played a major role to conduct number of experiments using the agent base model, it was not included in the system dynamic model. Rather the delivery lead-time (the range between the order reception and order delivery) was used in the system dynamic model as an objective.

Another example, the agent based model employed criterion like earliest due date for order allocation to a given plant and for scheduling orders for production. But this criterion is not practicable in the system dynamic model, due to the fact that it is not possible to capture the individual attributes. Instead, expected completion time from each plant was used as an evaluation criterion for the order allocation to a given plant. And the order is handled in the global sales department on FCFS (first come first served) bases.

The scheduling process in each plant is based on the earliest due date in the agent based model. In the system dynamics modeling approach, it was not applicable to prioritize order. Instead another different criterion, namely number of order allocated, was used. The influence of this criterion on the overall performance of the enterprise system dynamic model as compared to the agent based model, which uses a different criterion, is justifiable.

Considering the degree of aggregation of the problem analysis, system dynamic modeling is difficult to capture some of the important concept of the problem under study, where as it is a very simple task in agent based modeling.

Ease of extending the Model

The ease of extending the model is closely related to the previous performance measure. If the model used an easy way to express a concept, it will be very easy to extend that model. While, if a model uses an indirect ways to capture a concept then it will require a considerable effort to make a change. Depending on the number of desired extension to the model, the level of effort required to bring this change to each model can be estimated.

As far as changing some of the parameters are concerned, both modeling paradigms have the same levels of ease. But, the inclusion of one new parameter is very time taking in system dynamic model as compared to agent based modeling. This is because of the draw backs of system dynamics modeling approach. In system dynamic approach the structure has to be determined before starting the simulation (Schieritz and Grobler, 2002). So, any new variables have to be checked its implication to the overall structure of the model in general and the feedback structure in particular which makes the task of extending system dynamic model more time consuming as compared to agent based modeling.

Adding a new agent into an already established agent based model is very easy and is less time consuming. The modeler can independently define the new variable and introduce to the existing model to see the effect of this new factor.

Ease of re-use

The integration of earlier works in to new projects makes modeling a more versatile tool in problem solving. This is an important aspect of model development. It is not only in terms of saving time and cost but also it will help models to have a previously made valid component. When parts of a model can be re-used it becomes easier to create larger models to study larger and more complex systems.

System dynamics models are much known for their reusability, if fact, the part of the model developed in this study is adapted from a model by Sterman (Sterman, 2000). The inventory management parts of the model which includes the procurement and storage process is modeled based on the Sterman inventory model. One system dynamic model can easily facilitate the development of another model in the same problem area.

The same is true for agent based model. It is possible to take part of a model and add it to another model. For example, one agent from a given model can be taken easily with its possible behavior and can be easily introduced to a new model.

With respect to this performance indicator both modeling paradigm have a good prospect of re-use once developed for a specific problem.

Ease of explaining

An important point after developing a model is how to explain the model and interpret the results. This will further be a challenge if the model developer and user is not same person, which is the case most of the time.

Agent based model is very difficult to communicate with other decision makers with no background on the agent based modeling paradigm. A much more simplified version of the actual model is used to verify and justify the outputs of the model. At a much higher degree of complexity, it is very difficult to explain why the model behaves in the ways it does using the model.

System dynamics is well equipped with different tools of conceptualization which will make it easy to explain what is happening and why the results are the way they are. No matter how complex is the relationship between the different variables of interest, system dynamic model can easily be understood by anyone who is willing to do so. This is because system dynamic model behavior emerges based on the predefined structures of the problem identified by the modeler.

4. Description of scenarios and their simulation

A benchmarking study is based on a number of experimentations that can be executed using both modeling paradigms. Here based on the performance indicator of the modeling paradigms, the results of each modeling paradigms will be evaluated for the specified sets of experiments.

The different experimentation conducted on the system dynamic model can be found in section 6.3 with their corresponding parameters used to experiment and the results on the performance indicators.

The agent based model used the same experimentation as in System dynamic model with the exclusion of some experiments related with capacity which the author has investigated further out of curiosity in the system dynamic model. In the agent based experimentation, the effects of the safety stock of raw material on the performance indicator was studied. The performance indicators (total tardiness and total number of late orders) have shown a considerable improvement as the percentage of the safety stock factor increases. In fact, it showed (figure 28) that the performance of the enterprise improves as the reorder factor (=safety stock factor) increases.

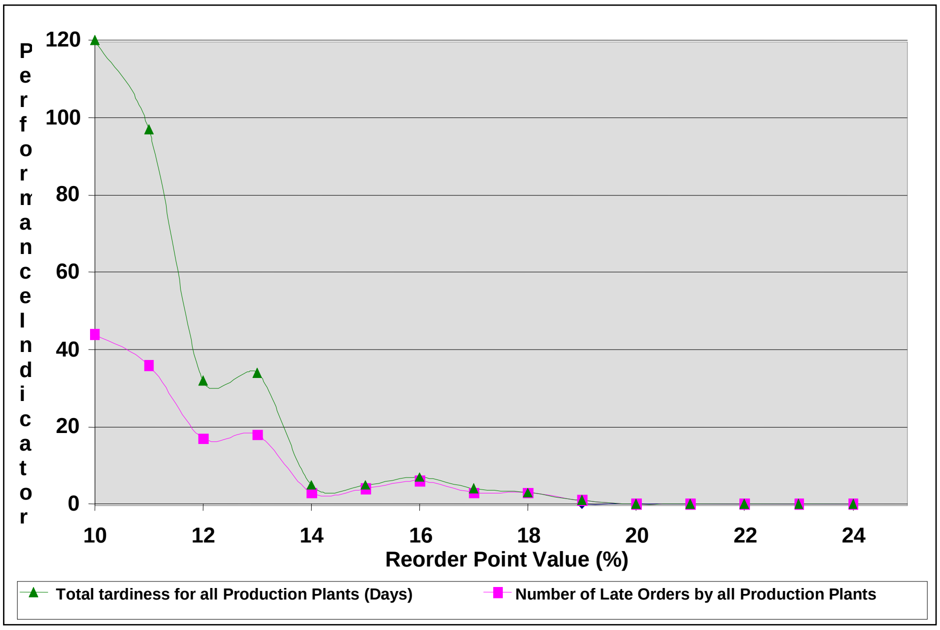

Figure 28. Effect of reorder point on overall system performance (Behdani et al, 2007)

In reference to the experiments with the safety stock, the results of the two modeling paradigms both show an improvement on the performance of the enterprise with an increase in the level of raw material safety stock factor.

5. Decision recommendations

Building models and running simulation is not an end by itself, rather the means to reach a decision. If we compare the resulting policy recommendations of the two modeling approach it is apparent that their policy recommendation is same.

The agent based model analysis suggested an optimal reorder point for raw material inventory to make sure inventory level will not be a bottle neck for production and order fulfillment. On the other hand, the system dynamic model analysis also suggested the same improvement if the safety stock factor is increased.

6. Conclusion

The two modeling paradigms used to create a model on the operations management of a multi-plant enterprise are benchmarked in this chapter. The modeling paradigms are Agent based modeling and system dynamics modeling. In general, model cross comparison reflects on bias of modelers, skill, preferences and experience with the specific model type. Hence, the two paradigms are evaluated based on the efficiency, robustness and flexibility of use.

Considering efficiency some of the important factors used to describe the problem are easily captured by agent based modeling where as it is very difficult, if not impossible, to incorporate in the system dynamics model.

Considering robustness both models can easily include new parametric change. In case of introducing a new factor, agent based model is much more robust. This is because system dynamic model is based on a predefined structure of the problem which makes it very difficult to easily include new factor without adjusting the predefined structure.

Flexibility is the strength of both modeling paradigms. One can easily use part or all of a model which is built using these two paradigms. Ease of explanation is not a strong point of agent based modeling. Rather a system dynamic model and its behavior can easily and understandable be explained and communicated with.

8. Model Development Process

Finally, before the conclusion and recommendation, the process in which the model is developed will be reviewed in this chapter. Besides, best practices and trade-offs will be discussed that assist the model development process. They came from the process of the author and from the observations of processes of others modelers. The focus is on the system dynamic modeling.

Modeling has played a significant role in decision making process. There is a hand full of modeling alternatives to chose from. But the choice the modeler made makes the model development process more complicated. In this chapter, solutions for these problems are sought. A distinction is made between trade-offs and recommendations on model translation and modeling in general. The findings in this chapter can assist in the model development process of future models. They were already applied and learnt during the process of this thesis.

Conceptualization versus parallelism

During the design of models, the modeler learns more on the concepts he models. However, beforehand you must have a clear starting point. In this thesis, the agent based model of the same problem and literature review was used as a starting point before model started. The modeler needs well-defined knowledge on the topic to be able to have a usable starting point for the model development process, but the level of detail needed at forehand can be debated. Because the development process is iterative, different phases of model development overlap. As a result, multiple processes occur parallel. Parallelism increases the modeler’s inspiration by making analogies between those phases.

In the course of developing this model the concepts about the problem area was continuously evolving as since my acquaintance with the problem area is also increasing. Though the conceptualization phase used as a starting point for the model development process, the actual modeling override much of the concepts at the conceptualization phase. A trade-off has to be made as explicit as possible between the amounts of knowledge that is acquired before the start of the modeling and the time it takes to conceptualize the problem. The former helps the modeler to model with progress while the latter has influence on the progress of the work.

Incremental versus iterative design

A trade-off has to be made between incremental and iterative design. Incremental design is the production of a series of models that are all fully functional and of increasing complexity. Iterative design is a process in which a consecutive step can start while the first has not finished yet. All steps are followed iteratively until the final step. A trade-off has to be found between those two extreme design methods, because both have advantages for the modeler.

The main reason to use incremental design is that it is impossible to grasp complex systems at one shot. At the same time, that is the reason why modeling and simulation is interesting and helpful in getting insight into the complexity and dynamics of systems related to complex problems. Progress of the design process is important. In order to have a functional starting point, it must be of lower complexity. Moreover, when the models complexity increases, many conceptual errors cannot be easily found and solved. As a consequence, validation will be difficult or unsuccessful. Small improving steps can each be verified, validated and tested. This can be done by taking extreme values for some parameters and read and interpret outcomes of the model.

The first working model should not be complex at all. A set of restrictive assumptions should be made for a first working model. It is very likely that the research questions cannot be answered because of those assumptions, but it is a necessity to finally be successful. Therefore, it is probably useful to first start focused on incremental design. Starting with modeling less complex components is more appropriate. Progress is easier with a less complex starting point.

Since modeling itself is a learning process, the modelers modeling abilities increase together with the complexity of the modeling steps. Another solution is to start with an existing model that is somewhere related to the models that the modeler wants to model. For example, I considered an inventory management model developed by Sterman as a starting point. By incrementally adapting a working model, a working version always exist which is a continuous driver for progress.

However, a modeling process is fundamentally iterative, because during the development, errors are made, and insight is achieved. As a consequence, iterative design will be advantageous. By using such a process, the robustness of the eventual model will increase. Path dependence (where circumstances are limited by the earlier decisions) and lock-in effects will be less when accepting this iterative character. Thus, a dynamic trade-off between incremental and iterative design is necessary.

In the process for this thesis, at the start small incremental steps were taken like building an inventor system of a single plant based on the model by Sterman (Sterman, 2000). Then, followed completing a single plant model with a single raw material, and single product type to produce. Then the number of raw material was increased to two, followed by the product type. But at this stage, as the complexity of the model is getting bigger, iterative design was dominant. Results are interpreted which causes finding errors in decisions or gaps in previous steps that need to be corrected. On the final stage of including the second plant, the model is more complex and large incremental steps were made.

High versus low abstraction

A main trade-off should be made in the level of abstraction. Too little detail results in irrelevant and invalid outcomes. Too much detail slows the process down. This trade-off must be made explicit. The choice for abstraction can be used in three ways to improve the model development process.

First, different levels of abstraction can be used in the same model if the choice can be made separately for the different parts of the model. This is the case when subsystems are distinct and are of main importance to the problem under study. For example, the degree of abstraction in the inventory decision process and production process is different. The inventory decision process included more detailed factors into consideration as compared to the production decision process.

Second, the complexity of a modeling exercise can be reduced by using higher abstraction. An abstract form might be easier to program and can still be adequate for the overall model.

Communication and collaboration versus progress

Both communication and collaboration, with experts and problem owners, can help keeping focus in the modeling process. However, communication and collaboration also take time. Therefore, a trade-off needs to be made between the progress of the model development and these two. The trade-off has to be such that both the communication and collaboration help to increase progress instead of slowing the model building process down. Communication helps because making choices often happen when talking about it with colleagues or friends or problem owners. Also presenting preliminary results help in the process of improving models. They are possibilities to get a modeler out of a conceptual loop it has locked in. It should be noted that choices made are never final; there is always a point of return as described as iterative design. Collaboration helps the modeling process to be creative. In addition, synergy effects of several modelers of different backgrounds increase the quality of the result, since no person can know all aspects of the content of the problem and the modeling tool. Innovative solutions to modeling problems are more easily found together. Note also that collaboration increases the modeler’s dependency on the other modelers.

9. Conclusion and Recommendation

9.1. Conclusion

A number of approaches have been developed by and repeated by various authors aimed at improving operation management in multi-plants enterprise. This research is designed in view of getting an additional insight of operations management in multi-plant enterprise system from the perspective of a system dynamic modeling approach and to compare the results of this study with that of another modeling paradigms.

The main question for this research was;

How can operations management in multi-plant enterprise be improved using a system dynamic simulation model?

About the multi-plant modeling

Identification of the important tasks of operations management in multi-plant enterprise is carried out by studying an already developed agent based model and literature. Scheduling, inventory management (procurement and storage) and production operations have been identified as key tasks of operations management in multi-plant enterprise. Moreover, criteria were set to determine the effectiveness of the operational functions from the perspective of the enterprise. The most widely used performance indicator from the enterprise perspective, the delivery lead time also used in this study as the performance indicator.

Then the system dynamics modeling is used for modeling. System dynamics perceives processes in the world in terms of stocks, flows between those stocks, and information that determines the values of the flows. Single events are less relevant than behavior; events are abstracted to an aggregated view on feedback loops and delay structures. This integrated view of a system as a unified whole as promoted by this method was used to investigate contribution of this modeling paradigm to the operations management problem in multi-plant set ups.

The process of modeling was started by conceptualization. During conceptualization, the different factors that influence operations management functions in multi-plant enterprise were developed from literatures and an existing agent based model. These factors have been also crossed check with experts for their dependability.

Before interpreting the results of the model, the model has to be verified and validate. Although there was no actual data for validation, some of the simulated results of an agent based model for the same problem were used to validate the model. The result of the verification and validation test shows viability of the model for the intended purpose.

To better understand how the model works, important parameters of the base case have been presented and their behavior has been explained. Results of the model experimentation in the strategy and tactic analysis shows that change in safety stock level, raw material supplier lead time, capacity of raw material inventory and the production capacity of each plant has a considerable influence on the performance indicator.

Plausible improvement tactics are defined based on the sensitivity analysis results. Increase safety stock, reduce the delivery lead time of each raw material, increase raw material inventory capacity and increase production plant capacity was the four tactics suggested. These tactics have been further combined in to strategies since these tactics generate desirable results. The strategies, which combine the tactics, are more aggressive in their impact on the performance indicator.

The two strategies considered are ‘Avoid material constraint’ and ‘the capacity change’. The former, which can be implemented by changing the safety stock factor and the raw material delivery lead time, can brings 20% reduction in the plant delivery lead time without changing any physical condition. The second strategy, ‘the capacity change’, the physical and/or technological condition of each plant has to be changed in order to improve the production capacity and the raw material inventory capacity of each plant. Under this strategy the delivery lead time of the enterprise reduces by 23%.

The robustness of these strategies in dealing with the uncertain future has been explored under three different future scenarios. Both strategies are robust with all the three scenarios except ‘the capacity change’ strategy under the scenario ‘demand fall’ is unreasonable. Because this strategy is about increasing the plant capacity and if the demand actually falls then is it unwise to have an enlarged capacity for a reduced demand.

Multi-plant enterprises managers has to give due attention to the safety stock factor and raw material suppliers lead time in each plants to dealing with the challenges of operation managements. Moreover, even though capacity related factors do not fall in to the category of short term plan, it can be a medium term plan for enterprises. In medium term horizon, both the plant and inventory capacity of each plant has to be an area of attention for multi-plant operation management.

About Modeling Paradigms

The two modeling paradigms used to create a model on the operations management of a multi-plant enterprise have also been benchmarked in this study. The modeling paradigms are Agent based modeling and system dynamics modeling. The two paradigms are evaluated based on the efficiency, robustness and flexibility.

Considering efficiency some of the important factors used to describe the problem are easily captured by agent based modeling where as it is very difficult, if not impossible, to incorporate in the system dynamics model.

Considering robustness both models can easily include new parametric change. In case of introducing a new factor to the model agent base model is much more robust. This is because system dynamic model is based on a predefined structure of the problem which makes it very difficult to easily include new factor without modifying the predefined structure.

Flexibility is the strength of both modeling paradigms. One can easily use part or all of a model which is built using these two paradigms. Ease of explanation is not a strong point of agent based modeling. Rather a system dynamic model and its behavior can easily and understandable be explained.

The results of the two modeling paradigm recommendation shows that the recommendation of the two modeling approaches may vary but the results of each recommendation shows that both their outputs are aligned to the pursuit of meeting the company objective.

9.2. Recommendation

Based on the finding of this exploratory study it is recommended to further explore the implication of production capacity and demand variation in a multi-plant enterprise operation management using other methods.

Another work can be change in the structure of the decision making process which bring a considerable improvement options in to the picture. Due to time limitation, the effect of changes in the decision making process (structural change) is not studied. It is the author's strong recommendation to see the implication of such structural changes.

Moreover, due to the added complexity, the cost implication of the strategies developed is not considered in this study. Any improvement options suggested in this study has to be evaluated against the cost implication of such changes. It is wise to see the effect of each strategy gradually.

A future work in the operations management in multi-plant enterprise can be of combining the two modeling paradigms (Agent Based and System Dynamics) which can be very useful to exploit the potential strength of each paradigm and overcome the limitations of each approach. For example, the different plants internal supply-chain can be modeled using a system dynamic model and the different plants interaction with that of the enterprise and external suppliers can be modeled using an agent based modeling. An already established internal supply chain model facilitates this effort. Even this model can be modified to include only one plant internal supply chain and be used to be part of the new mixed model.

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11. Appendix 1: Multi-plant model over view

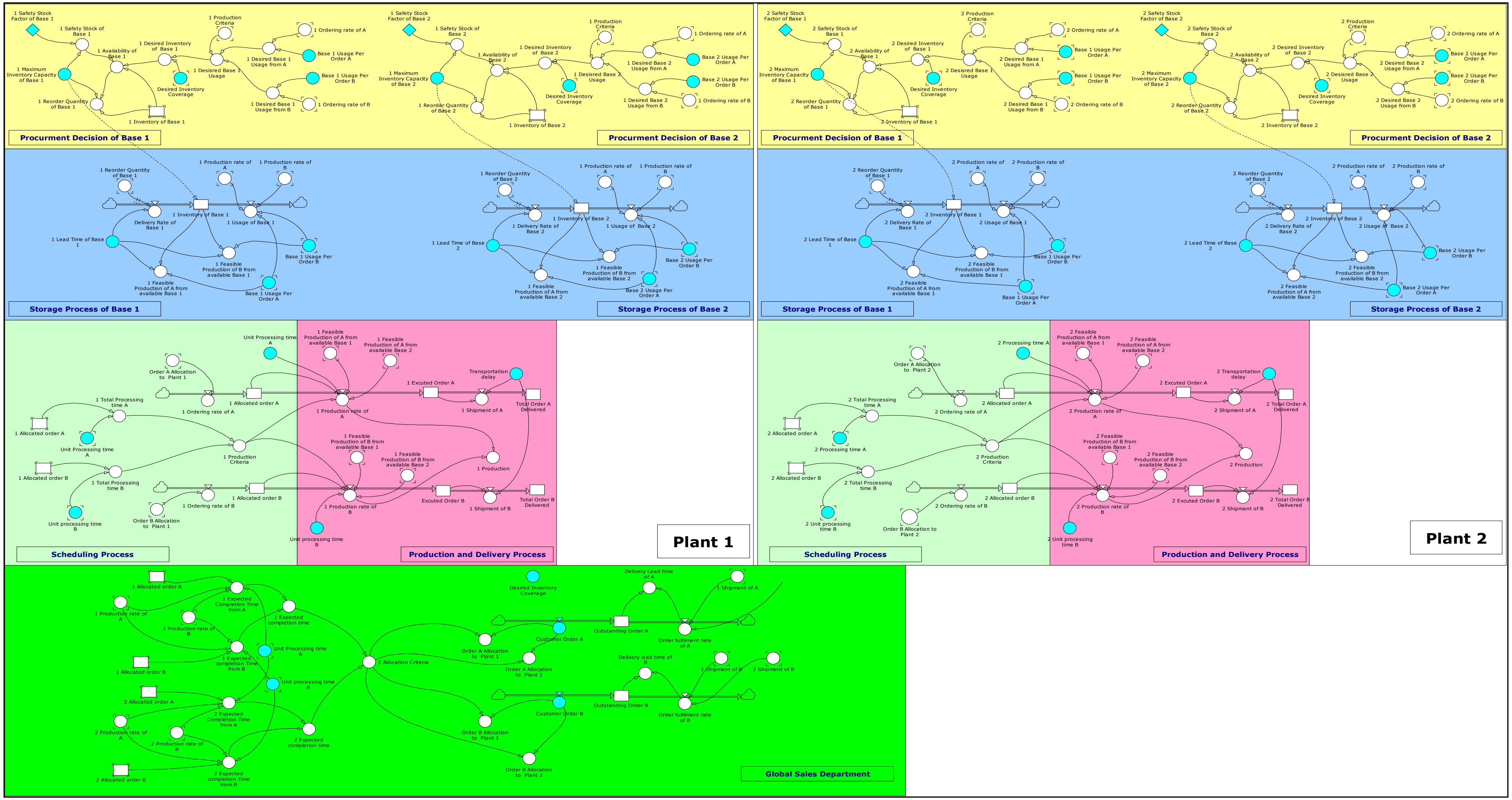

Figure 29. Multi-plant Model

12. Appendix 2: List of Variables

Table 6. List of Variables

Variable Name	**Variable Definition**
Allocated Order	Is the number of orders that found in a given plant at a given time
Allocation Criteria	Is the used to compare the different plant based on a given criteria for allocating an order
Allocation to plant	Is the number of orders allocated to a plant from the global sales department per a unit time
Customer order	Number of orders placed by the customer per day
Delivery lead time	The average time taken by the enterprise to process an order from order placement until it is delivered
Desired Inventory	The amount of raw material required to process a given order
Executed order	The number of orders finalized by the production department
Feasible Production from material	The number of orders that can be processed based on the actual raw material inventory at a given time
Inventory Level	The actual amount of raw material available in stock
Material delivery rate	Is the rate at which a raw material will be delivered to a given plant
Material Usage	Is the amount of raw material required to process a unit order
Maximum Inventory Capacity	Is the maximum amount of raw material that can be stored
Order Allocation	Is the number of orders allocated to a given plant per day based of the allocation criteria
Order fulfillment rate	Is the rate at which finished orders are sent to a customer
Outstanding Order	Is the number of order being processed in the enterprise
Expected completion time	Is the time required to finalize an already placed order to the plant
Production rate	Is the number of orders executed per unit day
Reorder quantity	Is the amount of raw material required to replenish inventory
Safety stock factor	Is the amount of minimum inventory that triggers replenishment
Shipment	The number of finished orders sent to customer in a unit day
Transportation delay Unit Processing time	Is the time elapsed for delivery from the factory to the customer Is the time required to produce a unit order

13. Appendix 3: Over all Specifications

Order A Allocation to Plant 1 = IF ('1 Allocation Criteria'=TRUE,’ Customer Order A',0<<Order/da>>)

Order A Allocation to Plant 2 = IF('1 Allocation Criteria'=FALSE, ‘Customer Order A',0<<Order/da>>)

Order A Generator = NORMAL (.49<<Order/da>>, 0.4<<Order/da>>, 0.3)

Order B Allocation to Plant 1 = IF ('1 Allocation Criteria'=TRUE, 'Customer Order B',0<<Order/da>>)

Order B Allocation to Plant 2 = IF ('1 Allocation Criteria'=FALSE, 'Customer Order B',0<<Order/da>>)

Order B Generator = NORMAL (.5<<Order/da>>, 0.4<<Order/da>>, 0.3)

Order fulfillment rate of A = '1 Shipment of A'+'2 Shipment of A'

Order fulfillment rate of B = ‘1 Shipment of B'+'2 Shipment of B'
1 Allocation Criteria = IF ('1 Expected completion time' <= '2 Expected completion time', TRUE, FALSE)

1 Availability of Base 1 = IF(('1 Desired Inventory of Base 1'+'1 Safety Stock of Base 1') >'1 Inventory of Base 1', FALSE, TRUE)

1 Availability of Base 2 = IF (('1 Desired Inventory of Base 2'+'1 Safety Stock of Base 2')>'1 Inventory of Base 2', FALSE, TRUE)

1 Delivery Rate of Base 1 = DELAYPPL ('1 Reorder Quantity of Base 1','1 Lead Time of Base 1')/ '1 Lead Time of Base 1'

1 Delivery Rate of Base 2 = DELAYPPL ('1 Reorder Quantity of Base 2','1 Lead Time of Base 2')/ '1 Lead Time of Base 2'

1 Desired Base 1 Usage from A = 'Base 1 Usage per Order A'*'1 Ordering rate of A'

1 Desired Base 1 Usage from B = 'Base 1 Usage per Order B'*'1 Ordering rate of B'

1 Desired Base 2 Usage from A = 'Base 2 Usage per Order A'*'1 Ordering rate of A'

1 Desired Base 2 Usage from B = 'Base 2 Usage per Order B'*'1 Ordering rate of B'

1 Desired Inventory of Base 1 = '1 Desired Base 1 Usage'*'Desired Inventory Coverage'

1 Desired Inventory of Base 2 = '1 Desired Base 2 Usage'*'Desired Inventory Coverage'

1 Desired Base 1 Usage = IF ('1 Production Criteria'=TRUE, '1 Desired Base 1 Usage from A','1 Desired Base 1 Usage from B')

1 Desired Base 2 Usage = IF ('1 Production Criteria'=TRUE, '1 Desired Base 2 Usage from A','1 Desired Base 2 Usage from B')

1 Expected completion time = '1 Expected Completion Time from A'+'1 Expected completion Time from B'

1 Expected Completion Time from A = IF ('1 Production rate of A'<>0<<Order/da>>,'1 Allocated order A'/'1 Production rate of A','1 Allocated order A'*'Unit processing time A')

1 Expected completion Time from B = IF ('1 Production rate of B'<>0<<Order/da>>,'1 Allocated order B'/'1 Production rate of B','1 Allocated order B'*'Unit Processing time B')

1 Feasible Production of A from available Base 1 = '1 Inventory of Base 1'/'Replenishment time'/'Base 1 Usage Per Order A'

1 Feasible Production of A from available Base 2 = '1 Inventory of Base 2'/'Replenishment time'/'Base 2 Usage Per Order A'

1 Feasible Production of B from available Base 1 = '1 Inventory of Base 1'/'Replenishment time'/'Base 1 Usage Per Order B'

1 Feasible Production of B from available Base 2 = '1 Inventory of Base 2'/'Replenishment time'/'Base 2 Usage Per Order B'

1 Ordering rate of A = 'Order A Allocation to Plant 1'

1 Ordering rate of B = 'Order B Allocation to Plant 1'

1 Production = '1 Production rate of A'+'1 Production rate of B'

1 Production Criteria = IF ('1 Allocated order A'>='1 Allocated order B',TRUE,FALSE)

1 Production rate of A = IF ('1 Production Criteria'=TRUE AND '1 Allocated order A'>0<<Order>>,MIN('1 Feasible Production of A from available Base 1','1 Feasible Production of A from available Base 2',1/'Unit processing time A'),0<<Order/da>>)

1 Production rate of B = IF('1 Production Criteria'=FALSE AND '1 Allocated order B'>0<<Order>>,MIN('1 Feasible Production of B from available Base 1','1 Feasible Production of B from available Base 2',1/'Unit Processing time B'),0<<Order/da>>)

1 Reorder Quantity of Base 1 = IF('1 Availability of Base 1'=FALSE,'1 Maximum Inventory Capacity of Base 1'-'1 Inventory of Base 1',0<<kg>>)

1 Reorder Quantity of Base 2 = IF('1 Availability of Base 2'=FALSE,'1 Maximum Inventory Capacity of Base 2'-'1 Inventory of Base 2',0<<kg>>)

1 Safety Stock of Base 1 = '1 Maximum Inventory Capacity of Base 1'*'1 Safety Stock Factor of Base 1'

1 Safety Stock of Base 2 = '1 Safety Stock Factor of Base 1'*'1 Maximum Inventory Capacity of Base 2'

1 Shipment of A = IF ('1 Executed Order A'>0<<Order>>,'1 Executed Order A'/'Transportation delay',0<<Order/da>>)

1 Shipment of B = IF ('Executed Order B'>0<<Order>>,'Executed Order B'/'Transportation delay',0<<Order/da>>)

1 Usage of Base 2 = IF ('1 Inventory of Base 2'>0<<kg>>,'Base 2 Usage Per Order A'*'1 Production rate of A'+ 'Base 2 Usage Per Order B'*'1 Production rate of B',0<<kg/da>>)

1 Usage of Base 1 = IF ('1 Inventory of Base 1'>0<<kg>>,'Base 1 Usage Per Order A'*'1 Production rate of A' + 'Base 1 Usage Per Order B'*'1 Production rate of B',0<<kg/da>>)

2 Availability of Base 1 = IF (('2 Desired Inventory of Base 1'+'2 Safety Stock of Base 1')>'2 Inventory of Base 1', FALSE, TRUE)

2 Availability of Base 2 = IF(('2 Desired Inventory of Base 2'+'2 Safety Stock of Base 2')>'2 Inventory of Base 2', FALSE, TRUE)

2 Delivery Rate of Base 1 = DELAYPPL ('2 Reorder Quantity of Base 1','2 Lead Time of Base 1')/ '2 Lead Time of Base 1'

2 Delivery Rate of Base 2 = DELAYPPL ('2 Reorder Quantity of Base 2','2 Lead Time of Base 2')/ '2 Lead Time of Base 2'

2 Desired Base 1 Usage from A = '2 Ordering rate of A'*'Base 1 Usage per Order A'

2 Desired Base 1 Usage from B = '2 Ordering rate of B'*'Base 1 Usage per Order B'

2 Desired Base 2 Usage from A = 'Base 2 Usage per Order A'*'2 Ordering rate of A'

2 Desired Base 2 Usage from B = 'Base 2 Usage per Order B'*'2 Ordering rate of B'

2 Desired Inventory of Base 1 = '2 Desired Base 1 Usage'*'Desired Inventory Coverage'

2 Desired Inventory of Base 2 = '2 Desired Base 2 Usage'*'Desired Inventory Coverage'

2 Desired Base 1 Usage = IF ('2 Production Criteria'=TRUE, '2 Desired Base 1 Usage from A','2 Desired Base 1 Usage from B')

2 Desired Base 2 Usage = IF ('2 Production Criteria'=TRUE, '2 Desired Base 2 Usage from A','2 Desired Base 2 Usage from B')

2 Expected completion time = '2 Expected Completion Time from A'+'2 Expected completion Time from B'

2 Expected Completion Time from A = IF ('2 Production rate of A'<>0<<Order/da>>,'2 Allocated order A'/'2 Production rate of A','2 Allocated order A'*'Unit processing time A')

2 Expected completion Time from B = IF('2 Production rate of B'<>0<<Order/da>>,'2 Allocated order B'/'2 Production rate of B','2 Allocated order B'*'Unit Processing time B')

2 Feasible Production of A from available Base 1= '2 Inventory of Base 1'/'Replenishment time'/'Base 1 Usage Per Order A'

2 Feasible Production of A from available Base 2 = '2 Inventory of Base 2'/'Replenishment time'/'Base 2 Usage Per Order A'

2 Feasible Production of B from available Base 1 = '2 Inventory of Base 1'/'Replenishment time'/'Base 1 Usage Per Order B'

2 Feasible Production of B from available Base 2 = '2 Inventory of Base 2'/'Replenishment time'/'Base 2 Usage Per Order B'

2 Ordering rate of A = 'Order A Allocation to Plant 2'

2 Ordering rate of B = 'Order B Allocation to Plant 2'

2 Production = ‘2 Production rate of A'+'2 Production rate of B'

2 Production Criteria = IF ('2 Allocated order A'>='2 Allocated order B', TRUE, FALSE)

2 Production rate of A = IF ('2 Production Criteria'=TRUE AND '2 Allocated order A'>0<<Order>>, MIN ('2 Feasible Production of A from available Base 1','2 Feasible Production of A from available Base 2',1/'Unit processing time A'),0<<Order/da>>)

2 Production rate of B = IF ('2 Production Criteria'=FALSE AND '2 Allocated order B'>0<<Order>>,MIN('2 Feasible Production of B from available Base 1','2 Feasible Production of B from available Base 2',1/'Unit Processing time B'),0<<Order/da>>)

2 Reorder Quantity of Base 1 = IF ('2 Availability of Base 1'=FALSE,'2 Maximum Inventory Capacity of Base 1'-'2 Inventory of Base 1',0<<kg>>)

2 Reorder Quantity of Base 2 = IF ('2 Availability of Base 2'=FALSE,'2 Maximum Inventory Capacity of Base 2'-'2 Inventory of Base 2',0<<kg>>)

2 Safety Stock of Base 1 = '2 Maximum Inventory Capacity of Base 1'*'1 Safety Stock Factor of Base 1'

2 Safety Stock of Base 2 = '2 Maximum Inventory Capacity of Base 2'*'1 Safety Stock Factor of Base 1'

2 Shipment of A = IF ('2 Executed Order A'>0<<Order>>,'2 Executed Order A'/'2 Transportation delay', 0<<Order/da>>)

2 Shipment of B = IF ('2 Executed Order B'>0<<Order>>,'2 Executed Order B'/'2 Transportation delay', 0<<Order/da>>)

2 Usage of Base 2 = IF ('2 Inventory of Base 2'>0<<kg>>,'Base 2 Usage Per Order A'*'2 Production rate of A' + 'Base 2 Usage Per Order B'*'2 Production rate of B',0<<kg/da>>)

2 Usage of Base 1 = IF ('2 Inventory of Base 1'>0<<kg>>,'Base 1 Usage Per Order A'*'2 Production rate of A' + 'Base 1 Usage Per Order B'*'2 Production rate of B',0<<kg/da>>)

Customer Order A = IF ('Order A Generator'<0<<Order/da>>,0<<Order/da>>,'Order A Generator')//NORMAL(.634<<Order/da>>,.818<<Order/da>>,0.6)

Customer Order B = IF ('Order B Generator'<0<<Order/da>>,0<<Order/da>>,'Order B Generator')

Delivery Lead time of A = 'Outstanding Order A'/'Order fulfillment rate of A'

Delivery lead time of B = 'Outstanding Order B'/'Order fulfillment rate of B'//IF('Order fulfillment rate of B'<>0<<Order/da>>,'Outstanding Order B'/'Order fulfillment rate of B',.1<<da>>)

14. Appendix 4: Extreme Condition test

Under these test, the expected behavior of three variables of interest, namely Actual inventory, Expected completion time and Production rate in each plant is compared with that of the simulated behavior in the following sections. These variables are chosen because of either they are important indicators for the validity of the model in comparison to their historical behavior as is the case with the Inventory and/or has an implication for the other decision process in the model as in the case of expected completion time, which is used as an internal criteria for allocating orders. In each extreme condition test, it will be compared the expected and actual behavior of these variables.

Extreme Condition 1: No customer order

Under such circumstances there will not be any order form customer. Under this extreme condition the expected and simulated behavior for our variable of interest is considered below;

Actual Inventory: If there is no order at all from customer, the expected amount of raw material inventory level is, it will remain intact from its initial value. This is what the simulated behavior also shows in figure 29 below.

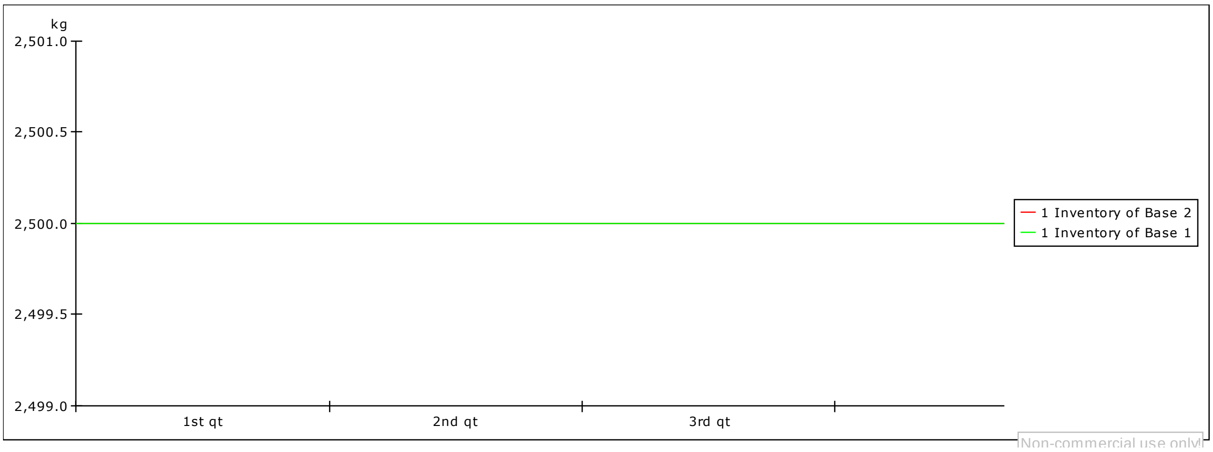

Figure 30: Actual inventory of Base 1 and Base 2 in Plant 1

Expected Completion Time: The expected behavior of the expected completion time is zero since there will not be any order waiting to be processed. The expected completion time is the criteria used by the global sales department to allocate new orders based on the possible waiting time of the new order in the different plants before it is processed, so any new order will wait zero days to start processing under this extreme condition. See the result of the simulation in Figure 30 below which reflects the expected behavior.

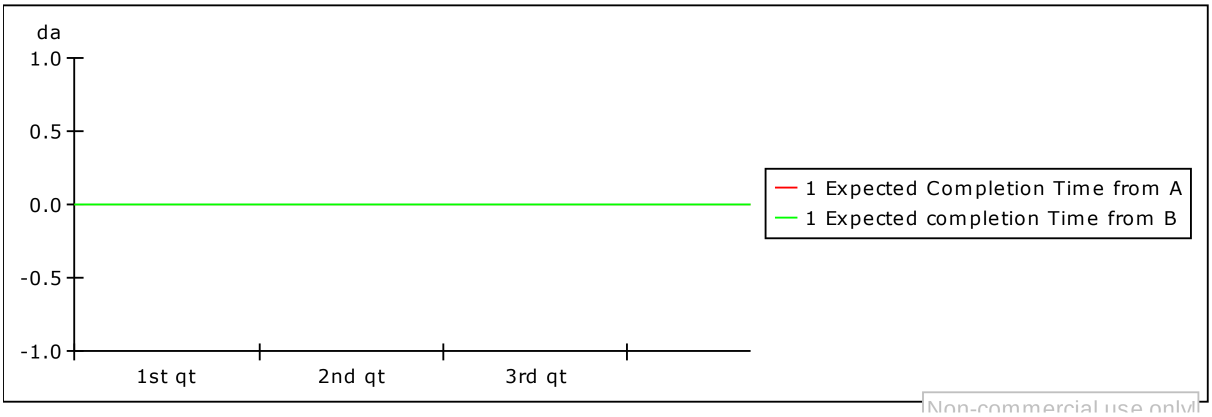

Figure 31: Expected completion time in plant 1 form product type A and B

Production Rate: The expected behavior of the production rate is a constant rate of zero since there is no order to process. And Figure 31 shows the simulation result which coincides with what is expected.

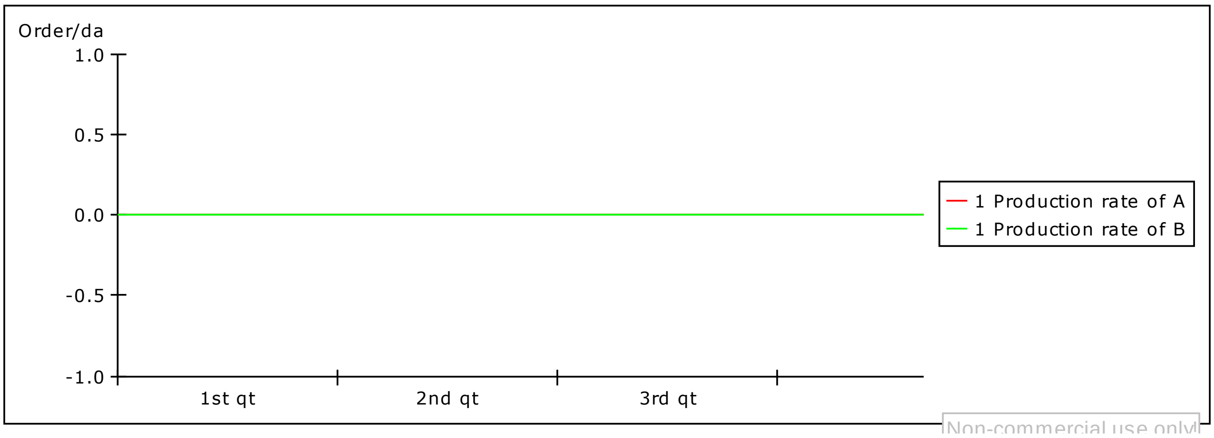

Figure 32: Production rate of product type A and B in plant 1

Extreme Condition 2: Very high customer order

The expected behavior and the simulated behavior of all the above three variables will also be discussed under this extreme condition where there will be a very high number of order arrival form customer.

Actual Inventory: A high number of customer orders will result in an increase of the inventory cycle. This is because there will be a very high consumption of raw material due to the high demand. Since there is limitation in inventory capacity it is not possible to procure whatever amount is needed rather there ordering cycle will considerably increase. The simulated result depicted in Figure 32 coincides with what is expected.

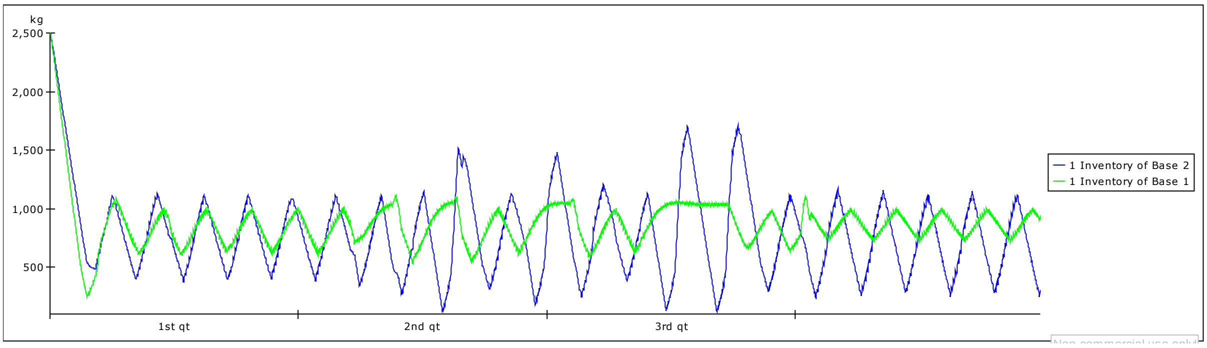

Figure 33: Actual Inventory of Base 1 and Base 2 in plant 1

Expected Completion Time: High number of customer order will result in an ever increasing expected completion time. This is because of the capacity limitation which each plant has. As the number of order keeps on adding the plant can not go beyond its maximum capacity, resulting in an ever increasing expected completion time in each plant. Figure 33 shows how the result of the simulation under this circumstance, hence the expected behavior.

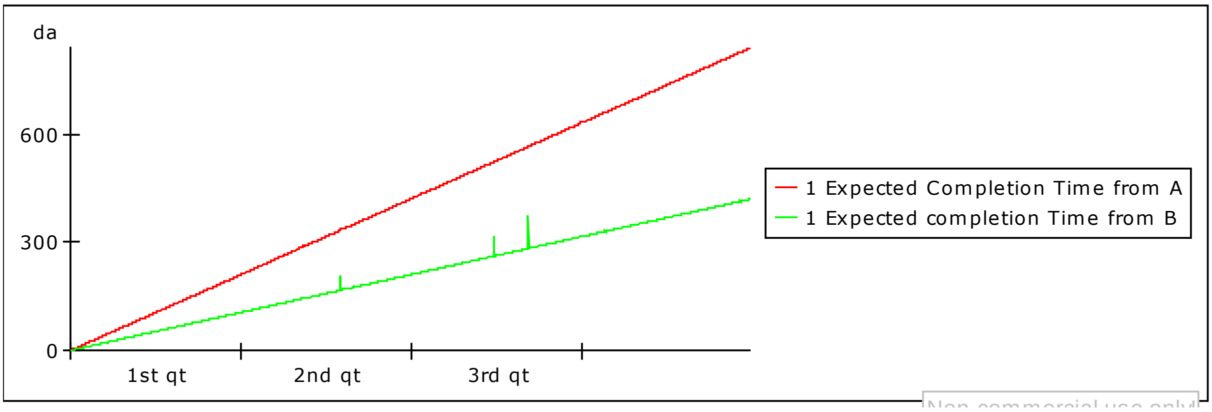

Figure 34: Expected completion time from product A and B in Plant 1

Production Rate: If there is abundant number of orders from customer the production plant will continuously run with it maximum production capacity in order to meet the huge demand. Figure 34 shows the production rate which runs at its full capacity continuously as expected. The plant will never rest, in other word the production rate will never be Zero under this condition. The sudden shift of the graph during the end of the third quarter is not because it is using less of its capacity rather it is because it started producing product type A which has a longer processing time of 2 days.

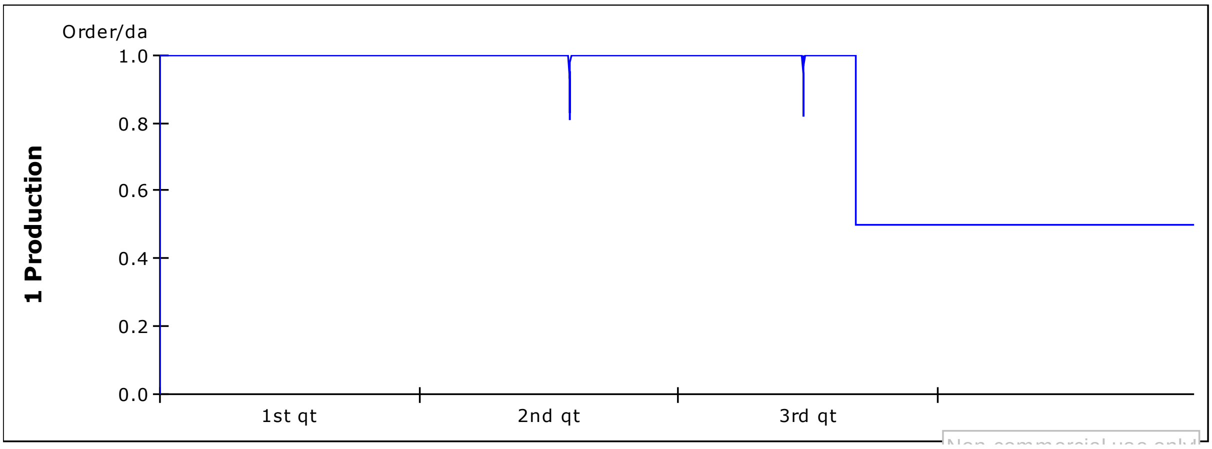

Figure 35: Production rate of Plant 1

15. Appendix 5: Sensitivity Analysis

Table 7: Sensetivity result for delivery lead time A and B

Input Parameter	Unit	Base Value	Base Value + 10%				Base Value - 10%			
			Delivery lead time of A (3.76 days)		Delivery lead time of B (3.81 days)		Delivery lead time of A(13.76 days)		Delivery lead time of B(13.81days)	
			Value	Percentage change	Value	Percentage change	Value	Percentage change	Value	Percentage change
Safety stock factor	%	10.00	3.39	-9.84	3.4	-10.76	3.89	3.46	4.02	5.51
Unit processing time of A	day/order	2.00	5.69	51.33	5.82	52.76	3.46	-7.98	3.49	-8.40
Unit processing time of B	day/order	1.00	4.00	6.38	4.07	6.82	3.57	-5.05	3.46	-9.19
Transportation delay	day	3.00	4.05	7.71	4.1	7.61	3.46	-7.98	3.52	-7.61
1 Maximum capacity of Base 1	Kg	2500.00	3.68	-2.13	3.72	-2.36	3.96	5.32	4.01	5.25
1 Maximum capacity of Base 2	Kg	2500.00	3.68	-2.13	3.69	-3.15	3.92	4.26	3.97	4.20
2 Maximum capacity of Base 1	Kg	2500.00	3.64	-3.19	3.7	-2.89	4.01	6.65	4.09	7.35
2 Maximum capacity of Base 2	Kg	2500.00	3.71	-1.33	3.75	-1.57	4.09	8.78	4.14	8.66
1 Lead time of Base 1	day	4.00	3.88	3.19	3.95	3.67	3.62	-3.72	3.67	-3.67
1 Lead time of Base 2	day	4.00	3.92	4.26	3.97	4.20	3.55	-5.59	3.57	-6.30
2 Lead time of Base 1	day	5.00	3.52	-6.38	3.56	-6.56	4.04	7.45	4.11	7.87
2 Lead time of Base 2	day	5.00	3.59	-4.52	3.64	-4.46	4.09	8.78	4.16	9.19

16. Appendix 6: Delivery lead time of product type B

This appendix includes the results of all the tactical analysis in the behavior of the delivery lead time of product type B which is the performance indicator of the model combined with the delivery lead time of product type A.

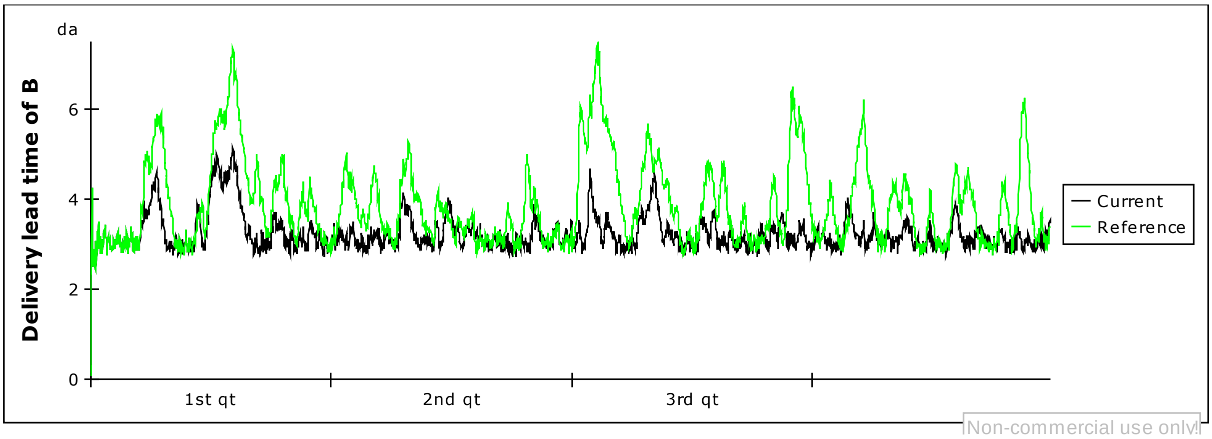

Figure 36. Results of Tactic 1 on the delivery lead time of product type B

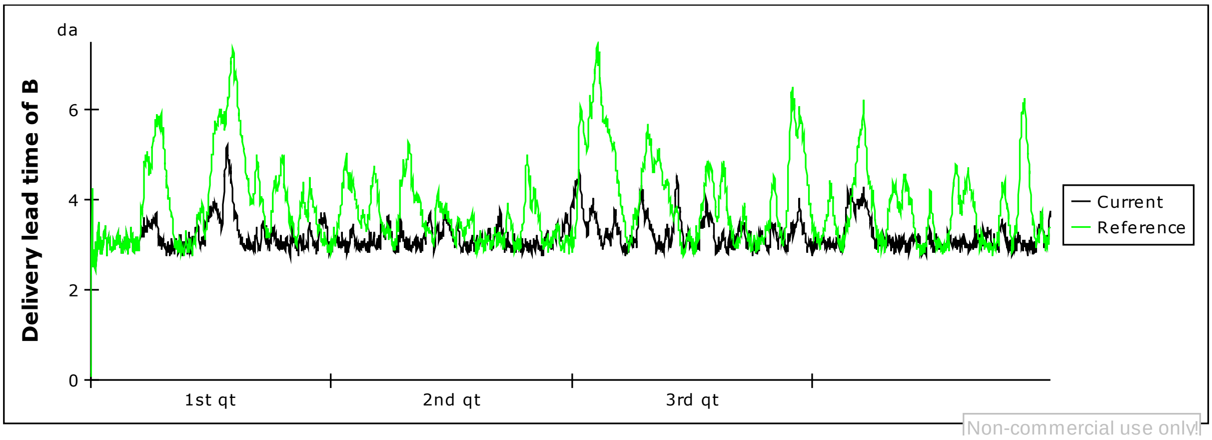

Figure 37. Results of Tactic 2 on the delivery lead time of product type B

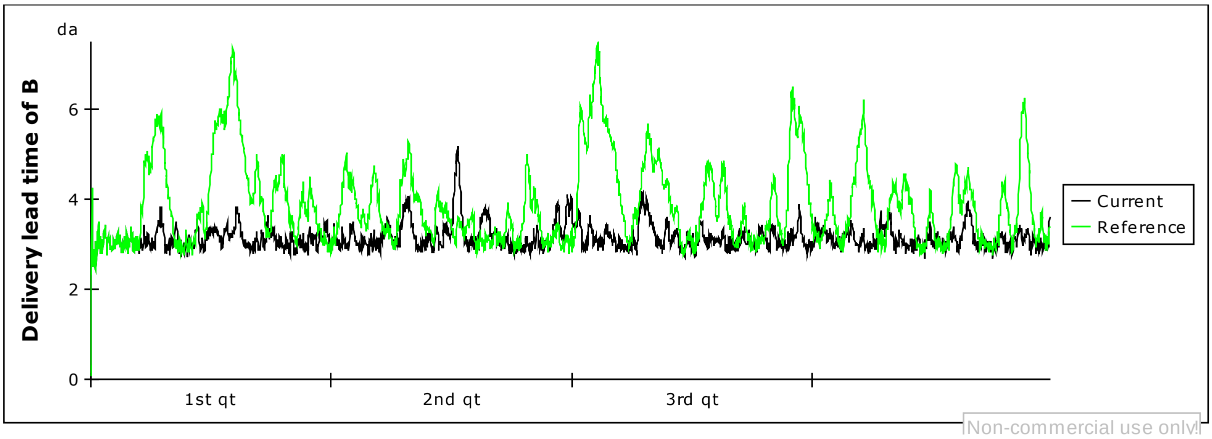

Figure 38. Results of Tactic 3 on the delivery lead time of product type B

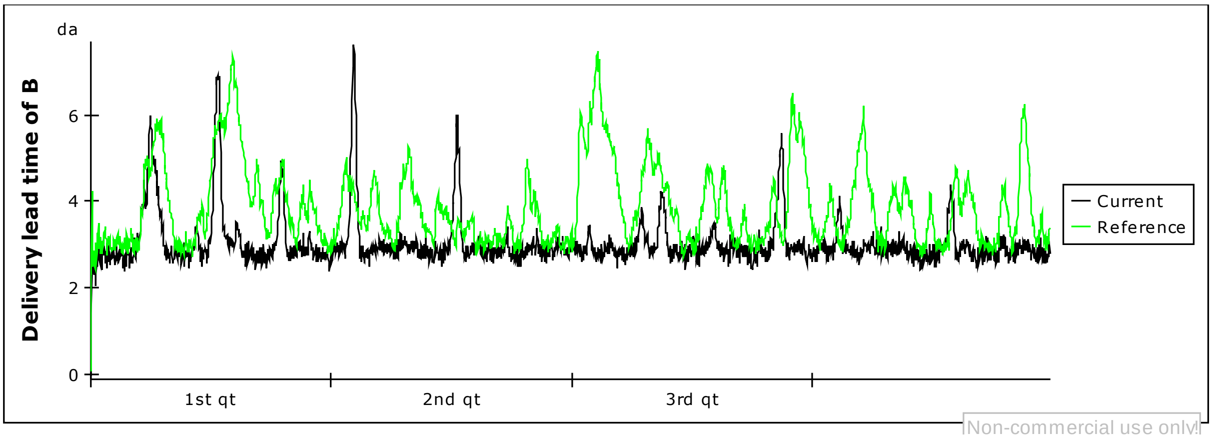

Figure 39. Results of Tactic 4 on the delivery lead time of product type B