STUDY OF CONTROL ACTIONS ON AMANUFACTURING SYSTEM SUBJECT TO A DYNAMIC ENVIRONMENT CREATED BY CUSTOMERS, SUPPLIERS AND COMPETITORS

By

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AND COMPETITORS

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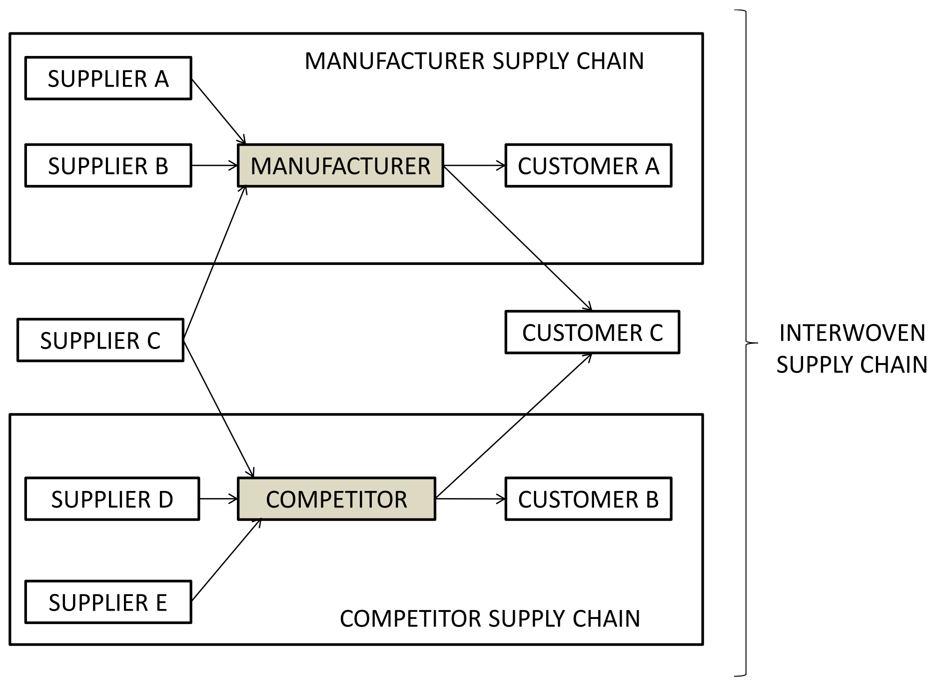
CHAPTER I

INTRODUCTION

In order to stay competitive in a dynamic market environment, a manufacturer must be able to meet the requirements of the customer. These customer expectations may result in increase in number of product specifications, demand fluctuations, product life cycle changes, and quality expectations. Mahoney (1997) names the customer, the competitor and the manufacturer as the three key players needed to develop a competitive strategy to address these dynamics. However, in order to meet changing customer expectations, a manufacturer must be able to rely on a network of one or more suppliers, which makes the supplier as the fourth key player in the relationship. Crandall, Crandall and Chen (2010) define the different types of interactions between the four key players in terms of supply chain networks. A dedicated or serial supply chain is one of the types where a supplier, delivers to the manufacturer and then the manufacturer delivers to the customer becomes a self-contained network. Vertical integration of a serial supply chain occurs when the manufacturer in the supply chain owns part or all of the suppliers. However, when a supplier provides an assortment of products or has additional capacity, additional customers may be added. When the customer addition scenario is expanded to include the other key players, an interwoven network is formed where one or more key players buy and sell as part of another network.

Figure 1 shows two supply chain networks where suppliers A and B constitute as dedicated supplier base for the manufacturer supply chain while suppliers D and E constitute as the dedicated supplier base for the competitor. The mutually exclusive network is interwoven with the introduction of another supplier C that supplies both the manufacturer as well as the competitor. This interweave will also open the possibility of sharing one or more customers such as customer C shown in the Figure 1.



(Figure adapted from Crandall, Crandall & Chen, 2010)

Figure 1 Multiple Supply Chains

This research investigates a manufacturing system within a single serial supply chain composed of internal and external elements. Internal elements are elements such as workstations, labor, material handling systems, and inventory control systems. Between a manufacturing system and its surrounding environment exists a boundary. Beyond this boundary, in the surrounding environment, there exist external elements, which include the other three key players: suppliers (materials and/or service), competitors, and customers. There are also several other external elements such as the economy, weather, and federal agencies. Each of these external elements can exert one or more influences on the manufacturing system; some of the effects of change exerted by the external influences may be mitigated or exploited by control actions embedded in the manufacturing system while others are not. These disturbances or external influences could occur as discrete random events (event based) or accumulate over a period.

A number of studies have been conducted to understand the effects of change caused by internal elements on a manufacturing system, such as machine breakdowns, labor absenteeism, product defects, and schedule problems (Subramaniam, 1993). There are also a number of studies included in the literature review section that focus on modeling and analysis of manufacturing systems with external influences. These studies focus on the individual effects of the influences on the manufacturing system performance and ignore the combinatorial effects of the influences. This research study will focus on the single as well as the group effects of the external influences on the manufacturing system. A comprehensive list of external influences that can affect generic manufacturing systems is discussed in later section. From this list, four external influences are chosen for the research. The four external influences are competitor(s) going out of business, supplier(s) going out of business, diminished supplies over a period of time, and product customization. In order to mitigate or exploit the effects of external influences on the performance metrics of the manufacturing system, control actions are applied. As a working definition for this research, a control action is a tool or plan that could be implemented in a manufacturing system and has the ability to mitigate or exploit the effect of one or more external influences on the system.

Figure 2 shows the relationship between external influences, control actions and the metrics that define the performance of a manufacturing system. The external elements such as customers, suppliers, and competitors create one or more external influences that can penetrate the system boundary of the manufacturing system to create adverse impacts on the system performance metrics such as throughput, work in process (WIP), utilization, and time in system. The manufacturing philosophies such as lean, agile, quick response manufacturing and theory of constraints each suggest control actions through which the manufacturing system might mitigate or exploit the adverse impacts of the external influences on the system performance metrics.

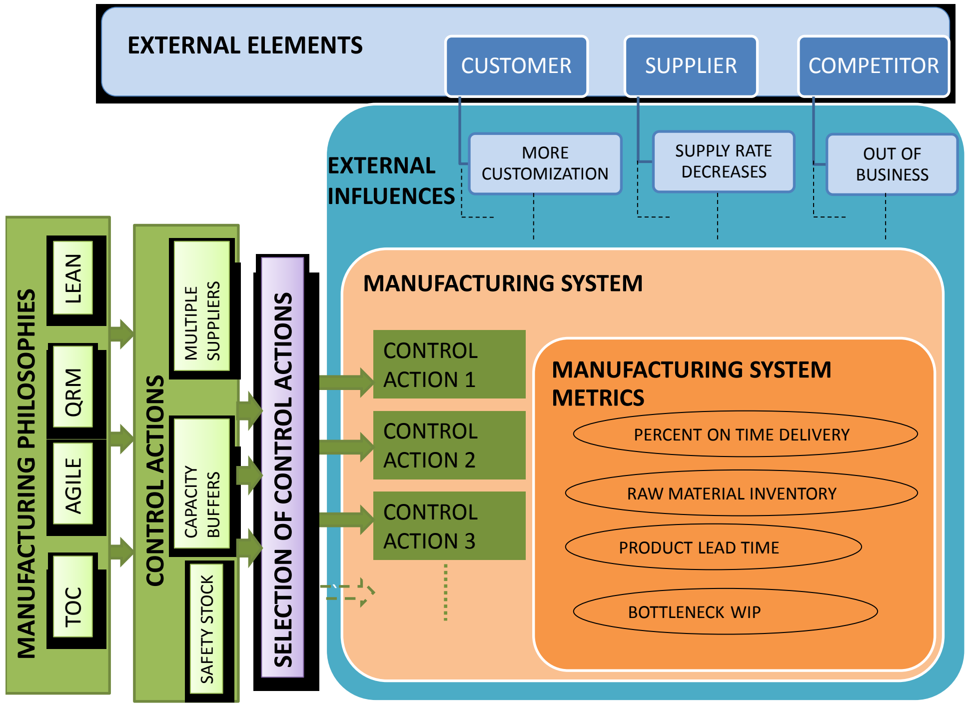


Figure 2 Effect of External Influences and Control Actions

The literature consists of many references to manufacturing philosophies and strategies. Swamidass and Newell (1987) along with Skinner (1985), Wheelwright and Hayes (1985) define philosophies and strategies as the application of manufacturing strengths that contribute to enhanced long-term competitiveness and performance of the business. Philosophies and strategies are higher-level terms and they are associated with a lower level collection of tools and methods able to improve one or more performance metrics of a system. Another problem area identified through this research is that a list of many overlapping manufacturing systems philosophies have emerged over the past several decades such as lean systems, adaptable systems, agile manufacturing, leagile manufacturing, quick response manufacturing, etc. For each manufacturing philosophy that has emerged, a host of articles and/or books provide philosophy goals, definitions, and characteristics. Some attempt to distinguish the often-overlapping philosophies. A decomposition of all these philosophies reveals each shares one or more similar control actions at their lower level.

This study attempted to use the Quality Function Deployment matrix (Juran & Godfrey, 1998) by considering value from the external influences perspective. Figure 3 shows a QFD model that maps the relations between the different levels of manufacturing philosophies to control actions to performance metrics to external influences. The attempt to structure a QFD matrix proved difficult in several areas described as follows. There are multiple levels philosophies between the main philosophy and the control actions. For example, Lean philosophy refers to use of Cellular manufacturing concept, which in turns advocates production flow analysis technique. Production flow analysis (Burbidge, 1989) is used to convert a "process" oriented production line to a "product" oriented production line. Between the production flow analysis and the main philosophy lean manufacturing, exists another level of philosophy named Cellular manufacturing systems.

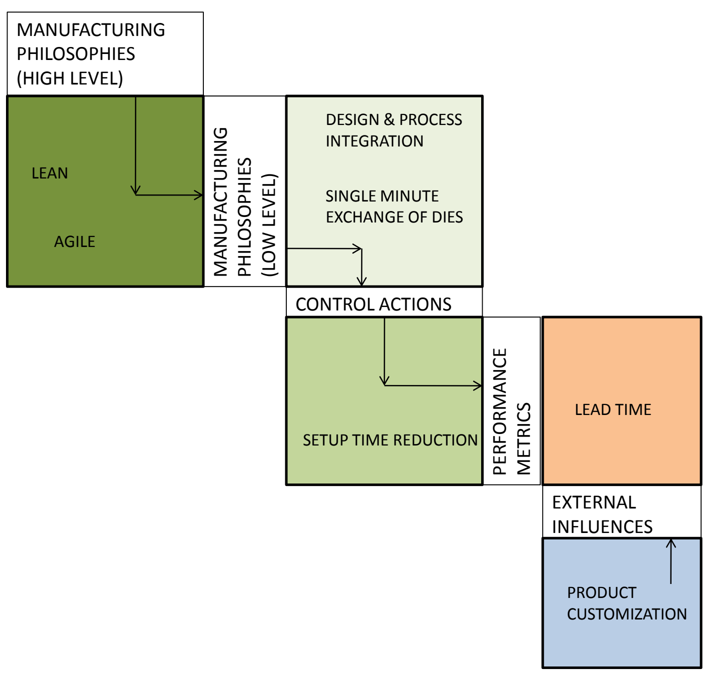


Figure 3 Quality Function Deployment Mapping of Manufacturing Philosophies

In an another example using the main philosophy Agile manufacturing, advocates the use of "sneakerization"(Goldman et al, 1995) which is finding new market niche with existing products. There is no intermediate level between the main philosophy agile manufacturing and the final method "sneakerization". In the lean example, one additional level exists between the main philosophy and the method applied to the manufacturing system, whereas in agile example, there are no additional levels between the main philosophy and the method. In addition, some of the control actions are associated with several manufacturing philosophies. An example of a control action overlapping several manufacturing philosophies such as lean, agile and quick response manufacturing is setup time reduction. If a manufacturing system caters to a medium to high product mix market scenario, then by applying the setup time reduction control action the system may be able to improve the system performance metrics used to measure the performance of these philosophies such as reduced lead-time, lowered cost per unit, reduced finished goods inventory and better customer response rate. Although lean, agile and quick response manufacturing philosophies recommend the use of setup reduction methodology, QRM philosophy (Suri, 1998) recommends the combination of lot size reduction along with setup time reduction to achieve the maximum reduction in lead time performance metric.

In order to respond to external influences in a dynamic environment, appropriate control actions are used in a manufacturing system to hold or bring system performance back to the desired level when external influence changes have had a negative impact. For example, an external element such as the supplier could influence a manufacturing system by going out of business or by decreasing its supply rate over a period. In order to mitigate or exploit the impact of this external influence, control actions such as using alternate vendors and/or having inventory buffer may be implemented in the manufacturing system. The literature fails to relate the strength of the relationship between the philosophies, strategies and the mitigation of external influences on the system.

Performance metrics are used to measure the mitigation of changes in the external influences by the control actions embedded in the manufacturing system. Existing literature provides a variety of performance metrics for manufacturing systems. White (1996) proposes that two basic questions must be answered in selecting manufacturing performance metrics: what is important to be measured and how can it be measured. Several studies have discussed the use of performance metrics to measure a systems reaction to external influence changes in the presence of control actions. However, these studies do not provide a performance metric selection process for the different types of manufacturing systems under consideration.

1.1 Problem Statement

The existence of multiple, overlapping manufacturing philosophies creates confusion among manufacturing system managers who aim at improving the performance of the manufacturing system. Given the scenario where a set of external influences may impact the performance metrics of the system, a manager is unable to pick most cost effective control actions to mitigate or exploit the effects of the influences. The scenario gets further complicated when the group of external influences can simultaneously act upon a system throwing the system into dynamic chaos. Several studies research both the internal and external influences on the system. The studies have missing links between the influences created by the external elements, control actions and their effects on the performance metrics. This research study aims to address the managerial aspects of understanding the effects of control actions in the face of individual as well a group of external influences acting on a system's right performance metrics. With this goal, after selecting a system to study the next step in research selects the control actions from the existing philosophies. Comprehensive methodologies for the selection of performance metrics as well as the control actions will also be addressed.

1.2 Research Objectives

The goal of this research is to understand the relationships between the different external influences and the available control actions based on the outcome of a series of experiments. A case study organization, which is a manufacturer of industrial wireless communication products, is modeled using discrete event simulation. During the research process, a methodology is developed for the identification and selection of the performance metrics as well as the control actions. Using this model, an experimental design is developed to analyze the impact of individual and group interactions of the external influences on the manufacturing system performance, with and without the embedded control actions. The research objectives for this study are as follows.

Objective 1

The first objective is to study and understand the results from a managerial aspect in order to help a manger to decide on several options for a control action for each external influence, which includes the selection and application of the control action. The methodology involves designing and conducting a series of experiments where selected levels of several factors called external influences are studied in the absence of any control actions in order to enable the manager to make a decision whether the degree of change in performance metrics and the recovery time of the system when change in the influence is removed is acceptable. The understanding of the results from a managerial aspect will help a manager to decide on several options for a control action, which includes the application and level of the control action.

Objective 2

The second objective is to design and conduct a series of single factor experiments where each control action is applied to mitigate or exploit the impact of individual external influences acting alone on a manufacturing system. By knowing the system performance and recovery rate under the change in influence being reversed, when the control action is applied, a manager is able to understand the options involved in not applying versus applying varying levels of control action.

Objective 3

The third objective of the research is a special case scenario where more than one control action is necessary to mitigate or exploit the effects of a single external influence effect. The outcome from this analysis will assist a manager to understand the confounding effects of the external influence and understand the strengths and weaknesses of the control actions in mitigating the influences various effects.

Objective 4

The fourth objective of this study is to develop methodology for guiding a manager in the selection of control actions as well as the performance metrics.

1.3 Organization of the Research

Following this introduction, the remainder of the dissertation begins with literature review on the control actions, external influences, and the performance metrics used to measure their effects on a manufacturing system. The literature review section also covers the areas of experimental design and simulation. A research approach section introduces the problem, provides details on the case study organization from which data was collected, and reviews the simulation model and methodology for selection of control actions. The results section of this document discusses the individual analysis of the four external influences on the manufacturing system model. The research section introduces the experimental design and the statistical methods to be used in analyzing the results.

CHAPTER II

LITERATURE REVIEW

This chapter provides a review of the literature relevant to the study of the impact of external influences, both individually and as a group, on the performance of a manufacturing system and examines the effect of control actions, in a single product family, multistage manufacturing system. The chapter begins with an overview of the manufacturing systems relevant to the study. The manufacturing systems review is followed by discussion of the literature on the effect of influences. The section following the effect of influences discusses the major current philosophies, summary of the tools under each philosophy and the evolution of control actions. The last section in this chapter discusses the literature review of the selection process involving the performance metrics of the manufacturing system.

2.1 Manufacturing Systems

The boundary of a manufacturing organization is defined as ownership of business processes and activities (Chen, Daugherty & Roath, 2009). A manufacturing organization is considered as one of the elements in a supply chain. APICS Dictionary (Blackstone, 2008) defines supply chain as “the global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution and cash”.

Integration in a supply chain defines the boundaries of a manufacturing system. Lawrence and Lorsch (1967) define integration as the collaboration that exists among different departments in a manufacturing organization in order to provide a united effort to meet the demands of the environment.

Chen, Daugherty and Roath (2009) conducted an extensive literature review about internal and external and both. Internal integration occurs between one or more departments inside a manufacturing system in a supply chain. An internal integration could be between a manufacturing department and supporting departments such as purchasing (Narasimhan & Das, 2001), marketing (Kahn & Mentzer, 1998), and human resources (Youndt, Scott, Dean & Lepak, 1996). The literature supports the integration of the manufacturing processes inside an organization to the supporting processes. In order to eliminate any bias of the integration of supporting process , this research draws the boundary of a manufacturing system by including all processes, and resources associated with direct product manufacturing and places all the supporting processes and resources boundary of outside the manufacturing system.

Manufacturing systems can be categorized into different types. They can be categorized by customized product systems to mass product in systems, single product systems (dedicated) to multiple product systems (batch), or low volume to high volume. Assembly processes, which are common in manufacturing, can be classified into two types (Subramaniam, 1993). In the first type, assembly processes involve a base part that flows through a sequence of stages with components added along the route. This type is called a serial assembly line. In the second type, several base parts exist and are assembled at different stages, which are brought together as subassemblies together in a final assembly portion of the line. This type is called a parallel assembly line. In some cases, a parallel assembly line will operate the upstream / subassembly line as serial assembly line. Figure 4 provides a graphical representation of the two assembly types described. The figure also shows the two sub types for parallel assembly lines. The parallel assembly line with two stations (stations 1 and station 4) could be reduced to a simple form of serial assembly line. In this reduction, the three stations in parallel assembly line sub type 1(stations numbering 1 to 3) are modeled as a single stage station with the throughput rate for each station equal to the slowest processing station among stations 1, 2 and 3. This reduces the parallel assembly line to serial assembly line with two workstations. Thus, the serial assembly line model is selected for this study because of this generalization.

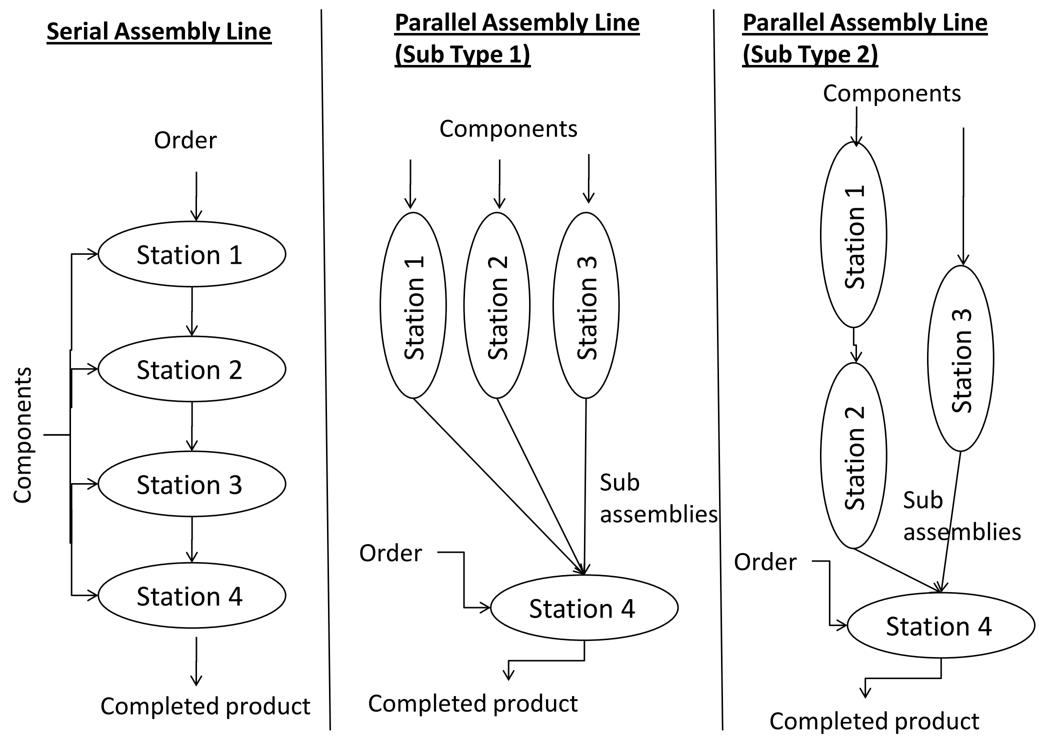


Figure 4 Assembly Line Types (Subramaniam, 1993)

2.2 Effect of Influences

One of earliest seminal articles in the literature that discusses the uncertain environment is one by Emory and Trist (1965) which analyzes the organization in each of four operating environments. The first environment called placid and randomized environment where the goals of the organization as well as the outside environment remains unchanged or nonexistent. Organizations of this type exist as small, single units. The second type is called as the placid and clustered environment where goals and uncertainty are not randomly distributed. In this environment, a need arises for the organization to have strategies in place. This condition forces an organization to grow in size, multiply into individual units and centralize coordination of different business units. The third environment type is the dynamic, disturbed and reactive environment. In this environment, several similar type organizations exist and compete. The study found that in order to attain stability, the organizations tend to be decentralized allowing the individual sub units to employ strategies and tactics to handle the competitors. The last type of is a dynamic environment where the dynamic properties arise from the behavior of the identifiable components but also from all the other characters existing in the system such as multiple suppliers, government agencies, weather etc. This type of dynamic environment is caused by complex interactions of the different characters. Emory and Trist also mention that in this dynamic environment, importance must be given to control mechanisms that are necessary to control performance measures and provide response to the factors changing / acting unpredictable. The dynamic environment forms the basis for the origin of the external influences in this study. However, several studies exist that expand the turbulent environment defined by Emory and Trist to include the disturbances that exist inside and outside the organization. For example Jina, Bhattacharya and Walton (1995) classified turbulence into five categories: volume turbulence, variety or mix turbulence, schedule turbulence, process turbulence, and design turbulence. It could be argued that volume turbulence and variety mix turbulence are generated from the outside environment through actions of customers and competitors. Bhattacharya, Jina and Walton (1996) adapt the manufacturing system design parameters to the turbulent environment by introducing flexibility in the system.

The literature on flexible manufacturing application uses the term turbulence to mean any disturbances on a system and the literature advocate the use of manufacturing flexibility to hedge the effects of turbulence. Manufacturing flexibility is a necessity to cope with disturbances both in the external and internal environments of the organization (Garret, 1986). Buzacott & Mandelbaum, (1985) list equipment breakdowns, variable task times, queues, rejects and rework as internal turbulences affecting a system. They introduced the term machine flexibility that addresses the internal disturbances. In their study, Gupta & Somers (1992) add to the internal disturbance list of Buzacott and Mandelbaum, a list of external influences which include fluctuations in customer demand, required part variety, and competitor actions. Gupta and Somers introduce several types of flexibility that would address the disturbances, in general; they do not however provide a direct link between each disturbance, the element or character that created it and the type of flexibility to be used to address the effect. Zelenovic (1982) defines turbulence as disturbances on the system and lists them as international competition, environmental changes and technology innovations. Inside the manufacturing system, Zelenovic lists manufacturing methods, throughput time, productions cost, job humanization, participation in decision-making process as the parameters to change. The metrics used to measure are the number of product variants handled, productivity and company future. The link between the influences, application of flexibility and the use of performance metrics remains vague in this article. Thus the flexibility literature does not provide a direct link between the disturbances, the performance metrics used to measure the effect of disturbance and the type of flexibility used to best mitigate or exploit the effect of each type of disturbance.

Though these categories are the effects of turbulences on the system, it does not provide effective links between the external elements, the influences caused by them and the possible effects on the performance of the system. Also a number of terms such as turbulence, disturbances, address the effects of uncertainty created by the characters or elements outside the system. For the purpose of this research, the term external influence is introduced which is defined as the effect created by external elements outside the boundary of the system.

Sheffi and Rice (2005) analyze the different types of disruptions in a supply chain and try to rate the disruption probability and the consequences for each disruption for a single organization. Figure 5 provides a vulnerability map of the supply chain for a single organization. Through this map Sheffi and Rice attempt to classify the vulnerabilities that might impact an organization's supply chain and tries to map it to the consequence of each vulnerability. This vulnerability map varies from organization to organization. This article paved the path to structure the process of selection of external influences in the study. The vulnerabilities in the article result from a lack of effective controls on the external influences in this study. This article is used as a basis for this study in terms of defining the external influences and to link them to control action that could mitigate or exploit their potential impacts on the manufacturing system performance metrics.

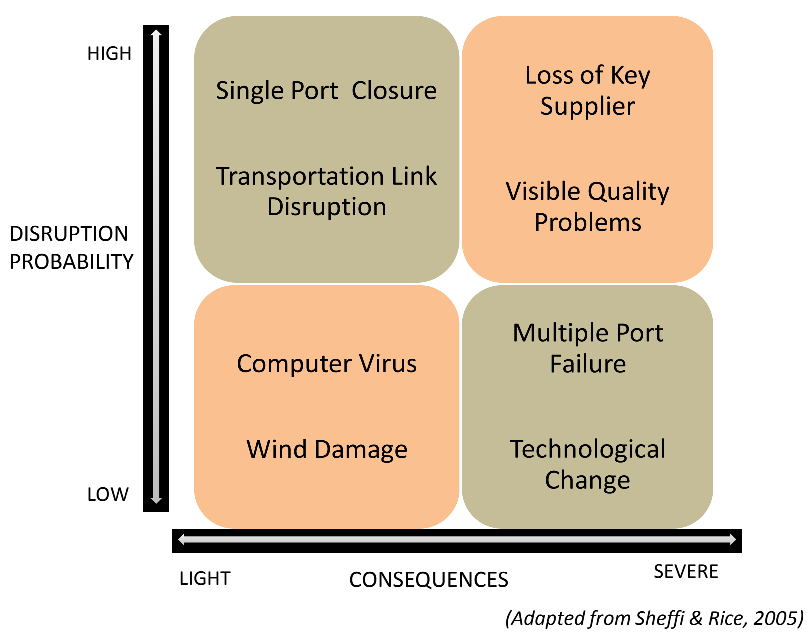


Figure 5 Supply Chain Vulnerability Map for a Single Company

2.3 Manufacturing Philosophies and Evolution of Control Actions

During the last few decades, a number of manufacturing philosophies with various names have emerged with each terms / name representing different combination of similar concepts. As a result, a manager in a manufacturing environment might be confused regarding the right philosophy to use in order to improve the performance of the manufacturing system. This research study proposes the study of control actions commonly used in a number of these philosophies rather than the philosophies themselves. This literature review section provides a background on the three most popular philosophies: agile, lean and quick response manufacturing, and that each espouses control actions.

2.3.1 Lean Manufacturing

The term lean manufacturing had its origins from the Toyota production system (Ohno, 1988). Womack, Jones, and Roos (1991) coined the term lean manufacturing in their book "The Machine that Changed the World". One of the initial lean tools derived from the Toyota production system is the 5 Why's, which are used to determine the root cause of performance problems. Womack and Jones (1996) state that a manufacturing system employing the lean philosophy would strive to operate with optimum resources in order to get optimum performance. There are five basic principles behind lean thinking: 1) specify value by product, 2) identify the value stream for each product, 3) make value flow without interruptions, 4) pull value from the manufacturer, and 5) pursue perfection. Lean manufacturing is a philosophy that focuses on developing a value stream for all products that eliminates waste in waiting time, transport, inventories, and defects, and as long as the manufacturing system operates on a level production schedule.

The Toyota production system, on which the lean philosophy originated, was implemented originally in a Toyota manufacturing plant and is defined "as a system for the absolute elimination of waste" (Shingo, 1989). This manufacturing system, according to Shingo

(1989), achieves optimum performance through three foci: 80 percent from waste elimination, 15 percent from Just In Time production system and 5 percent from use of a Kanban system.

Cellular manufacturing is a lean manufacturing system concept, which physically or virtually groups dissimilar machines that produce similar parts using identical or similarly related process flows (Hyer and Wemmerlov, 2002). Cellular manufacturing uses group technology to configure part families (Hyer and Wemmerlov, 2002). Part families configured are used to group machines into cells. A Kanban system is a production control mechanism that uses some version of a card as an information carrier and / or authorization to act. Cellular manufacturing systems perform better with Kanban systems as their production control mechanism because of the dedicated cells for each product line.

Hyer and Wemmerlov (2002) describe different variants of the cellular approach such as Mini cells, Phantom cells, Virtual cells, and Focused factories. Mini cells are cells where equipment and operators complete a small sequence of operations within a cell layout. A Phantom cell is a temporary regrouping of machines physically into a cell to satisfy an immediate demand. A Virtual cell is an arrangement where the locations of the equipment do not change, but the product routings change. Focused factories address the problem where the products, markets, customers, and suppliers lead to complexity in a single manufacturing facility. Focused factories are split manufacturing systems, based on the customer supplied to, manufacturing process, product volume, or markets.

Another lean tool is Value stream mapping. Using value stream mapping (Hines & Rich, 1997), the seven types of waste in a production system (waste due to over production, over processing, material handling, waiting, inappropriate processing, unnecessary inventory and defects) can be identified and decreased. Hines and Rich list seven variations of value stream mapping which are process activity mapping, supply chain response matrix, quality filter matrix, demand amplification mapping, decision point analysis, physical structure mapping and production variety funnel. The process activity mapping studies the flow of processes and rearranges the flow sequence and transportation logistics between processes in order to increase the efficiency and reduce waste. This helps to identify locations to reduce the lot sizes, reduce manufacturing lead time, reduce setup times, increase level production and decrease floor utilization. Machine utilization and worker utilization metrics vary because sometimes resources are underutilized in order to reduce manufacturing lead time. A supply chain response matrix uses a time based process mapping where the critical lead time constraints are shown. This mapping helps to reduce the supplier lead time and improve responsiveness to customer expectations in terms of lead time.

The production variety funnel provides a mapping of the manufacturing system in terms of capability in products, processes, and raw materials. It helps a firm to research the similarities between their products to that of other similar industry products. This mapping tool could be used to increase market share, vary the size and number of part families, and increase responsiveness to changing customer expectations in terms of customized products. The quality filter mapping tool is used to identify the potential areas in the process that affect the quality of the product. It is used to reduce the waste due to defects. Demand amplification mapping is based on the principle of industrial dynamics which states that as demand is transferred through a series of stock keeping points the demand variation amplifies at each point. This helps to reduce the demand variation at all the inventory areas in a manufacturing system or in a supply chain. Decision point analysis is used to identify the point that separates a demand forecasted push system from an actual demand driven pull system in a manufacturing system or a supply chain. The last type of value stream mapping is the physical structure mapping that maps the overall manufacturing system from an organization perspective.

Elimination of process related wastes in Lean manufacturing could also be achieved with a concept named Poka Yoke. Poka yoke (Shingo, 1997) is a Japanese term that roughly translates to mistake proofing. Poka yoke techniques are used in a production system to eliminate mistakes that produce defects and then improve production quality. Poka yoke methods are used to prevent the possibility of variation in the process by. Operators in manual processes cannot be expected to be absolutely consistent throughout a large number of repetitions. In order to avoid operator errors, Poke yoke methods are applied. Although Poka yoke techniques (Monden, 1983) originated from reducing waste due to process variations / errors, its application could be extended to eliminate other types of wastes such as wastes due to over production, over processing, material handling, waiting, inappropriate processing, and unnecessary inventory. Supplier lead time could be improved if fool proof methods of on time order and delivery methods are implemented in the supply chain. Responsiveness to customer expectations in terms of time could be improved with a decrease in manufacturing lead time. Setup time in a process may be decreased by implementing error proof methods such as fixtures and jigs in a production process.

2.3.2 Agile Manufacturing

The term agile manufacturing stems from the Agile Manufacturing Enterprise Forum at Lehigh University in a 1991 study initiated by the Iacocca Institute. One of the early definitions of agile manufacturing is the ability of an enterprise to survive in a competitive environment characterized by continuous and unanticipated change by responding quickly. Control action implementation enables response to rapidly changing markets that are driven by the customers changing valuation of products and services (Lengyel, 1994). Dove (1995) defines agility as change proficiency and introduces four change proficiency metrics: time, cost, robustness, and scope. Goldman, Nagel and Preiss, (1995) outline the definition of agility as a competitive strategy through four principal aims: to enrich customers, improve co-operation to improve competitiveness, 'master' change and uncertainty through organizational structure, and realizing the benefit of the people. An organization following an agile manufacturing philosophy displays the ability to reconfigure itself in a dynamic, competitive environment. A dynamic environment with respect to agile manufacturing is defined as one with continuous and unanticipated changes occurring both within and outside the organization (Kasarda and Rondinelli, 1998). Van Assen, Hans and Van de Velde (2000) describe an agile organization structure as a decentralized, logistics and business oriented approach. A decentralized structure allows different segments of the organization to be able to react faster to the changing environment. Dove, (1995) describes an ideal agile system as one that implements a quick and economical change without sacrificing the quality and functionality of the product. There is a host of literature that discusses the concept of agility but a very small number of literatures describe how to achieve agility in an organization.

An agile system is more forecast driven rather than demand-driven, this allows them to read and respond to real market demand (Christopher and Towill, 2000). Using forecasts, an agile organization is able to stock up the inventory to a level where the excess inventory helps to mitigate the variation in demands. Sneakerization is an agile control strategy used to fragment the products into a variety of specialized products (Goldman, Nagel and Preiss, 1995). Cross training is another tool/method that helps manufacturing facility to be agile.

Agile manufacturing philosophy extends beyond the boundaries of a single organization. Goldman, Nagel and Preiss, (1995) introduce a strategy called “Agile virtual enterprise”. They define the agile competitive environment as a dynamically changing environment that reacts to opportunity. An agile virtual enterprise model reflects and facilitates three basic ideas. The model organization expresses the need of agile competitors to assemble new product resources rapidly. The model expresses the need of agile competitors to create and assemble new products with new (productive) resources more frequently and concurrently. The complexity of the products might force the agile competitors to have access to world-class competencies such as research, design, marketing, distribution, and service. The criteria to be an agile virtual enterprise eliminate organizations that have stable demand, limited variety of products and dedicated resources. Supporting the agile virtual enterprise, Wu, Mao and Qian (1999) define an agile virtual enterprise as collection of product oriented and networked manufacturing systems, that conglomerate with each other based on market opportunity.

A new philosophy called "leagile" originated where the both agile and lean exists together in a mutually exclusive subgroups in a supply chain (Mason-Jones, Naylor, and Towill, 2000) (Aitken, Christopher, and Towill, 2002) (McCullen and Towill, 2001) (Takahashi and Nakamura, 2000) or in a single manufacturing system (Prince, and Kay, 2003). In all these leagile systems, there exists a decoupling point between the lean and agile sub systems. In theory the decoupling point acts as an inventory buffer between the lean and agile subs systems. For example in a supply chain the agile manufacturing characteristics exists in the downstream starting from the customer. With the customer demanding variations in product mix, volume and competitive pricing, agile characteristics of the downstream supply chain helps to mitigate the uncertainties. On the other hand, the lean characteristics existing upstream in the manufacturing as well as the suppliers help the supply chain to operate efficiently. Krishnamurthy and Yauch (2007) proposed a theoretical framework of a leagile corporate structure based on a case study where several lean production units exists under an agile corporate umbrella. The decoupling point exists between the lean production units and the agile corporation.

2.3.3 Quick Response Manufacturing

Quick Response Manufacturing (Suri, 1998) is based on the time based competition strategies used by many Japanese companies. Quick Response Manufacturing or QRM places emphasis on lead time reduction by every aspect of the organization. In his book "Quick Response Manufacturing", Suri describes QRM as a concept that encompasses, flow manufacturing, cellular manufacturing, and other concepts. The major benefit of applying quick response to a manufacturing system is shorter (lead) time to procure raw material, produce and deliver products. QRM embraces lead time reduction concepts that can be applied to any manufacturing facility. There might be some cases where the cellular approach might not be a fit, but the rest of the QRM strategies and tools could be used on a case by case basis depending on industry type, volume, variety and product complexity. One of the suggestions by Suri is to have the utilization levels of the cells/stations not be greater than 80%. This additional capacity would help the system to handle unexpected spikes in demand without a proliferation of WIP.

Time slicing is a concept discussed under QRM. Time slicing (Suri, 1998) is a method of dedicating a shared resource based on a pre-determined schedule. Time slicing is used in cases where the capacity of a resource equipment or manpower is divided and distributed to different product lines in the manufacturing system. Using time slicing, the total production time available at the shared resource is divided based on the production requirements of two or more products / processes. One of the benefits of time slicing is a reduction in manufacturing lead time. The other benefits are decrease in waste due to over processing and work in process in the system.

2.3.4 Evolution of Control Actions

A control action in this study is defined as an operational change that logically has the potential to mitigate the negative effects or exploit the positive effects of the external influences on the performance of a manufacturing system. The term closely associated with control actions in the literature is manufacturing strategy. Manufacturing control strategy is defined as an effective use of actions or a set of actions used to enhance the competitiveness and performance of an organization. Wheelwright and Hayes (1985) define a manufacturing strategy as a reflection of goals and strategies of an organization and enable a manufacturing system to contribute to the long-term competitiveness and performance of the organization. One of the early articles on manufacturing strategy is by Skinner (1969) who defines the selection and implementation processes for manufacturing strategies. This process is a top down approach that involves establishment of the manufacturing tasks that contain goals and means, alignment of the manufacturing policies and infrastructure to the tasks and trigger the involvement of the key stakeholders in the organization to reconsider / review strategic decisions. Miller (1981) and Wheelwright and Hayes (1985) have concurred on the need for process controls to modify manufacturing operations to improving the performance of an organization. Swamidass (1988) suggested two types of control strategies: offensive and defensive strategies. A manager uses an offensive strategy to be proactive and continuously change the manufacturing system to provide better performance metrics even if the operating environment remains the same. A defensive strategy is used to react to changes in the environment. The offensive strategies relate to the continuous process improvement tools and methods in the different manufacturing philosophies, which would be applied with or without the external influences acting on the system. A defensive strategy would monitor one or more metrics and have one or more control actions (equations / algorithms) to mitigate or exploit the effects of changes in external influences.

Though a lot of literature discusses the use of manufacturing strategies in an organization, they seem to fail to address the selection of the strategies suggested in the ever-growing list of manufacturing philosophies and their relative effectiveness / impact on a system under the effects of external influence. In addition, the term "strategy" covers a wide cluster of functional concepts including financial strategy, marketing strategy, and others (Swamidass & Newell, 1987). In order to avoid the confusion in terminology and to provide a term to include the effects of external influences on an organization, the control action term is utilized in this study.

Wheelwright (1984) introduces a concept of categorizing the different strategies under eight operating parameter set point categories: capacity, facilities, level of technology, degree of vertical integration, size of work force, quality, number / type of production planning /materials controls and type of organization. Based on this categorization process, this study redefines the dimensions into seven categories: supplier control, inventory control, capacity control, manufacturing process control, defect control, and maintenance. This categorization is used in this study to list the control actions selected from the manufacturing philosophies. Wheelwright and Hayes (1984) define strategies into three different categories based on application time horizon: short, medium and long term strategies. Short term strategies involve using existing resources more efficiently. Medium term strategies involve use of new or expanded sets of resources beyond the existing ones such as additional labor, different labor skills, additional material safety stock etc. Long term strategies involve development of new product and processes which takes a considerable amount of time. Control actions defined in this research fall in both the medium as well as long term strategies because a short term fix will not mitigate the negative effects or exploit the positive effects of an influence permanently.

2.4 Simulation Experiments

This section discusses the use of simulation along with experimental design techniques. Shang and Tadikamalla (1993) conducted a research study that combined the experimental design approach along with simulation address the impact of various operational decisions and system parameters set points on the yield of an automated printed circuit board manufacturing system. They developed a discrete simulation model, which assisted in determining an empirical relationship between the hourly yield rate and each one of the system variables such as lot size, balance of the line, mean-time-between-failures, mean-time-between-repairs, paste life restriction (process variable) and input buffer capacity. A fractional factorial design with three levels was used to limit the number of simulation runs and to screen for significant factors. Response surface methodology was used to determine what levels of input factors will maximize the yield for the specific problem. The authors conclude that the results from the experiment demonstrate the effectiveness of studying manufacturing problems by integrating simulation and statistical methods.

Kenne and Gharbi (1999) examined a simple manufacturing system with a single machine and single product using a discrete simulation model and combine the model with a three-factor, three-level experimental design to provide an estimation of cost function. The factors used are inventory policies, preventive maintenance (machine state levels) and production control policies. Abdul-Kader and Gharbi (2002) proposed a simulation-based experimental design methodology to improve the performance of a multi-product production line. The performance measures used to evaluate system performance were percentage of time work stations spent in operation, setup, downtime, blocking and starving. The buffer between each stage is considered a factor, and the authors used a four- factor three-level experimental design. This methodology provided results for the best strategy of buffer allocation between the manufacturing stages.

There are several research articles focused on the use of individual manufacturing strategies to study their effect on manufacturing systems. Akturk and Erhun (1999) conducted research on the design and operation of kanban systems. The authors developed an experimental design to determine the withdrawal cycle length of the kanbans, kanban sizes, and kanban sequences at each stage of a multistage manufacturing system. They used an analytical simulation model of a multi-item, multi-stage, multiple-period kanban manufacturing system. The factors used in the two-level design of experiments were number of part families, number of parts in each family, demand average, demand variability, imbalance, average processing time, and ratio of backorder to inventory holding costs.

Beamon and Chen (2001) applied simulation tools and experimental design methods to study a supply chain. They used a co-joined supply chain model (convergent and divergent supply chains joined) to examine the effects of various operational factors on five performance measures. The experimental design is a five-factor, three-level design with the following performance measures: inventory system stock-out risk, supplier lead time deviation, demand distribution deviation, transportation time deviation, and processing time deviation. Statistical results from the research indicate that the inventory system stock-out risk, probability distribution of demand and transportation time are more important in determining the effectiveness of a supply chain.

There were several other research studies that used simulation and experimental design methodologies to study manufacturing settings in areas related to the proposed research. Dabbas et al. (2003) studied the effect of dispatching rules in a hybrid simulation model (discrete event and analytical) to identify the combination of dispatching rules to be used in a semiconductor facility. The performance measures used in the analysis were time delivery, variance of lateness, mean cycle time, and variance of cycle time. Spedding et al. (1998) described a three station serial keyboard assembly cell that is optimized using a combination of discrete event simulation and experimental design methods. The four factors used in the study are the number of pallets and buffer sizes between the three stations (three factors), and the performance measure used is the throughput rate.

Table 1 Analysis of Simulation Experiments Literature With Respect to Control Actions and Influences

Literature Authors	**Study Goal**	**Methodology**	**Control Actions, External & Internal Influences**	**Dependant variables**
Dabbas, Fowler, Rollier, McCarvilles (2003)	Evaluation of global dispatching rules	Use design of experiments with discrete event simulation	*Control action-* Two dispatching rules Shortest processing time & Critical Ratio *External/Internal influences -* None	On time delivery, Variability of lateness, Mean cycle time, & Variance of cycle time
Shang & Tadikamalla (1993)	Evaluation of the impact of system variables on yield rate	Use of design of experiments with discrete event simulation	*Control action-* Change in system variables such as Lot size, Degree of production line balance, & Capacity of input buffer. *Internal Influences -* Mean time between failures, Mean time to repair failed machine, & Flow time restriction	Yield rate
Kenne & Gharbi (1999)	Evaluate the relationship between machine age, stock and incurred cost	Use of design of experiments with discrete event simulation model	*Control action-* Preventive maintenance schedule, Machine age at which parts are stocked & Stock size *External/Internal Influences -*none	Incurred costs
Abdul-Kader & Gharbi (2002)	Identify the best strategy for buffer allocation	Use of design of experiments with discrete event simulation model	*Control action-* Buffer size between stations *External/Internal Influences –*Influences built into the system product mix, & Setup time between each product mix (NOT VARIABLE)	Cycle time

Literature Authors	Study Goal	Methodology	Control Actions, External & Internal Influences	Dependant variables
Akturk & Erhun (1999)	Design and operation of Kanban systems	Use of experimental design using an analytical model	*Control action-* Number of part families, & Part number in each family *External Influences –* Demand average, & Demand variability. *Internal Influences –* Imbalance, Average processing time, & Ratio of back order to inventory holding costs.	Withdrawal cycle length of the kanbans, kanban sizes, and kanban sequences
Beamon & Chen (2001)	Study the performance behavior of conjoined supply chain	Use of experimental design using an network model	*Control action-* None *External Influences –* Supplier lead time deviation, Demand distribution deviation, & Transportation time deviation. *Internal Influences –* Inventory system Stock-out risk, & Processing time deviation	Resource measurement, Output measurement & Flexibility measurement
Spedding, De Souza, Lee & Lee (1998)	Optimizing an assembly cell configuration	Use of design of experiments with discrete event simulation model	*Control action-* Buffer spaces between stations & Number of pallets along the conveyor *External/Internal Influences* -none	Throughput of the cell.

Table 1 compiles the literature that has used experimental design and simulation to analyze the manufacturing system design parameters and variables, including influences and control actions. A column titled control actions, external and internal influences is added and the independent variables used to manipulate the system in the literature are classified under the three categories. This study provides a first attempt to classify the independent variables under the above-mentioned categories across the literature. The most common external influences are supplier related, product variety related and demand related. The product variety related influences can be related to the customer element. The demand related could be related to the customer, competitor or both the elements acting together.

2.5 Manufacturing Performance Metrics

There are many metrics advanced by the literature to evaluating the performance of manufacturing systems. These metrics depend on a number of factors such as the type of system used, the boundary of the system under study (supply chain systems vs. stand-alone systems), the strategies used on the system, and the type of system (real world vs. simulation) used in the study. As listed in Table 1 the most common performance metrics used are on time delivery, variability of lateness, mean cycle time, variance of cycle time, yield rate, incurred costs and throughput rate. One literature discusses measures related to application of the kanban control action (Akturk & Erhun, 1999). In order to identify the right performance metrics that would help in analyzing the external influences as well as the effect of control actions in mitigating them, this literature review section is expanded beyond the metrics discussed in the simulation literature.

The main article discussed in this literature review is a survey and classification of performance measures for the manufacturing system by Gregory White (1996). This article draws a comprehensive list of 125 performance measures from a wide variety of literature sources and develops taxonomy for categorizing the measures. White classified the performance metrics under five generic categories: quality, cost, flexibility, delivery dependability and speed. White further classifies the list of measures based on data type (subjective or objective), data source (internal or external), reference (benchmark or self-referenced), and process orientation (input or outcome). The author compiled the list from a host of literature that has appeared in cost accounting to engineering trade journals with little input from operations management journals. To compensate for the absence of operations management journals, metrics from simulation literature (Law and Kelton, 2000) were reviewed, and two additional metrics were added to this list: utilization and throughput rate. This complete list of performance metrics is shown in a table in Appendix A of this document. The table also facilitated the selection process of metrics apt for this study described later in the research methods section.

2.6 Summary of the Literature

1. The literature calls for integration of different processes in a manufacturing organization across the supply chain. The boundary for a manufacturing system in this research is defined by including all the direct processes and resources related to manufacturing a product. The direct processes include inventory control mechanisms, work in process buffers, resources (equipment and people) and manufacturing processes such as forging, stamping, assembling etc.
2. A disruption of normal operations in a manufacturing system is given several different terms by the literature such as turbulence, dynamic environment, uncertainty, and disturbances. The term "turbulence" is sometimes defined as inclusion of both internal as well as external disruptions to the system. While some of the literature defines turbulence as external disruptions to the system. In order to avoid confusion, this study termed the disruptions caused by external elements as external influences.
3. In each manufacturing philosophy, there are two types of tools and methods. The first type is the problem identification tools. An example for such tool is the value stream mapping used in lean manufacturing philosophies. With the identification of the problem, the tools that provide solutions are applied. In this study the control action is defined as a solution tool that would help in mitigating the effect of external influences
4. Manufacturing strategies literature use one or more tools from the philosophies and apply them to the manufacturing system. Based on literature, the strategies position themselves between the tools or methods and the higher level manufacturing philosophy. There are several levels of strategy in between the philosophy and the tools and these levels vary for each philosophy. Also one or more tools are being used by the different philosophies making it a many to many relationship.

5. Based on the different classifications proposed in the literature a control action typically falls under long term or medium term defensive type strategy where it could be applied to mitigate or exploit the extreme effects of the influences.
6. Research in the area of mitigation external influences caused by external elements using control action is nonexistent. A vast amount of literature discusses the effect of disturbances both internal as well as external. A few authors (Literature in Table 1) discuss the combinatorial action of these influences. The literature does not relate the influences to the external elements that caused it, nor does it include a list of control actions that could be applied.
7. There are approximately 125 different types of performance metrics. Selection of the right performance metric is confounding because some of the metrics could be used as dependent or independent variables and the metrics are correlated to each other empirically or mathematically.

CHAPTER III

RESEARCH APPROACH

3.1 Introduction

This research study seeks to understand the relationships between the different external influences and the available control actions based on the outcome of a series of experiments. The research methodology employed in this study selects and models a case study organization using a discrete event simulation. The study selects and then investigates, using experimental design, the effect of external influences and control actions on the performance metrics of the case study system. After obtaining preliminary results, an experimental design was set with the levels for each factor defined and then simulation experiments were conducted and analyzed. The following research questions were addressed by analyzing the experimental results for the case study and generalizing the results.

Research Question 1

- For each environmental influence, when acting alone on a manufacturing system, which performance measures are influenced the most and to what degree?

Research Question 2

- For each control action applied to mitigate the negative impact or exploit the positive impact of individual environmental influences acting alone on a manufacturing system, which performance measures are influenced the most and to what degree? Is it possible to relate the actions to the positive response rate of performance measures?

Research Question 3

- For a group of control actions applied to mitigate the negative impact or exploit the positive impact of individual environmental influences acting alone on a manufacturing system, which performance measures are influenced the most and to what degree? Is it possible to relate the actions to the positive response rate of performance measures?

3.2 Case Study Approach

In order to study the effects of external influences as well as the control actions on the case study organization, a discrete event simulation model was created. In this type of study, the effect of a particular influence with or without one or more control actions is simulated; the results are analyzed and related to the research questions. Simulation is used instead of a study of the effects of the influences on an actual manufacturing system because of simulation's ability to control and isolate the parameters, its lower cost and its ability to obtain the estimated results faster than the real world system. The manufacturing system modeled is one that produces a wireless electronic data transfer system using a four station serial assembly line. The products are sold in the industrial wireless communication market and the organization manufacturing the product has a share of the North American market of around 8%. For confidentiality reasons, the name of the organization is withheld. At the time of data collection, the products manufactured by the case study organization were newly introduced into the market and had a sales history of less than 18 months.

3.3 Case Study Organization Data

Relevant data was collected during the author's employment with the organization from May 2003 to May 2005. The manufacturing line was set up, and the production was started in December 2003. The manufacturing setup was an unbalanced manual assembly line. The data from the actual manufacturing system is used to define the base model for simulation. The manufacturing data collected for creating the simulation model are interarrival time of orders, size of orders, cycle times for processing the orders at each station and ordering intervals for each component at each station. The sales volume at the time of the data collection created resource utilization levels of approximately 40%. Since the line imbalance and low utilization would not be a typical situation in industry, the processing times in the assembly line were modified to balance the line by redistributing the tasks among the stations. The demand was increased based on the expected sales forecast for the next 6 months to increase the utilization levels for the workstations to the 60% to 80% range. With the utilization levels around and above 70%, the wait time increases exponentially (Suri, 1998) and increases the total lead time of the product. The system is more sensitive to the effects of external influences beyond this utilization level range.

3.3.1 Order Data

The order interarrival time data was collected for eighteen months and was fit to a distribution using ARENA Input analyzer. The results are attached in Appendix B. The highest ranked distribution based on the least square error is the triangular distribution followed by the normal distribution. The results for the p- value from the Chi-Square and the Kolmogorov-Smirnov tests (Kelton, Sadowski, & Sturrock, 2003) are greater than 0.15 which indicates that the triangular distribution for the order interarrival time with a minimum value of 0.20 hour, most likely value of 0.40 hour and a maximum of 0.53 hour is a good representation of the data. These numbers were the minimum, maximum and mode values of the 18 months of data available. The average interarrival time between orders is 0.37 hour. The size of each order is one unit, and the stations process each order unit separately.

3.3.2 Process Data

Following the same steps as the order interarrival time data fit using ARENA Input Analyzer, the highest ranking distributions that fit the data for the four station processing times is the triangular distribution. The Chi-Square and the Kolmogorov-Smirnov tests (Kelton, Sadowski, & Sturrock, 2003) were done for triangular distribution data fit for the processing all stations results and the p- value from are greater than 0.15 which means that triangular distribution is a good representation of the data. Table 2 shows the triangular distribution parameters obtained through the data fit for the four stations, the average and variance of the processing times in each station.

Table 2 Processing Time Data for Each Station

Station Name	**Work Time in hours**			**Discrete Model Parameter (Processing Time Distribution)**	**Average Processing Time**	**Processing Time Variance**
	Min	**Mode**	**Max**			
Enclosure Prep station	0.120	0.130	0.140	Triangular(0.12, 0.13, 0.14)	0.130	0.00016
Assembly station	0.160	0.284	0.330	Triangular(0.16, 0.284,0.33)	0.258	0.00128
Testing station	0.150	0.293	0.370	Triangular(0.15, 0.293,0.37)	0.271	0.00207
Labeling/packing station	0.190	0.240	0.270	Triangular(0.19, 0.24, 0.27)	0.233	0.00027

3.3.3 Components Data

Each station uses one person and hence one set of tools is necessary for the manufacturing of the product. The critical components used at each station are shown in Table 3 along with approximate vendor cost/ unit. The table also provides a description for each of the critical components. A critical component is defined as a component that has custom specifications and is available initially through one vendor. A non-critical component is defined as a component that has the following characteristics: standard, stocked at more than one supplier, and does not have a supply interarrival time. One critical component is used per product at each assembly stage. All the critical components have a maximum supplier delivery lot size of 240 units per delivery.

Table 3 Supplier and Critical Components Information

Supplier	Material Cost/unit ($)	Station Used	Critical Component Description
Enclosure Supplier	$16	Enclosure prep station	Enclosure certified for Commercial use in Europe and North America
Radio Supplier	$69	Assembly station	928 MhZ Radio certified for use in Europe and North America
Battery Supplier	$18	Assembly station	D-cell type Lithium ion Battery with circuitry to prevent quick discharge
Printed Circuit (PC) Board Supplier	$ 76	Assembly station	Printed Circuit board
Wiring Harness Supplier	$12	Assembly station	Wiring Harness to connect components
Label Supplier	$1	Labeling/ packing station	Weather resistant certification labels
Bracket Supplier	$20	Labeling/ packing station	Stainless steel brackets

3.3.4 Supplier Data

The organization is a new venture with new products. In addition, while the similarity of the functionality of organization's products to that of the competitor is high. The critical components used by the organization are different from that of the competitors. However, these are products in other industry segments, which use all of the critical components except the Printed Circuit (PC) board in their products. A supplier licensed to use a patented design owned by the case study organization manufactures the PC board. The issues faced by the organization in securing a strong supplier base include cash flow issues due to startup, new venture bankruptcy risk, and lower sales volume than required by the supplier to justify dedicating capacity to manufacture the components. In the actual organization, after negotiations, the suppliers for the seven critical components agreed to supply a lot size less than or equal to 240 units of components at an average delivery time of about 2 weeks. A supplier takes about two weeks to have a lot size of the critical component manufactured and delivered to the facility. Based on this information, the minimum, maximum, and most likely supply interarrival times are selected as 80 hours, 90 hours, and 85 hours respectively. The triangular distribution is selected for modeling the supplier interarrival times due to limited data. The organization can procure a maximum lot size of 240 units from the suppliers with an average lead time of 85 hours. However, if the demand drops for the organization, the organization can procure lot sizes smaller than 240 units.

In the early stages of the startup, the organization had difficulty trying to establish a line of credit with its suppliers. The supplier risks associated with taking on a startup organization as a customer and diverting capacity from its existing customer base to the new startup organization, carrying inventory for an organization with no prior purchases and supplying smaller quantities at a potentially higher cost. In order to hedge themselves against these risks, the suppliers entered into an agreement that dictated a supply interval of two weeks, a lot size no greater than 240 units and an annual usage quantity of around 5760 units. Any change in the supply quantity or supply time beyond the agreement would necessitate an increase in cost to the case study organization. A sudden demand increase in orders for the organization would have to be met initially with the remaining inventory and the organization would have to find an additional supplier or renegotiate with the existing supplier for an increase in supply size. Due to warehouse space and resource constraints, the organization has decided to fix the inventory storage size as 240 units. At each supply delivery interval, the organization will check the existing inventory and top the storage bin with components up to 240 units. Due to this limiting the storage bin size, there is a possibility for some inventory to be left at the supplier and the organization will eventually buy back this inventory. This condition is forced by the supplier because of the custom nature of components, which cannot be sold to any customers other than the organization.

3.4 Selection of External Influences

External influences cause random disturbances that occur over a period and originate outside the manufacturing system. The external elements are located outside the boundaries of a manufacturing system. Some examples of external elements are customers, competitors, suppliers, and federal agencies.

Table 4 Examples of External Elements and Influences

External Elements	**Possible External Influences**	**Expected Impact to Manufacturing System**
Suppliers	Change in design for supplied material	Increases raw material lead time, possible shut down, inventory level change in WIP, finished goods.
	Increase in supplier price for raw material	Increases product cost
	Increase in raw material lead time	Increases lead time
	No supply due to supplier going out of business	Shut down, increases lead time
	Decrease in supply rate	Increases lead time
Competitors	Competitor going out of business	Increases demand, Increases utilization
	Decrease in competitor delivery lead time	Motivate reduction in lead time/ reduced sales
	Decrease in competitor product pricing	Motivates reduction in cost
Government agencies	Change in import policies such as tariffs, subsidies	Changes product cost
	Increase in regulations leading to design change	Increases lead time
Weather	Impacts from weather directly on system	No throughput
	Impacts due to weather on customer base	Increases demand, increases utilization
	Impacts due to weather impacts on supplier base	Increases cost, increases lead time

External Elements	Possible External Influences	Expected Impact to Manufacturing System
Economy	Strong economy	Increases resource turnover, increases utilization, Increases demand
	Slowdown in economy	Reduces demand, reduces utilization
	Higher interest rates (for leveraged companies)	Forces restriction on capacity increase through expansion
Technology growth	Increased automation in the system	Possible reduction in production lead time
	Product design changes	Increases lead time, product cost
	Product complexity	Increases lead time, product cost
Customers	Number of customers	Increases lead time, increases utilization
	Desire for more product customization	Increases lead time, product cost

Table 4 provides a list of external elements, possible influences they exert, and the possible impact of the influence effects on a manufacturing system. The table shows the seven primary external elements that affect a manufacturing system. For each of these seven external elements, some of the ways they can change and influence the performance of a manufacturing system are listed in Table 4. For example, the competitor external element can impact the system through events such as competitor going out of business, shorter/longer competitor delivery time, and lower/higher competitive product pricing. These influence effects create a change in sales volume, which could affect one or more performance metrics for the manufacturing system of interest, some of which are lead-time, throughput, and utilization. Some of the external influences could be created by one or more external elements. For example, high manufacturing costs or lack of constant demand could force a supplier to reduce or stop delivery of a component, forcing the manufacturing system to find alternative. Apart from the supplier, a design change in an assembly component for a product initiated by the customer could produce a ripple effect through the supply chain, which may result in the supplier reducing or stopping delivery. From this list of external influences, and based on the experiences of the case study organization, four external influences were selected: product customization, diminished supplies over time, supplier goes out of business and competitor goes out of business.

The organization faced the four influence effects mentioned in the table: competitor going out of business, supplier going out of business, diminished supplies over time and product customization. The organization was one of the three key players in an emerging market for wireless controls in the fluid process control industry. Due to issues with product design and high failure rates, one of the competitors exited the market leaving the remaining two key players to absorb the stranded customers. The supplier for printed circuit board was a private family owned/operated contract electronics assembly manufacturer and was bought out by one of their major customers. This created a scenario where the supply was stopped to the remaining customers and merge with the customer. The new supplier for the printed circuit board committed to the supply lot size of no greater than 240 units per delivery. However, quality issues forced this supplier to reduce delivery lot size to be less than the committed number thereby creating the diminished supplies over time influence effect.

The product customization influence occurs when the organization must supply customers with product variations. The case study organization felt that this would be one of the most important influences affecting it because of the product's end use. The products are used in a variety of flow process control environments that require customization based on geographic location and customer systems. The products use as an industrial wireless device is used to remotely collect data from various sensors attached to the flow control systems in a processing plant to control the flow by opening / closing the valves in the system. These customizations result / can require multiple instances of software changes, which influence can create several processing times different from the (single) processing time of the standard product. An increase in the number of customized products would produce a multi model process time distribution and likely increase the average as well as the variance of the processing time for products in the manufacturing system. The next influence, diminishing supplies over a period, occurs when the supplier/sub-contractor that supplies part of the assemblies or critical components is having capacity or cost related issues, or experience delays in receiving raw materials for the supplier to manufacture the components. These issues could result in a decrease in the supply lot size and/or delivery frequency for a period and although in some cases the supplier lot size may stay at a reduced level. The special case of the diminishing supplies is a supplier going out of business. In this influence, a supplier goes out of business for various reasons such as poor business practices, labor issues, general economy downturn or the amount of raw material supply is reduced over time without any notice to the supplier. It could arise due to capacity issues caused by demand from customers in other industry segments.

The last influence selected is a competitor going out of business. Like the supplier in the previous discussion, a competitor in business could also be facing marketing and product functionality issues forcing them to downsize or go bankrupt. The list of external influences from Table 4 was reduced to the table shown in Table 5 based on the actual scenarios observed by the case study organization.

Table 5 Modeled list of Influences

External Elements	External Influences	Expected Impact(s) to Manufacturing System
Suppliers	No supply due to supplier going out of business	Shut down, increases lead time
	Decrease in supply rate	Increases lead time
Competitors	Competitor going out of business	Increases demand, increases utilization
Customers	Desire for more product customization	Increases lead time, increases utilization

3.5 Derivation and Selection of Control Actions

A control action is an operational change that logically has the potential to mitigate the negative effects or exploit the positive effects of the influences exerted by the external elements on the performance of a manufacturing system. Control actions are derived from the philosophy inspired tools and methodologies that could be applied to the system under consideration. The possible tools and methodologies were distilled from the different manufacturing philosophies. An eight step methodology is created for the selection of a control action and is listed in figure 6. Step 1 is to identify a manufacturing philosophy. A manufacturing philosophy is a system operation concept, which seeks to guide decisions and affect system performance through application of various tools and methodologies. The second step in the process is to list all the tools and methodologies discussed in the philosophy.

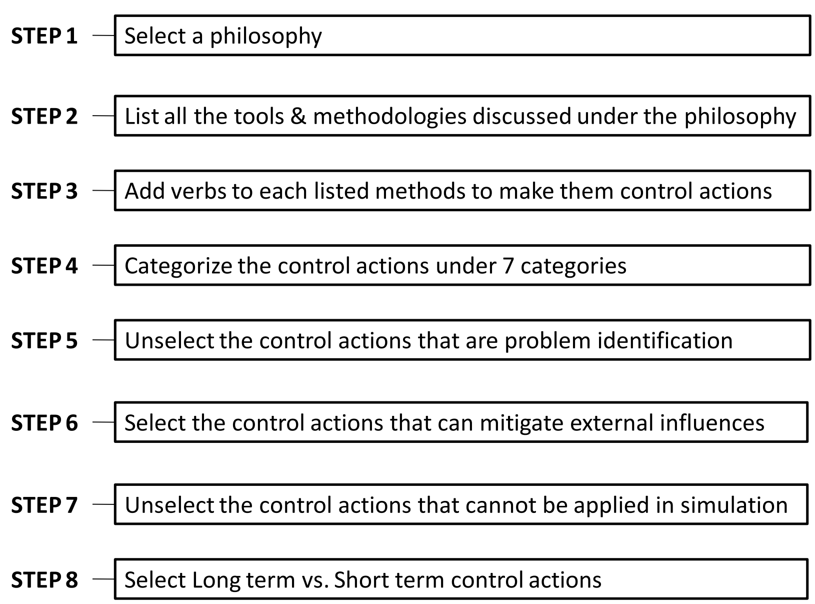


Figure 6 Steps to Derive and Select Control Actions

The third step involves adding verbs to each of the listed tools and methodologies. The most common verbs used to describe the use of a tool or a methodology are “implement”, “add”, “change” and “analyze”. The verbs describe how a tool or methodology can be used and it helps to classify the control actions under different categories discussed in the next steps. In the fourth step, these control actions are categorized under the following categories: Supplier Control, Inventory Control, Capacity Control, Manufacturing Process Control, Demand Management/Production Scheduling Control, Defect Control/Quality, and Maintenance. This categorization helps in mapping the control actions to the external influences it can be used to mitigate or exploit. The fifth step in the process flow is to unselect the tools and methods that are used to define, identify or analyze problems and categorize them under a separate category named “Problem identification”. An example of this type of tool is value stream mapping. Value stream mapping is creating a comprehensive visual process flow map that helps to identify problem areas that affect the system. These types of tools do not offer a solution but rather assist in the identifying and/or quantifying problems and are typically identified by the use of the verb “analyze.”

The sixth step is the selection of control actions that help to mitigate or exploit the effect of one or more external influences. The categories provide a general collection of control actions and help to narrow the search for appropriate control actions to mitigate or exploit the impact of changes in the corresponding external influences. One of the external influences selected for this study is the supplier going out of business scenario. The category Supplier Control provides a list of the control actions that might have a potential to mitigate/exploit the influence.

The seventh step in the selection process is the assessment of the applicability of the control actions to the research questions and the system under consideration. The manufacturing system in this study is an adaptation of a case study organization into a discrete event simulation model. Some of the control actions such as “Implement 5 S” cannot be applied to a simulation and thus is deselected for the study purposes. The eighth step in the process is to identify if the control action is either a long term or a short-term control action. A long-term control action is one where the control action can be applied until the control action effectively mitigates/exploits the effect of the external influence. A short-term control action can provide only a temporary or time limited mitigation of the influence. An example for short-term control action is adding safety stock to raw materials. When an influence like diminished supplies over a period occurs, the safety stock will help to mitigate the influences until exhausted and then is no longer able to mitigate the impact. Eventually the system will have to find a long-term control action such as adding an alternate supplier if the disturbance persists. Also several control actions have the potential to exploit the permanent effect of the temporary sales gains that result when the external influence occurs. In the case study, the additional capacity and additional supplier control actions applied together will exploit the effect of competitor going out of business. A surge in number of orders due to the competitor out of business influence effect requires additional resources and additional raw material components. This surge is a positive effect of the influence and the control actions applied will exploit this positive influence effect to improve the system performance metrics.

Table 6 provides a list of Control Actions under the seven categories along with their relevance to external influence mitigation. Under each category, the possible control actions are listed and are selected based on their ability to mitigate the selected external influence. Based on these selections, the “apply to this simulation” column will select the control actions that could be applied to the simulation. The column titled “Long-term Control Actions” provides a final list of the control actions that could be applied to the simulation model when the corresponding external influences persistently act on the system. The list of long-term control actions obtained through this methodology provides a starting point for the manager to select the appropriate control actions to mitigate/exploit the external influence effects on the manufacturing system.

An example is selected in order to explain the selection process. Sobek. et al. (1999) discuss the product design integration phase by the manufacturer with the supplier in a Toyota production system in order to achieve a reduction in time line from prototype design to manufacturing the product. This control action is termed as “Implement Integration of Design with Suppliers”. Since it is related to managing suppliers in a manufacturing system, it is categorized under the Supplier control category. The next step in the process is to logically deduce if the control action can mitigate/exploit the effects of the four external influences. All the four influences selected for this study affect the manufacturing system after the design and transfer of a product from prototype to manufacturing and hence this control action is not selected for the study.

From the table, the control action could be applied to three of the four external influences selected by the case study organization is adding an alternate supplier. Though lean manufacturing theoretically advocates a single source of supplier, it encourages the use of an additional supplier in order to have an alternate source through the “keiretsu” model (Liker and Choi, 2004). A Keiretsu model is defined as group of organizations that have interlocking shareholding and business relationships. This control action have the potential to mitigate/exploit the effects of a supplier going out of business, diminishing supplies over time, and a competitor going out of business. The second control action selected for this study is the addition of capacity buffers. These control actions has the potential to the exploit competitors going out business influence effects and mitigate the product customization influence effects. Both these control actions are long-term control actions and could be applied to the simulation model under consideration in this study. Even though the addition of safety stock control action has the potential to mitigate the effects of the supplier and competitor related influences, it is considered as a short-term control action. Short-term control actions mitigate/exploit the external influences effects temporarily and hence the study limits its scope to include only the long-term control actions.

Table 6 Table with the Results of the Control Actions Selection Process

		Selected External Influences					
Category	**Possible Control Actions**	**Supplier out of business**	**Diminishing supplies over time**	**Competitor going out of business**	**Product customization**	**Apply to study simulation**	**Long Term Control Actions**
Supplier Control	Implement integration of design with supplier						
	Add Alternate Supplier	✓	✓	✓		✓	✓
Inventory Control	Implement CONWIP system						
	Implement one/two card Kanban systems						
Capacity control	Implement POLCA						
	Add Capacity Buffers			✓	✓	✓	✓
	Implement Time Slicing						
	Implement Subcontracting			✓		✓	✓
Manufacturing Process control	Implement Single Minute Exchange of Dies						
	Implement One Piece Flow*					✓	
	Implement Production Smoothing						
	Add Safety Stock in finished goods inventory			✓		✓	
Defect control / Quality	Add Safety Stock in raw material inventory	✓	✓	✓		✓	
	Implement Poka Yoke						
Maintenance	Implement Total Productive Maintenance						
	Implement 5 S (Seiri, Seiton, Seiso, seiketsu, shitsuki)						

(* Part of the base system)

3.6 Simulation Modeling

The external influence is a discrete event in time that creates a disturbance in a manufacturing system. A discrete event simulation is the most appropriate fit for the modeling the case study organization and understand the effects of external influences and the control actions that help to mitigate/exploit them. The simulation package “Arena” is used for building the simulation model. Arena is a simulation package from Rockwell Software (www.arenasimulation.com), which is capable of modeling discrete, continuous, and hybrid systems. Its simulation engine is based on the SIMAN language. The simulation model of the case study organization without the external influences is called the base model in this study. The simulation study is conducted using a series of modules starting with the base model, then adding a logic for each of the external influences and then for each of the control actions. In order to avoid modeling and managing multiple model files in Arena, all of the logics for each of the external influences included with the base model in a single model file. Arena Process Analyzer is used to activate the logic for each external influence according to required scenario combinations in the experimental design. As far as modeling the control actions, the parameters required for each workstation in the model are discussed in the section 3.3. The base model used for the manufacturing system has been verified and is discussed in the following sections. Validation of the model against the actual system is not possible because of the changes made to balance the station processing times and select a period with high level of demand, which are different from the actual system. Recall that these changes along with the simulation of the effects of external influence allowed the study to understand the potential response characteristics of the system.

3.6.1 Baseline Scenario

The study established a baseline scenario by modeling the existing case study system without the effects of any external influences. The performance metrics of this baseline scenario were used as a base against which to compare against other scenarios where an external influence is applied with or without the control actions. This base line scenario of the manufacturing system is shown in Figure 7.

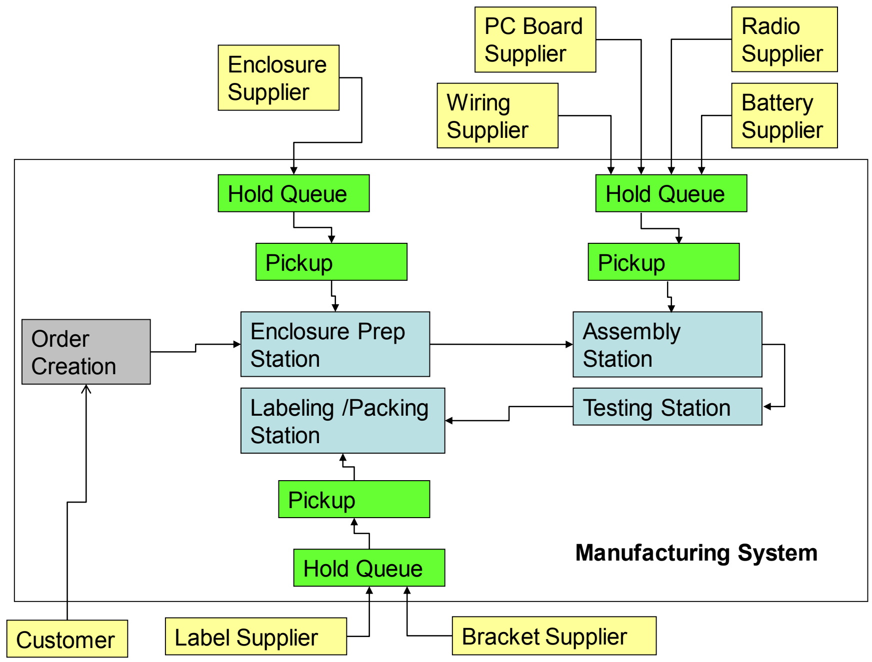


Figure 7 Process Flow of Baseline Manufacturing System

There are two parts to the model for the case study organization. One part consists of the vendors that supply critical components to the assembly line and are located outside the boundary of the system. In the baseline scenario, each critical component has a unique vendor (7 vendors). Each vendor is modeled with a create block which creates component entities and delivers them in batch sizes of up to 240 units at an interarrival time based on a triangular distribution with a minimum value of 80 hours, most likely value of 85 hours and a maximum of 90 hours as previously discussed section 3.3.4. The components are stored in seven Queue blocks named "component name_bin", where the "*component name*" is the name of the component stored in the bin. In the actual case, the system receives enough material to restock the bins back to their maximum level. For example, during the next delivery period (after an average of 85 hours), if the system contains 120 units remaining, the system will receive the remaining 120 units to refill the bins back to 240 units. To model this scenario in ARENA and also to keep count of the stock remaining at the vendor site, at the time of delivery the Decide block will check to see if the bin holds a maximum of 240 units (defined through a variable "MaxInventory") as a safety stock between each delivery period. Any additional delivery of components beyond that size is returned to the vendor by being disposed outside the system, and the number of excess components are counted and reported as part of the statistics output report in Arena. This excess inventory variable is later used to assess the investment required to implement the additional supplier control action.

The second part is the manufacturing system inside the boundary line which is an assembly line with four stations, namely the Enclosure Prep Station, Assembly Station, Testing Station and Labeling/Packing Station; a Process block is used to model each station in the Arena model. An order entity named "Production Order" of batch size one is created by an Arena create block named "Order Creation" in the model orders are created at an interarrival time drawn from a triangular distribution with a minimum value of 0.2 hour, most likely value of 0.4 hour and a maximum of 0.53 hour. The created order is assigned processing times based on the type of order. The logic for custom order types will be discussed in the next section. Since it is the base scenario, all orders are assigned the base processing times discussed earlier in Table 3-1. The customer order is transferred to a waiting queue (Hold Block in Arena) before the enclosure preparation station. Before each processing station, there is a Hold and Pickup block. The Hold block is used to delay the production order entity until all the components that are used to complete the assembly operation at that particular station are available. The order will be held in the wait queue of the hold block until there is at least one component of each of the required critical components in the bins that supply to the station. The Pickup block will allow the order to pick up components based on the bill of materials shown in Table 3-2 in section 3.3.3. The Hold block before the prep process station is named "PrepStation_hold" in the model. Upon receiving the order at the PrepStation_hold block, the availability of components in the corresponding bins is checked. In this station, only one component (enclosure) is being used. With the availability of at least one enclosure in the component bin, a Pick block named "Pickup_Enclosure" will pick one enclosure and transfer it with the order to the enclosure prep station queue to be processed. If an enclosure is not present in the enclosure bin, the order waits in a Hold block queue until the enclosure vendor sends at least one enclosure to the bin.

After completion of the process in the prep process station, the order is grouped and along with the enclosure entity is transferred to the Hold block named "AssemblyStation_hold" before the assembly station. ARENA uses the term "grouping of entities" to combine entities such as components into a single entity. With the grouped order waiting in AssemblyStation_hold queue, availability of the other components (radio, wiring harness, printed circuit board, and battery) in the respective bins is checked before the transfer of the grouped components to the Assembly Station begins. If there is a shortage in one or more of the components, the grouped order entity will be held at the AssemblyStation_hold queue until the corresponding vendor sends the needed component and at least one of the components is in each of the hold bins, enabling the order to be released from queue. Once all the components are available, the grouped order entity passes through the Pickup block for each corresponding component, decreasing the bin quantity and the order is transferred to the assembly station queue to be processed.

The Testing Station is the third station in the serial assembly line. Product testing occurs at this station and all the grouped order entities will be transferred to the Testing station wait queue instead of waiting in a hold block queue; a hold block is not necessary because no components are added at the testing station. Rework of the assembled components is not included as part of this model. In the real system, rework is carried out at a separate rework station, and this station is not included as part of this study. The suppliers for the case study company ensure that every component has passed the quality inspections before being delivered to the facility. In the actual organization, the defective products received back from the customers had design flaws and not manufacturing defects. The most common defects arising from design flaws are condensation inside the product due to use in a high humidity environment, drained battery due to excessive signal transmission requirements, inability to communicate with the client's process control software and improper location of the products in the customer fields resulting in loss of radio signals. Hence, it is assumed that all the grouped orders passing through the testing station will pass the quality check and will be transferred to the last station. The last station is the labeling/packing process station. This station uses two components and hence the grouped entity from the testing station is transferred to a Hold block named "LabelingStation_hold". After checking on the availability of the label and bracket from the corresponding bins for order(s) in the LabelingStation_hold block, the grouped order entity is transferred through a series of two Pickup blocks (Pickup label and Pickup brackets) to be grouped with one of each corresponding component and is transferred to the labeling/packing process station to be processed. After completion of the labeling/packing process, the grouped order is transferred out of the system as a completed order. The processing time at each station consists of the station cycle time of the product, which follows a triangular distribution. The entire simulation is run for 12,000 hours, and statistics are collected for 12,000 hours after the end of warm up time. Determination of warm up time will be discussed in a later section. For each external influence and control actions, additional model logic is added. The following sections provide a brief description of the external influences, control actions, and simulation logic.

3.6.2 Simulation Logic for Product Customization Influence

The product customization influence is created by the customer element. Many manufacturing systems manufacture one or more customized products apart from the standard products. In such cases, the level of customization depends on the manufacturing line capability, production cost and the target market. The product analyzed in the case study system is of two types: standard and customized. The processing model for the custom products differs from the processing of standard products in two areas: the time it takes to complete one unit of the customized product and the components used in the product. In the case study system, the time to complete custom products varies from the standard by a percentage change in the average of the processing time for each station. The product customization scenario / experiment have two types of products in the system; a base type and custom type. Figure 8 shows two logic boxes in a series after the order creation block.

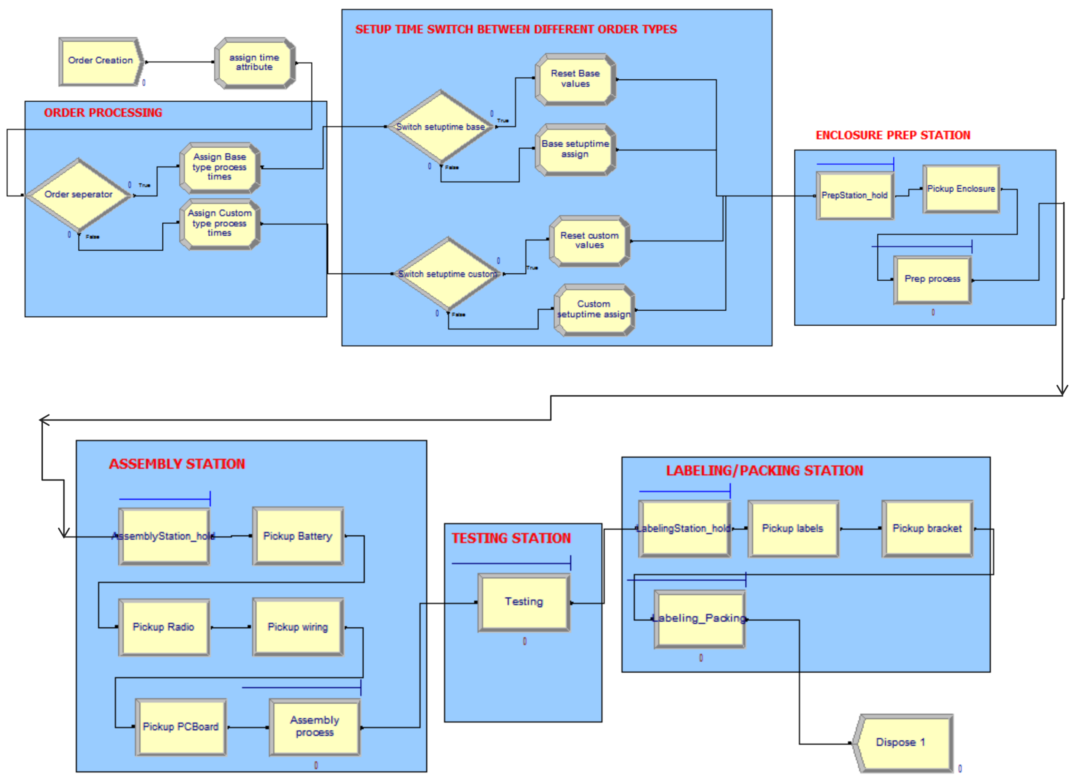


Figure 8 ARENA Screenshot of Product Customization Influence Logic

The first part of the logic controls the proportion of the two types of products. After the order entity is created from the Order Creation block, the order is transferred to an order separation logic which has a Decide block named Order Separator and two Assign Blocks named "Assign Custom type Process times" and "Assign Base type Process times" respectively. The Order separator will designate the created order entities either as a base type or a custom type entity and the percentage of base type vs. custom type orders in this block is defined by a variable named "Orderseparation." If the Orderseparation variable has a value of 100, then all the orders entering the system will be for base type products and if the Orderseparation variable is 90, then 10 percent of the orders entering the system are custom orders. The two Assign blocks, standard and custom are used to assign processing times to the custom and standard orders that pass through them. The base product has the processing times mentioned previously in Table 2. The customized product type has a 25% higher processing time (25% increase in the average processing time values of the three parameters of the triangular distribution for each station) than the base product type as shown in Table 7.

Table 7 Processing Time for Customized Product Types

Station name	Standard Process Time in hours			Custom Process Time in hours			Standard Product		Custom Product	
	Min	Mode	Max	Min	Mode	Max	Average Processing time	Processing Time Variance	Average Processing time	Processing Time Variance
Enclosure Prep station	.120	.130	.140	.152	.162	.172	0.130	0.00016	0.1625	0.00016
Assembly station	.160	.284	.330	.224	.348	.394	0.258	0.00128	0.3225	0.00128
Testing station	.150	.293	.370	.217	.360	.437	0.271	0.00207	0.3387	0.00207
Labeling/ Packing station	.190	.240	.270	.248	.298	.328	0.233	0.00027	0.2916	0.00027

After the processing times are assigned, the order types are transferred to another logic part called "Setup time Switch logic" where setup times are assigned. Setup time is defined in this study as the time it takes to switch from one product to another product type. A Decide block and two Assign blocks are used for each product type to ensure that a setup time of 0.1 hour occurs whenever the order is not the same as the one that precedes it and there are no consecutive similar product types entering the system. In this scenario / experiment, orders for both product types arrive in random order and are processed First In First Out at each station. When there is a series/string of orders for one type of product being processed consecutively, the setup time will be applied as a delay of .1 hour for the first order. However, when a stream of other product type order enters the system, the setup time will again be applied to the first order in the string / stream. For every change in product type, the setup time is reapplied. In the experiment, the independent variable is the proportion of customized products vs. standard products in the system. The setup time is set as 0.9 hours for both the standard as well as the custom order product types. In actual system the set up time to switch from one product to another was considered the same as the average time taken to complete processing one order. The set up time is not applied in the baseline scenario / experiment because all products are of standard type.

3.6.3 Simulation Logic for Diminished Supply Rate Influence

The supplier(s) for each critical component deliver(s) a constant batch size at an interarrival time estimated according to a triangular distribution. The parameters for the interarrival time distribution and the supply batch size is the same for each component vendor. The external influence on supply rate is related to the number of products (supply batch size) delivered at a certain interarrival period. Due to quality, end of product lifecycle, maintenance and/or capacity constraints, the supplier may not be able to supply a constant batch size of product at a certain supply interval. As a result, the quantity delivered could decrease by a certain percentage, resulting in the supplier becoming further and further behind. In the real system, the vendor for the printed circuit boards faced capacity issues and reduced the quantity twice between one year intervals by a percentage over a period delivered to system. This incident prompted the selection of the decrease in supply as one of the external influences on the system.

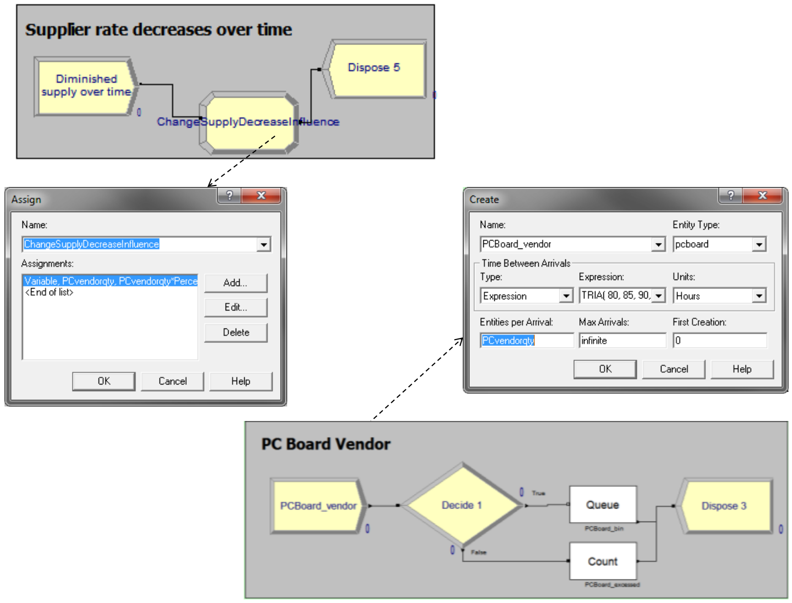


Figure 9 Diminished Supplies over a Period Influence Logic

Figure 9 shows the diminished supply rate logic influence affecting the PC Board supplier along with the PC vendor supply logic. For the model with this influence, the logic is created such that a separate entity named "SupplyDecreaseInfluence" is created in the "Diminished supply over time" create block after the warm-up period, which triggers the PC Board vendor to reduce supply to the PC Board bin. In the simulation model, the batch size of PC boards supplied is decreased by a set percentage of the previous quantity over a period of two consecutive deliveries after the initial delivery, and it occurs after the warm-up period. The batch size decreases cumulatively after each period for the set percentage. The levels for this factor are changed by varying the percentage. Each percentage change in the model is run as a separate model, and the statistics are collected for the performance measures at each run. For a 2% decrease in supply quantity, the supply is 98% of the original lot size of 240 units. This reduced lots size of 236 units will be supplied for about 2000 hours after warm-up period. A subsequent reduction of 2% will result in 96.04% of the original lot size being delivered (231 units) and will stay at this delivery level until the end of simulation period. The percentage change is stopped at

10% decrease in supply quantity because the resulting cumulative decrease in the supply quantity over time is 19%, and in the real system, the quantity supplied did not drop below 80% of the original quantity over 2 years. For the design of experiments, the base model with two level changes in quantity will be considered as the low level and high levels. Table 8 provides the actual lot size after the end of the influence in each level. The first time the percent decrease occurs in the model is at 850 hours and it remains in effect until 2850 hours. The second decrease occurs at 2850 hours and remains in effect until 12000 hours after warm up. The selection of the percentage level is discussed in the section 3.8.

Table 8 Competitor Going Out of Business Experiment Levels

Scenario	Final % decrease in quantity	Supply lot size /delivery between 80 and 2080 hrs	Quantity delivered beyond 2080 hrs
No change in supply quantity	0	240	240
2% decrease in supply quantity	3.9%	236	231
4% decrease in supply quantity	7.8%	231	222
6% decrease in supply quantity	11.6%	226	213
8% decrease in supply quantity	15.4%	221	204
10% decrease in supply quantity	19%	216	195

3.6.4 Simulation Logic for Competitor Going Out of Business Influence

A competitor going out of business creates a void in the market, and the existing players in the market get a chance to serve the defunct competitor's customers. The assumption associated with this influence is that the market is stable or growing and the competitor shuts its doors because of product issues. This external influence creates a positive influence through an increase in sales and hence any control action applied will exploit the positive effect to the advantage of the manufacturing system. In the real system, the product manufactured has two direct competitors and is a relatively new developing technology. This creates the potential for one or more competitors to drop out the market, leaving those needing the product to select suppliers from the remaining manufacturers.

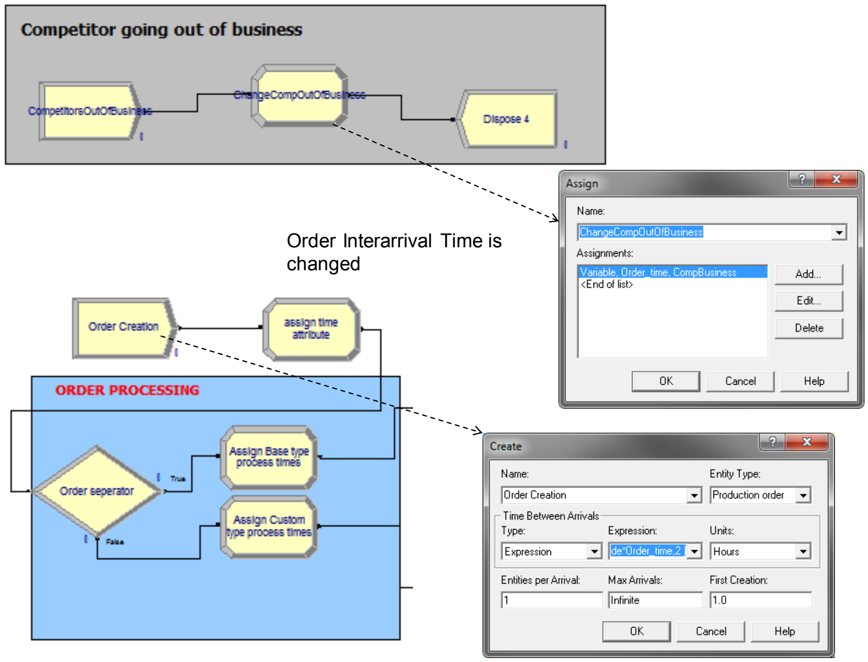


Figure 10 Competitor Going Out of Business Influence Logic

In the simulation model, the increase in number of customers (increased demand) is accomplished by reducing the most likely value interarrival time for orders by a certain percentage without affecting the variance. The actual case study organization experienced a spike the number of orders being placed in the system. This increase in the number of order within a short interval could be modeled as a decrease in the order interarrival time. The range of increase is between 0% to 30% in the most likely values of the order inter-arrival time. Figure 10 shows the part where the competitor going out of business influence affects the simulation model. A separate Create block named “CompetitorsOutOfBusiness” is created and an event is created through an entity named “CompOutOfBusiness” after 80 hours (warmup period), and this entity changes a variable named “Order_time”. This variable Order_time is a percentage that reduces the various parameters in the interarrival time. A variable named “OrderIATMode” is defined with a default value of 0.4 hour, which corresponds to the most likely interarrival time value of the base model. In order to shift the average and not the variance of the distribution, the difference in spread between the minimum and maximum parameters of the distribution is kept constant for each experiment level change and the Table 3-8 shows the constant variance for the different levels. In order to accomplish that the minimum, mode and maximum values of the triangular distribution for the order interarrival time is defined as ((OrderIATMode*Order_time) - 0.2), (OrderIATMode*Order_time) , and (0.13 + (OrderIATMode*Order_time)) respectively. The variable Order_time percentage is decreased in order to increase the number of orders entering the system.

Table shows a change in the average and variance of the triangular distribution for customer order inter-arrival time. The column titled" Average number of orders in 12000 hours" in the table has the calculated results of the average number of orders in the system for each scenario after 12,000 hours of simulation. It is obtained from the average inter-arrival time, and the simulation time (12,000 hrs excluding warm up time). The percentage increase in the number of orders entering the system is calculated based on the average number of orders entering the system during the simulation time period and is shown in the last column of the table.

Table 9 Distribution Average and Variance for Order Inter-arrival Time

	Order Inter-arrival Times (in hrs)						
% Decrease	Min	Most likely	Max	Average	Variance	Average number of orders in 12,000 hours	% Increase in order Throughput
0%	0.200	0.400	0.530	0.376	0.004605	31914	0%
5%	0.180	0.380	0.510	0.356	0.004605	33644	5.42%
10%	0.160	0.360	0.490	0.336	0.004605	35643	11.68%
15%	0.14	0.340	0.470	0.316	0.004605	37894	18.73%
20%	0.120	0.320	0.450	0.296	0.004605	40449	26.74%
25%	0.100	0.300	0.43	0.276	0.004605	43373	35.90%
30%	0.080	0.280	0.410	0.256	0.004605	46875	46.87%

The diminished supplies influence change is a one-time change, and the interarrival time change remains the same until completion of the simulation. The experiment range is stopped at 30% decrease in interarrival time. A 30% decrease in order interarrival time coincides close with the actual scenario where one of the three competitors goes out of business. Statistics are collected for the performance measures after each run. The selection of the percentage levels used in the design of experiments is discussed in the section 3.8.

3.6.5 Simulation Logic for Supplier Going Out of Business Influence

A supplier going out of business is considered as the worst case scenario of the external influences resulting in supply rate decreases over a period of time. Due to bankruptcy, manufacturability issues, customer/ supplier relations or capacity constraints, a supplier may not be able to supply a component. As a result, the manufacturing system is forced to find an alternate source of supply in order to recover. In the real system, the supplier for the printed circuit board faced procurement issues for the components used on the printed circuit board and dropped the supply contract, citing higher procurement and manufacturing costs. The real system was able to recover from this incident by finding an alternate supplier after a period of approximately 6 months (approximately 1000 simulation hours) with changes in design to reduce procurement and manufacturing costs. This incident prompted selection of the supplier going out of business as one of the external influences on the system. Figure 11 shows the ARENA module where the supplier out of business logic is embedded in the model. Since the PC Boards component was impacted in the actual scenario, the PC board supplier is used for implementing this logic.

In the simulation model, the delivery period of the PC boards to the system is varied to model the supplier going out of business influence. An event occurs after a period of 80 hours (warm-up period), after which the manufacturing system will not receive PC boards from the supplier for a specified period. Another Decide Block is added to the PC Board supply logic and a variable named “Vendortimeout” is defined with a default value of 0. The Vendortimeout variable is the number of hours a supplier is not supplying or in other words the amount of time it takes for the system to find another replacement supplier. In the Decide block, an expression is built in such that between 80 and Vendortimeout+80 hours after start of simulation, any PC Board components trying to enter the system will be dropped,diverted,disposed without sending them to the PC Board bin. To activate the influence, the Vendortimeout variable is increased from its initial value of zero.

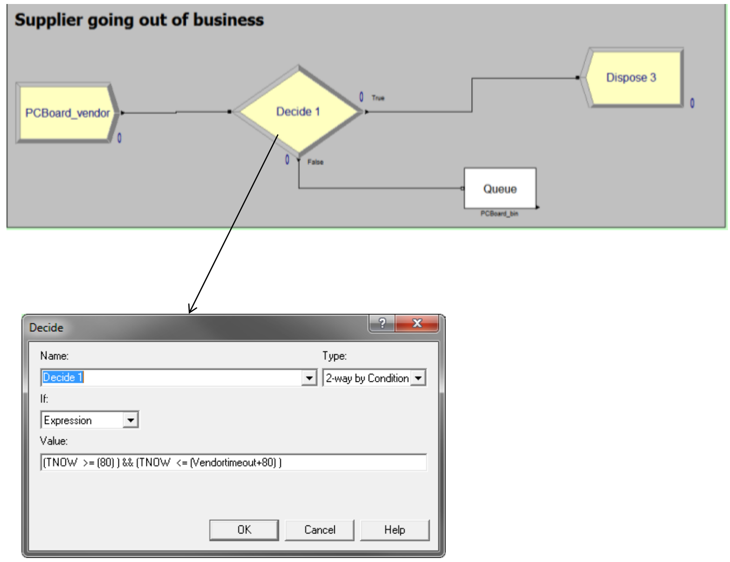


Figure 11 Supplier Going Out of Business Influence Logic

3.6.6 Simulation Logic for Additional Resource Control Action

The ability to rapidly change capacity is a possible control action for a manufacturing system and it requires a manufacturing system to have additional resources either in the form of people, equipment or both in order to adapt to customer demand changes. In the base line scenario, each station has one unit of resource. A resource is a worker at each process station. Each process station is capable of handling infinite number of resources without duplicating the station. In cases where special jigs, fixtures are used, there may be additional quantity of equipment involved at each station in order to accommodate the second resource, but the location, and area required at each station remains the same. In order to model this strategy in the simulation, a new resource "Floater" is created and added to the bottleneck stations. Different experimental levels are defined for the application of this control strategy by varying the number of floaters available. In the first level, the resource capacity at each station is fixed as one. The Floater resource is shared across the four stations (enclosure prep station, assembly station, testing station and labeling/packing station) through the uses of "sets" feature in ARENA. For each station, a “set” of workers are created and under each set the resource corresponding to the station is added. This will constitute the baseline scenario. When the control action is to be applied, the floater is added to each of the sets as a common resource. The rule for selecting a resource by an entity for processing is set as “Preferred order”. Based on this rule, an order when entering a process station will select first the dedicated resource at the station and if the dedicated resource is not available, the floater resource will be selected. The different experiments are completed at various levels by varying the floater capacity number from 0 to ‘x’ as whole integer increments.

From a managerial perspective, the value of adding capacity as a control action to mitigate/exploit the external influences depends on the length of application of the control action, the costs associated with adding an additional resource, and balancing the line by scheduling the additional resources across the assembly lines. By understanding the relationship between these variables, and the change in the mitigation effects of capacity with regard to the external influences as measured through the performance metrics, a manager would be able to balance the costs related to application of control strategies with respect to the value of their ability to mitigate/exploit the external influences.

3.6.7 Simulation logic for Add Alternate Supplier Control Action

The alternate supplier strategy helps a manufacturing system with unreliable suppliers for its purchased components. When these suppliers fail to deliver or decrease their delivery quantities due to capacity, quality, or financial issues, the system performance is affected. To implement this strategy, adding one or two additional suppliers, apart from the existing supplier, were implemented. For this study, modeling one additional supplier is sufficient because the single additional supplier is assumed capable of delivering any desired lot size, up to and including the highest level in the study experiment. The independent variables selected for this control strategy are supply lot size and supplier interarrival times. The lot size of the added supplier could be varied ranging from zero to the lot size of the current main vendor. The lowest level in the experimental design setup for this control strategy is “no” supply from the alternate vendor. The highest level in the experimental setup is the supply capacity of the existing main vendor (240 units per arrival) along with the alternate vendor (supplying up to 240 units per delivery period). The other independent variable is the supplier interarrival time. The new additional supplier could be negotiated to delivery smaller lot sizes at lesser interarrival time than the regular supplier.

A manager has to justify the cost of adding another supplier vs. the mitigation of external influence benefit cost ratio. Recalling the previous discussion about the annual usage contract negotiated by the supplier and the manufacturing system, the inventory that is not used by the manufacturing system is the excess inventory and will have to be bought out by the system. In order to consider the cost of adding another supplier, the excess inventory supplied by the new supplier, and the setup costs associated with adding an additional supplier must be considered. From the change in traditional performance metrics due to the mitigation effect of the control action on the influence, a manager would be able to perform a scenario analysis, which would enable balancing the costs related to application of control action with respect to the impact of external influences.

3.6.8 Verification

Verification of a simulation model is defined as the process of verifying whether the performance measures of the simulation model output are calculated as expected by the simulation logic. In the verification process, the base model with variation is converted into a deterministic model by replacing the random number distributions for inter-arrival times of the orders and components, as well as the processing times at each station, with a constant value to verify if the calculations result in the statistics estimated by the model matching the manual estimates. The interarrival time for the orders was set to a constant value of 1 hour. The size of the order is a constant size of one order. The inter-arrival times of all the components from each vendor are changed from their respective distributions to a constant of 85 hours and a batch size of up to240 units per arrival. The vendor supply portion of the simulation is unchanged except for the constant values instead of distributions. The processing times for each station have been changed from their respective distributions to constant values. The constant processing time values for the four processing stations are the most likely value from the triangular distribution namely 0.130, 0.284, 0.293 and 0.240. With the changes made, the simulation model is run for 1000 hours. The output results are compared to the expected results for the four performance measures.

Time in System:

The average time in system for each order from the simulation is 0.947 hour. This is the sum of the processing time of the order at each station, the time-in-queue before each station waiting for the resource to be available, and the time-in-queue waiting for the components to be available. The total processing time for a single production order is the sum of Processing time (Prep process station), Processing time (Assembly process station), Processing time (Testing process station), and Processing time (Labeling/packing process station). Numerically, the total time in system = 0.130 hour + 0.284 hour + 0.293 hour + 0.240 hour = 0.947 hour. The calculated value matches the total time in system value (Production Order.Total time) from the simulation results. There is no queue time in this case since the interarrival time per order is greater than the processing time for the bottleneck station (Testing process station).The size of an order is one unit and is standard throughout the study.

Work in Process:

The average work in process (WIP) can be calculated manually using Little's Law, which states that WIP = Average time in system for each product * system throughput for the period. The system throughput is calculated from the number completed (999 units) and simulation time

(1000 hours). The system throughput for the simulation model is the ratio of the number of items completed to the simulation time. The calculated WIP from Little's law is

Average WIP= (0.947* 999/1000) = 0.946.

The average WIP from the simulation results is 0.946.

Number Completed:

The first set of orders enters the system after one hour of simulation time is completed. This accommodates the time for the component bins to fill up and for the initial startup period, a real system might encounter. For the 1000 hours remaining, 1000 orders are created. However, because of the initial delay of one hour, one unit is left in the process queue and the total number of units exiting the system after a time period of 1000 hours is 999 units, which is the same value as in the simulation output.

Utilization:

The utilization of the four stations is calculated mathematically as the ratio of the resource being busy for the (Number of parts * Processing time) / total simulation time. For example, the prep station had seized 1000 orders and has a processing time of 0.13 hours per unit. The time the server was busy is 1000 * 0.13 = 130 hours. The utilization of the station for the simulation time of 1000 hours is 0.130. Table 10 provides a comparison of the manual vs. simulation results for resource utilizations. The simulation results closely match the calculated results. Therefore, the model is verified to see if right results are being estimated with the 'obvious" input.

Table 10 Utilization Verification

Resource	Prep station	Assembly station	Testing station	Labeling and packing
Time server was busy in hrs = (Number seized * processing time**)**	=1000 *0.130 =130 hrs (less setup 0.1 hr) =129.9	=999 *0.284 =283.72 hrs	=999*0.293 =292.71 hrs	=999*0.240 =239.76 hrs
Simulation time in hrs	1000 hrs	1000 hrs	1000 hrs	1000 hrs
Utilization (calculated)	0.1299	0.2837	0.2927	0.2397
Utilization (from simulation)	0.1299	0.2838	0.2928	0.2398

3.6.9 Validation

Validation of the model is defined as the process of determining whether the simulation model adequately represents the real system. In this case, the model is based on a real manufacturing system; however, several parameters were changed in order to make the simulation a balanced model with utilizations around 70% for most of the stations. The inter-arrival time for the orders is based on sales data for a two-year period. Due to the organization being a startup company, there were 212 data points over the 18 months period. The sales for the organization picked up towards the last few weeks of this period and 33 data points of the last week in this period was used to fit the data to a distribution. Based on the distribution fit analysis discussed in the Order Data section of this case study, a triangular distribution with a minimum of 0.2 hour, maximum of 0.53 hour and the most likely time of 0.4 hour was selected. The lack of any additional historical data makes validation of the order interarrival time portion of this model next to impossible. The processing times at the real stations created an unbalanced line. In cases where an external influence acts on a station in an unbalanced line, it can either amplify or negate the true effects of the external influences. In order to create a balanced line, some of the tasks from the high processing time stations were moved to the neighboring low processing time stations. In order to test if the line was balanced, 30 orders were created for finished goods stock by the case study organization and sent to the manufacturing system for processing. The resulting processing time data points at each station were fit to a distribution and the best fit distribution was a triangular distribution. The analysis of the distribution fit was discussed previously in Process Data section. There was not enough historical data after the implementation of the line balancing in the actual system. With the changes at the works stations and the lack of historical data after the changes, it is not possible to validate the results from the simulation model by comparing it to the real system. However, since the base model and the external influences were inspired by a real manufacturing system, the experiment results and findings obtained should be useful and applicable to practitioners. The case study organization reflects a small to medium scale organization in terms of the complexity of operations (four workstations), sales revenue (less than $1 million/year), and number of people employed (five people).

3.6.10 Warm-up period determination

The type of simulation used in this study is a steady state non-terminating simulation. In a non-terminating simulation, the simulation ends after a long period without any natural event specifying the length of run (Law and Kelton, 2000). In order to better estimate the convergence point of the transient mean to steady state mean, the data points for the initial transient state are deleted. This method is called the warm-up period determination and deletion method. Welch's (1983) procedure is one of the simplest and most general graphical techniques available for the warm-up period determination. The simulated time taken by each individual entity is recorded over a period and used for the Welch method. The "Y" axis in Welch Plot is the performance metric (Time in System in hours) and the "X" axis is the entity number; the entity numbers are serially assigned as the simulated orders were created corresponding to the time in system metric.

The Welch method was applied to the base model without any influences or control actions. The Welch procedure plots using the base model for window size 2 are shown in Figure 12. A complete set of plots in series with the number of entities between 0 to 2500, 2500 to 5000, 5000 to 7500, and 7500 to 10,000 is shown in figures 3-8, 3-9, 3-10 and 3-11 respectively. The plots in Figures 13 to 16 along with Figure 12 show that the process variation is stable beyond 200 entities in the system over the simulation period. Based on the plots, the performance measure (time in system) stabilizes with minor variations around a time in system value of 0.9 hours at about 80 hours after 200 entities have exited the system.

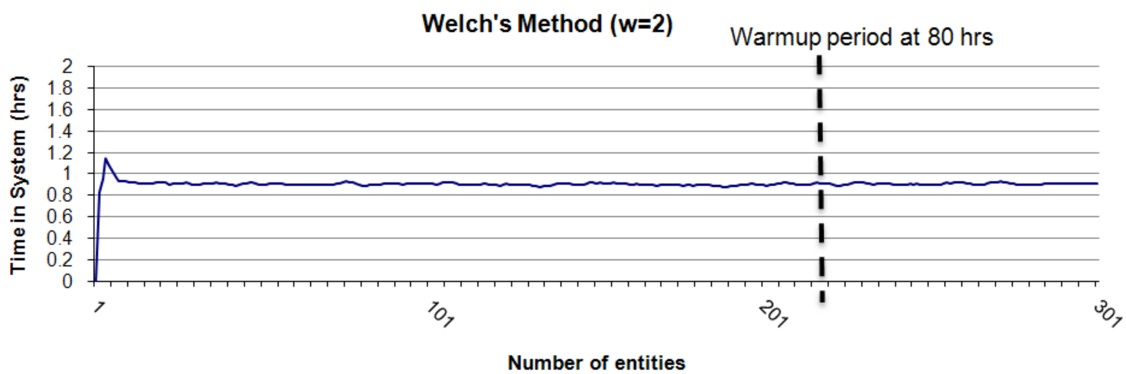


Figure 12 Base model Welch Plot with w=2 (snapshot of warmup period)

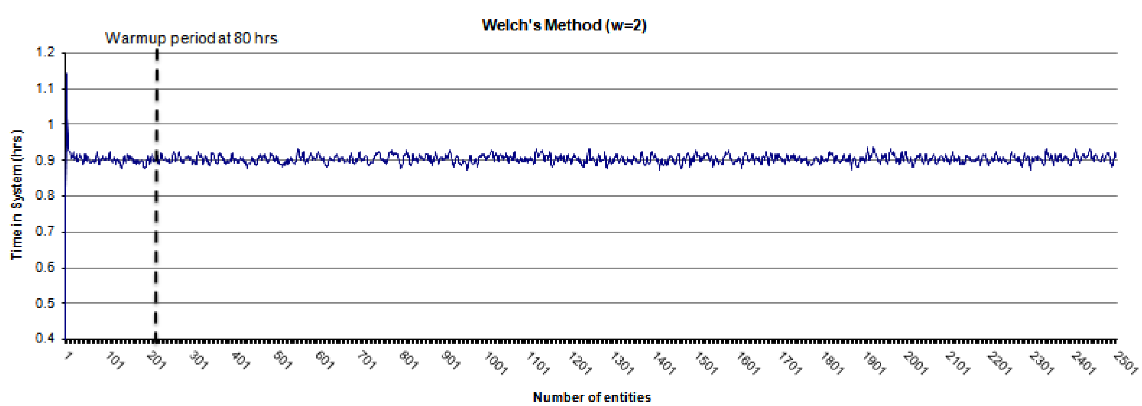


Figure 13 Base model Welch Plot with w=2 (from 0 to 2500 entities)

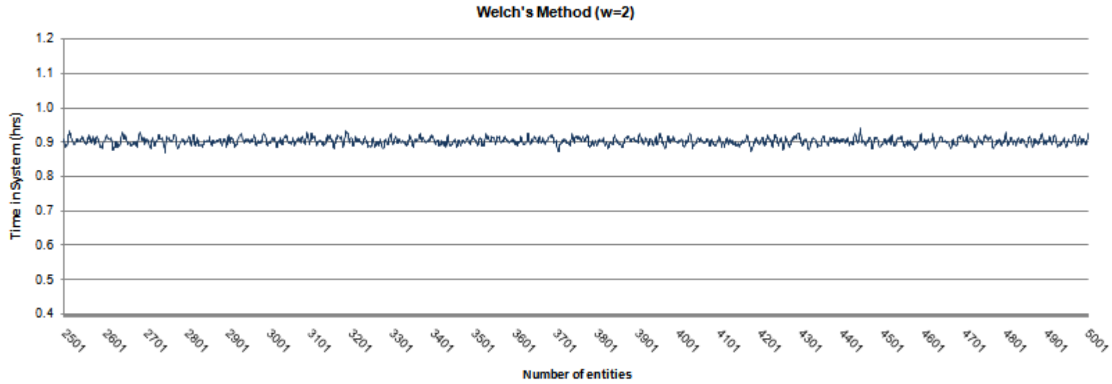


Figure 14 Base model Welch Plot with w=2 (from 2500 to 5000 entities)

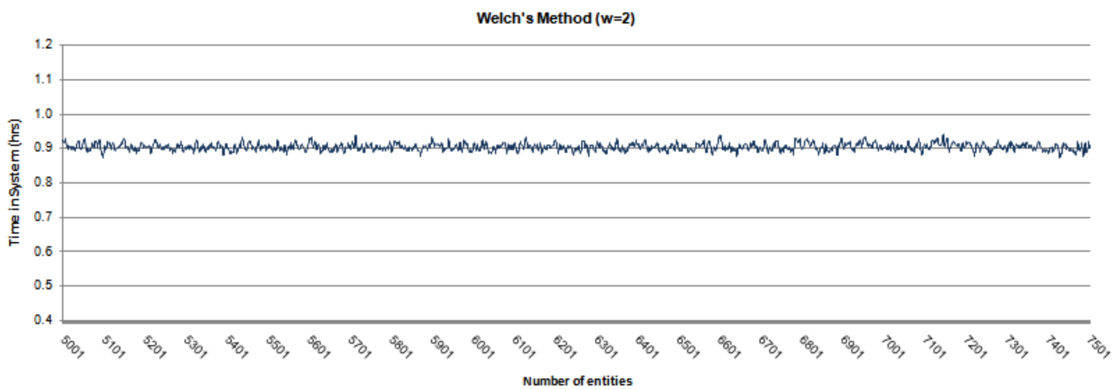


Figure 15 Base model Welch Plot with w=2 (from 5000 to 7500 entities)

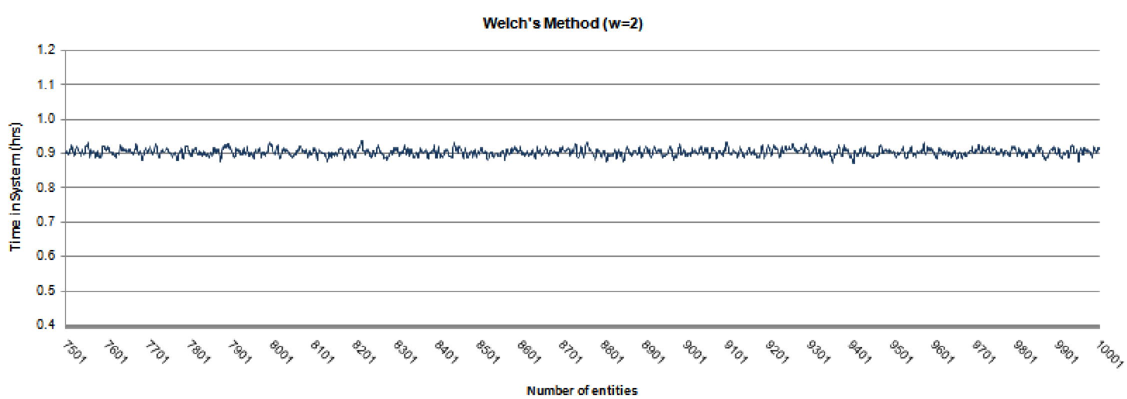


Figure 16 Base model Welch Plot with w=2 (from 7500 to 10000 entities)

In this study, the base model is modified to create change events for external influences as well as the implementation of control actions to mitigate/exploit them. Also, the impact of a change in external element will create periods of instability, for example higher time in system values following the appearance of an external influence application period for say diminished supplies over time influence, and the system may or may not recover from this perturbation over the finite simulation period depending on the size of change and its duration. It is time consuming to do a Welch method for all possible scenarios defined in the study. Hence, a model scenario that has high utilization, high variance, and large number of orders in the system was created. This scenario had the highest experiment level for the diminished supply influence (10% reduction) and the product customization influence (60% of the products are customized). Individually, the diminished supply influence and product customization influence increase the utilization (95%) and time in system variability (standard deviation of 440 hours), respectively. The Welch method was applied for this scenario and is plotted in the figure 3-12. The product customization influence event is triggered at the start of the simulation as per the logic discussed in the previous section, and the diminished supply influence is triggered at time 600 hours, which is after about 1500 entities have passed through the system.

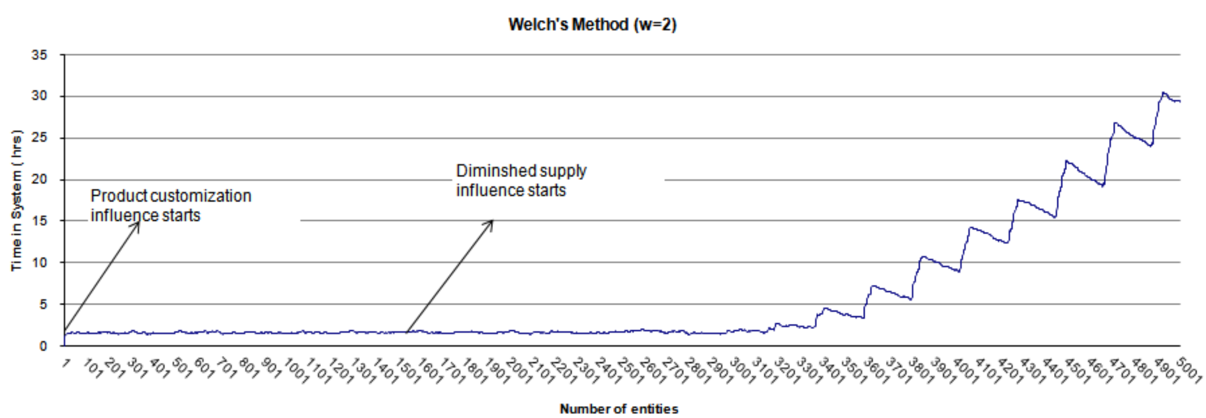


Figure 17 Welch Plot with high utilization and high variance scenario

The plot shows that the time in system value follows a stable minimum oscillation around the average value until about 3400 entities leave the system, after which it tends to follow a jagged trend line. This jagged trend line is due to the system starvation from application of the diminished supply influence. Figure 18 shows the initial portion of the complete Welch plot shown in figure 17, showing about 300 entities exiting the system. Due to the product customization influence, the average value of time-in-system has increased from about 0.9 hour to about 1.5 hours with a variation between 1.3 hours and 1.7 hours. Based on the plots in Figures 3-12 and 3-18, the warm up period is selected at 80 hours.

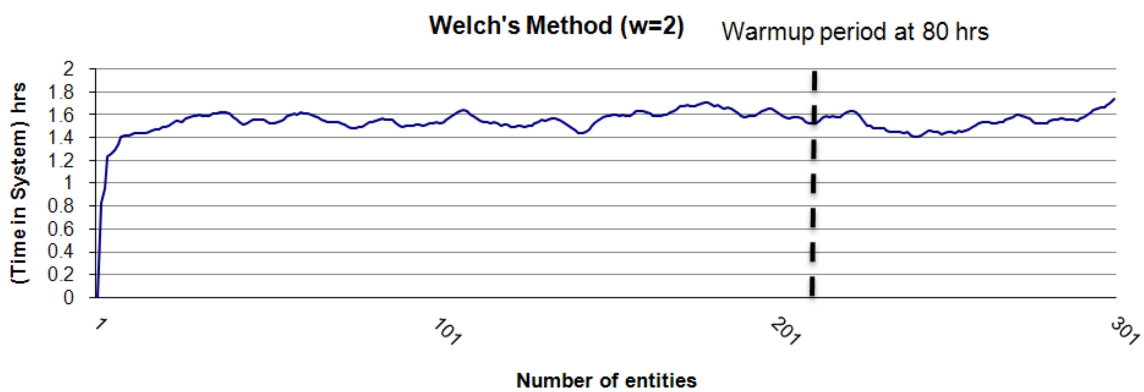


Figure 18 Welch Plot with high utilization and variance scenario (Snap Shot of warm up period)

3.6.11 Number of Replications and Run length

Managers of manufacturing facilities have short-term and long-term planning horizons that include growth and efficiency improvement targets. To understand the long-term effects of some of the influences on the system, a six-year planning horizon was selected. The organization long-term planning cycle was 5 years. Speculating that there might be some external influence effects making the performance metric longer to recover, another year is added to this planning horizon. Also, an extended period of time beyond the recovered time frame might prove that the system has recovered in a single cycle and is not in cycles of recovery.. The run length of six years is about 12,000 hours of simulation time. Most simulation studies select 95% confidence intervals where the true mean of the output metric will be covered within the interval (Law and Kelton, 2000). In this study, the time-in-system output metric is selected, and from the output results for a simulation run of 12,000 hrs after warmup period the halfwidth for 95% confidence interval on the expectations of the time-in-system metric was 0.0009, which is 0.1% of the sample mean time in system (0.903 hour). The number of replications for this trial run was 10. Since the half width is very small compared to the sample mean, the number of replications and the simulation run time are selected as 10 and 12,000 hours for all the experiments in the study. The model is also set to initialize both the statistics as well as the system between each replication. This means that the system will clear out the remaining entities (orders and inventory) in the system, as well as the statistics, and will start again at time zero for each replication.

3.7 Selection of Performance Metrics

Performance metrics are responsive to changes in the external elements and the manufacturing system that are used to compare the system performance under different conditions. A selection process was developed to identify the appropriate performance metrics to be used for this study. Figure 19 shows the sequence of steps used in this study to identify the performance metrics. The first step is a literature review of the performance metrics. Two primary literature sources were used to list the performance metrics. The first primary source is an article about survey and classification of strategy related performance measures for manufacturing by White (1996) which contains 125 performance metrics compiled from various sources. The remaining two performance metrics were selected from the book "Simulation modeling analysis" (Law & Kelton, 2000).

The second step is to define whether a performance metric is an input variable or an output variable for the system under consideration. Some metrics in the literature, such as research and development expenditure are considered as input variables for a manufacturing system. Only performance metrics that are output variables for this system under study can be used to measure system performance.

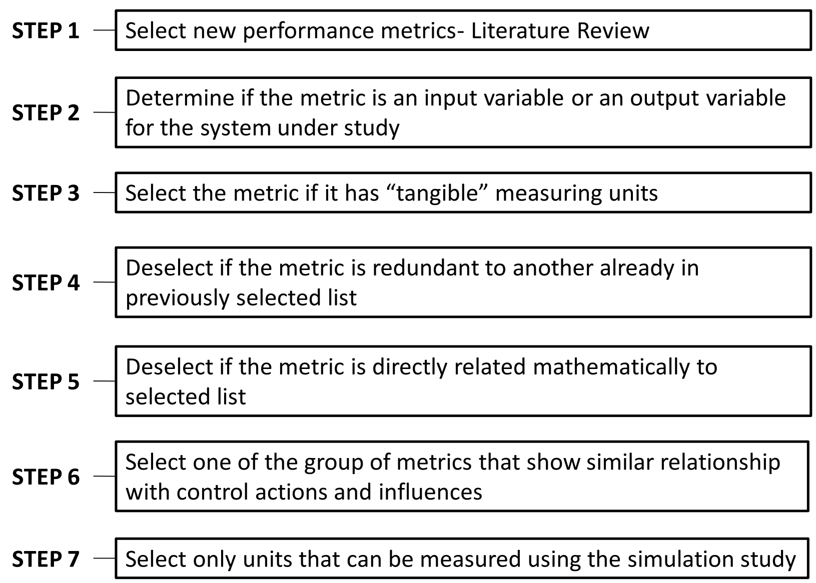


Figure 19 Steps to Derive and Select Performance Metrics

The third step was to select those metrics that have “tangible” measuring units. A tangible measuring unit could be cost, time, percentage, or count related. Metrics with ranking, percentile or any other subjective measuring units were eliminated at this stage of the process. For example, the metric “perceived relative quality performance” has subjective measuring methods since it varies from system to system and hence it was eliminated from the list. The fourth step of the process was to eliminate redundant metrics. Some metrics are synonymous, that is they are the same even though they have different terminology. An example would be uptime percentage and percentage downtime metrics. Both can be defined in terms of the other. The fifth step is to identify if the selected metrics can be related mathematically to each other. For example, Little’s law defines a relationship between work in process, lead-time and throughput rate. It makes sense to select only two of the three metrics since the third metric can be derived mathematically. The sixth step in the process was to identify metrics that are highly correlated to other metrics but not related to each other mathematically. For example, the uptime percentage of a workstation can be correlated to mean time between failures for the workstation. In the last step of the process, a performance metric was selected if it could be statistically measured in the simulation model used for this study. Examples of some performance metrics that cannot be measured using this simulation study are design costs, reliability, durability, and life cycle of a product. A complete list of all the 127 performance metrics considered for this study along with the description of how the metrics were selected are listed in a table in Appendix A. After the selection process, four performance metrics were selected for this study. The Table in Appendix A has the performance metrics listed in a column along with an identity number for reference. In the next column titled "Classify as Input/output for this model", step 2 of the process occurs. The next column titled "Units" separates the metrics as tangible by assigning units

If the metrics are subjective in nature even though units can be assigned, then the metrics are eliminated as subjective performance metrics. The "Analysis" and "Reason for Selection" columns document the selection process steps 4, 5 and 6. The last column in the table refers to Step 7 where it verifies to see if the metric should be applied to the simulation study. The metric "Inventory" is one of the metrics selected through this process. For this study, since the supplier element creates influences that affect the inventory, the performance metric selected is one that is focused on the critical component inventory level at the stations where the influence occurs. The next metric is the Work in Process (WIP) at the influence-impacted station(s). When an external influence affects the system through one or more work stations, then those work stations become the bottleneck stations in the system. WIP levels at these impacted station(s) provide a more insight to the systems overall response to influence effects. The remaining metrics are lead-time and on time percentage delivery. The on time performance is a metric that has the value driven from the customer. In the case study, the customer is quoted a standard lead time of 2.25 hours to manufacture a product. This is based on a minimum sales forecast of about 880 units per year. An order is considered late when the time-in-system value for the order exceeds the standard lead time value of 2.25 hours. The On time delivery percentage metric falls below 100% when the system lead time or time in system for an order is higher than the standard lead time.

3.8 Preliminary Results

This section presents the preliminary results of investigation into the effects of external influences on manufacturing system performance metrics so that factor levels can be set. The influences under consideration are product customization influence, customer going out of business, supplier going out of business, and diminished supplies over a period. The purpose of the preliminary experiments is to determine the influence levels at which there are statistically significant effects on the performance metrics. The performance metrics selected are average time in system, standard deviation of the time in system, percentage on time delivery, bottleneck station work in process and critical component inventory. Each external influence has one independent variable referred to as factor in this experimental study. The influence effects are assessed by a set of single factor experiment at varying parameter levels by running the simulation model for 12,000 hours after a warm up period of 80 hours for 10 replications. The parameter levels for each factor are determined by the range between the lowest and highest level and a minimum of at least two intervals so that linearity or non-linearity of the response could be verified. The lowest level in an experimental design is the minimum parameter level at which the system shows a statistically significant deviation in performance metrics from the baseline scenario. The highest level in an experiment design is set based on two criteria: the limitations posed by the real world as well as the simulation model computing. The results are provided in two segments. The first segment consists of a set of plots for all the performance metrics considered where the effect of each level change in the external influence is plotted. The second consists of a table where the results of the each influence level change are statistically compared with the base results.

3.8.1 Single Factor Analysis of External Influences

For this analysis, each of the factors in the experimental design is varied from the lowest possible level to the highest possible level, while all the other factors are kept constant, and the performance metrics observed. This analysis is used to determine the statistically significant range of the factors. Effective range is defined as the range between the lowest possible level at which the average of at least one performance measure is significant statistically from the base model. In the experiments, all levels start with level 1 or baseline scenario. For each level change a two-tailed t test comparing the base model result to each influence level change is conducted and summarized in a table for statistical significance. The results for factor changes for each external influence are discussed as follows.

Single Factor Analysis- Product Customization

When a product customization influence affects the manufacturing system, the proportion of the custom orders entering the system is increased from the base line scenario. The custom orders have a 25% increase in the processing time parameters compared to the base line and every time the product type switches between the two types of order, a setup time of 0.9 hours is applied at each station. Hence the higher the proportion of custom orders in the system, the higher will be the frequency of change between order types. In this analysis, the levels for the product customization influence are varied from 0% custom products in the system to 100% custom products in the system with a 10% change between levels. Since 10% increase in the number of orders in the system does impact the performance metric statistically significant, the 10% is considered as the increment levels between 0% custom products to 100% custom products. The performance metrics, Average time-in-system, standard deviation of time-in-system, percent on time delivery, and critical component inventory are plotted in Figures 20 to 24 respectively.

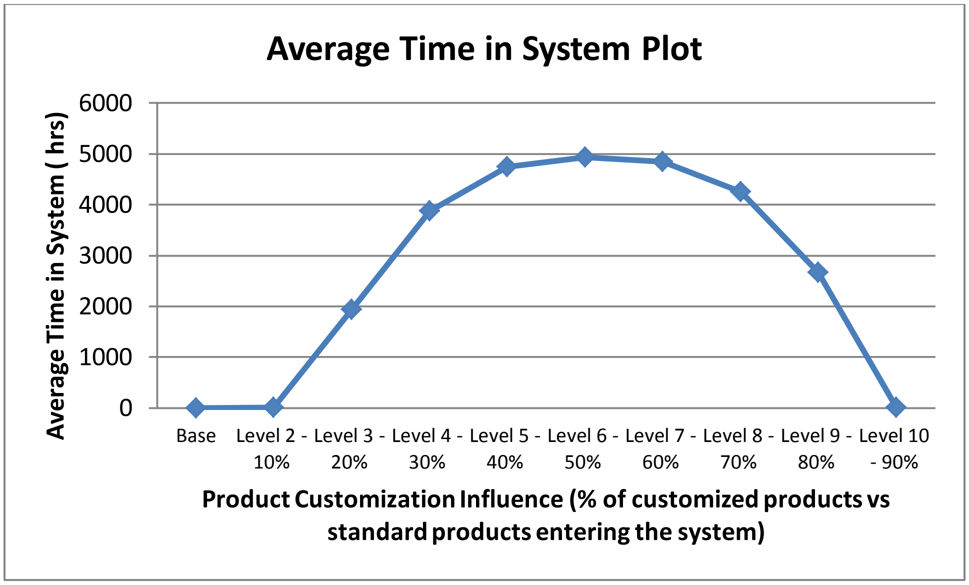


Figure 20 Plot of Average Time in System for Product customization influence

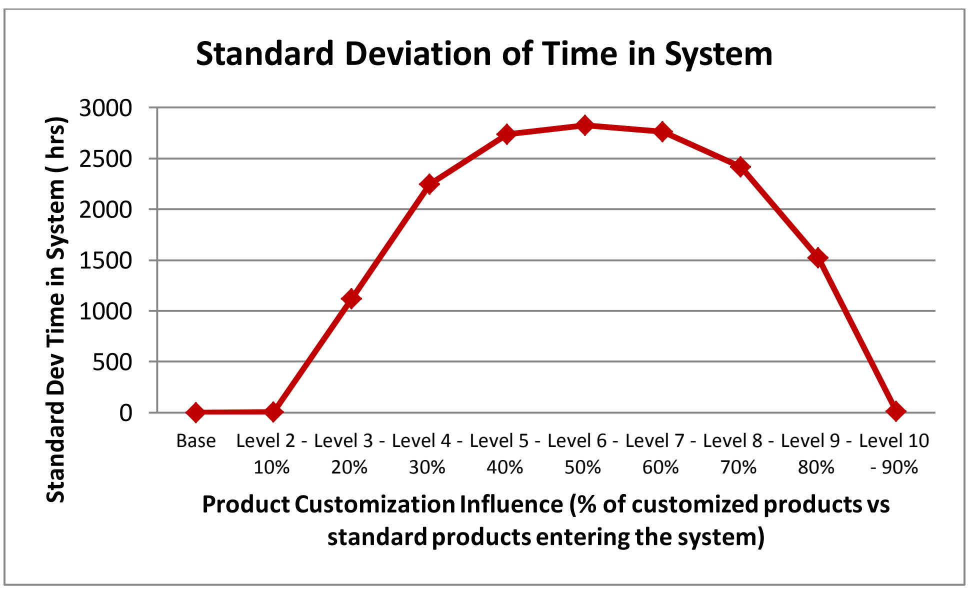


Figure 21 Plot of Standard Deviation of Time in System for Product customization influence

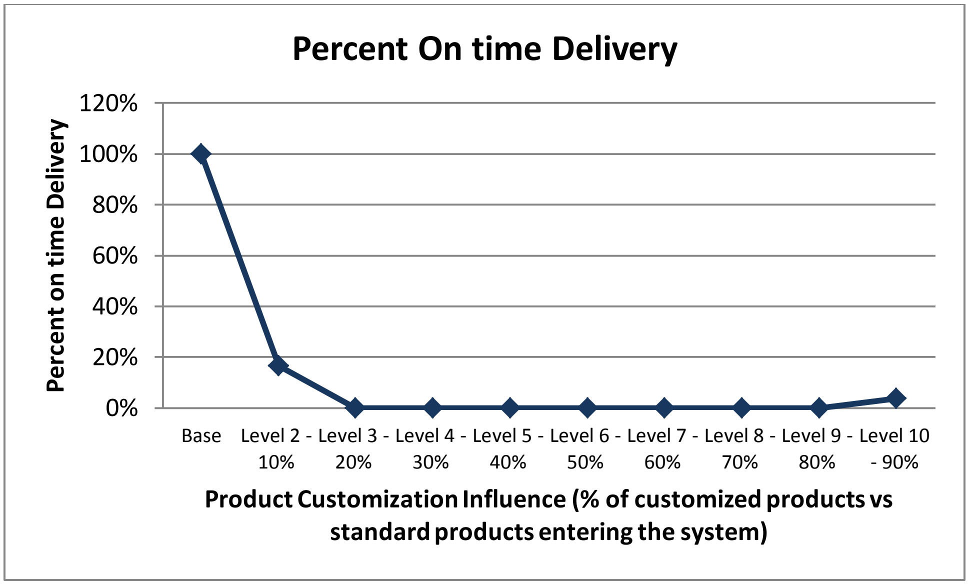


Figure 22 Plot of Percent On time Delivery for Product customization influence

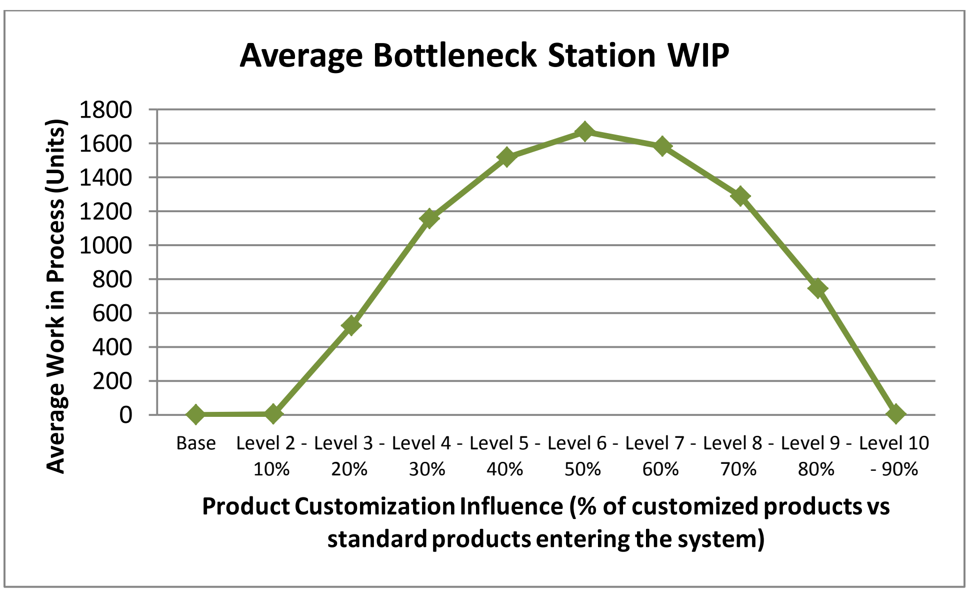


Figure 23 Plot of Bottleneck Station WIP for supply rate decreases influence

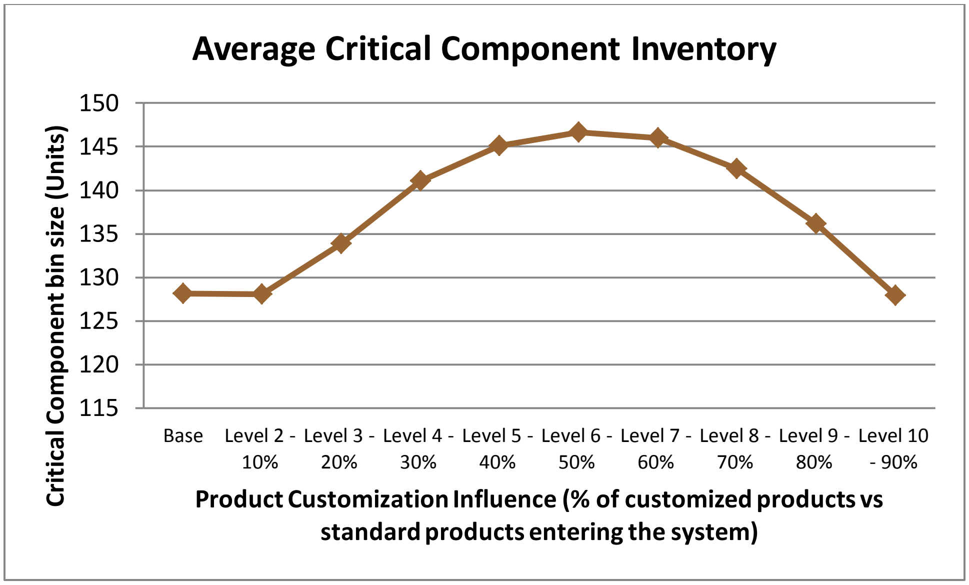


Figure 24 Plot of Critical Component Inventory for Product Customization Influence

The plot for each performance metric except percent on time delivery show a nonlinear increase as the proportion of custom products entering the system increases and starts to decrease after reaching a peak value between 50% and 60% custom level. This equal proportion of both product types creates the maximum number of switches between the two product types at each work station. With each switch from a standard product type to custom product type (and vice versa), the workstation adds a set up time of 0.9 hours along with its regular processing times. As the proportion decreases towards either side, the number of switches from one product type to the other also decreases, resulting in a bell shaped curve for average time-in-system, standard deviation of time-in-system, average bottleneck WIP, and critical component inventory size. Since the percent on time delivery is a function of customer required lead time input (2.25 hours), it reaches zero as soon as the time-in-system value reaches above the 2.25 hour mark. The standard deviation of the time in system performance metric captures the change in the time in system performance metric during the course of the simulation. A higher value indicates a higher level of disturbance in the time –in-system performance metric due to the effect of the product customization influence.

The Table 11 below shows a summary of t test analysis where "*" denotes that the change in simulation result of the performance metric is statistically significant compared to base model result. The critical component inventory change from the base level scenario is not statistically significant at the 10%. Also, the data points for 10% and 90% customization levels show that graphically there is not much change in values form the baseline scenario. The high level increase in the performance metrics for the remaining levels (y- axis) skewed the chart axis showing a negligible change in values from the baseline scenario for those two levels.

Table 11 t- Test Results Summary for Product Customization Influence

Performance Metric	Level 2 - 10%	Level 3 - 20%	Level 4 - 30%	Level 5 - 40%	Level 6 - 50%	Level 7 - 60%	Level 8 - 70%	Level 9 - 80%	Level 10 - 90%	Level 11 - 100%
Average Time in system	*	*	*	*	*	*	*	*	*	*
Standard deviation time in system	*	*	*	*	*	*	*	*	*	*
Percent on time delivery	*	*	*	*	*	*	*	*	*	*
Bottleneck station WIP	*	*	*	*	*	*	*	*	*	*
Critical Component Inventory		*	*	*	*	*	*	*	*	*

The experiment results show a pitfall in interpreting the data and answering the first research question. The results does answer one portion of the research question "which performance metrics are influenced the most". The standard deviation of the time-in-system performance metric was selected to answer to what degree does the performance measures are influenced. The standard deviation calculates the deviation from the average of the metric and does not represent completely the characteristics of the response to the influence effects during the course of the simulation. Hence the performance metrics and the data collection methods are revised to show the response rate of the system with respect to the impact of the external influence effects. However, since the average time in system flat lines between 40 % and the 60% levels and the curve is nonlinear, the levels selected for future experiments are 60% and 30% (shown in Table 12). The 30% level is selected because of its intermediary position between 0 and 60% for experimental design.

Table 12 Product Customization Influence Levels Selection

Influence Level Change Description	Low Level	High Level
Increasing the proportion of custom products entering the system	30%	60%

Single Factor Analysis- Diminished Supplies

A diminished supply over time influence effect occurs when a supplier reduces the delivery lot size by a certain percentage over time. In this influence, the supply lot size is reduced twice over a one working year (2000 hours) span and the supply remains at the diminished levels for the rest of the simulation period. The experiment factor supply lot size reduction percentage is increased for varying levels starting at 2% reduction level. At the two percent level, all performance metrics except the bottleneck WIP shows a statistically significant change from the base line scenario. The two percent level increment is considered to set the other levels for this experiment. Figures 25 to 29 are the plots of the performance metrics average time-in-system, standard deviation of time-in-system, percent on time delivery , bottleneck station WIP and critical component inventory respectively. The maximum level is stopped at 10% as the performance metrics tend to increase towards infinity for average time-in-system, standard deviation of time-in-system, and bottleneck station WIP and the performance metrics tend to move towards zero in case of percent on time delivery and critical component inventory. Both trends suggest that experiment levels could be limited below the 10% level. The performance metrics plots also indicate that the system shows more resilience between 2% reduction and 4% reduction levels, and levels higher than 4% breaks the system's ability to limit the effect of the external influence. Because the average time-in-system value is below the customer required lead time of 2.25 hours, the percent on time delivery is maintained at 100% for 2% level.

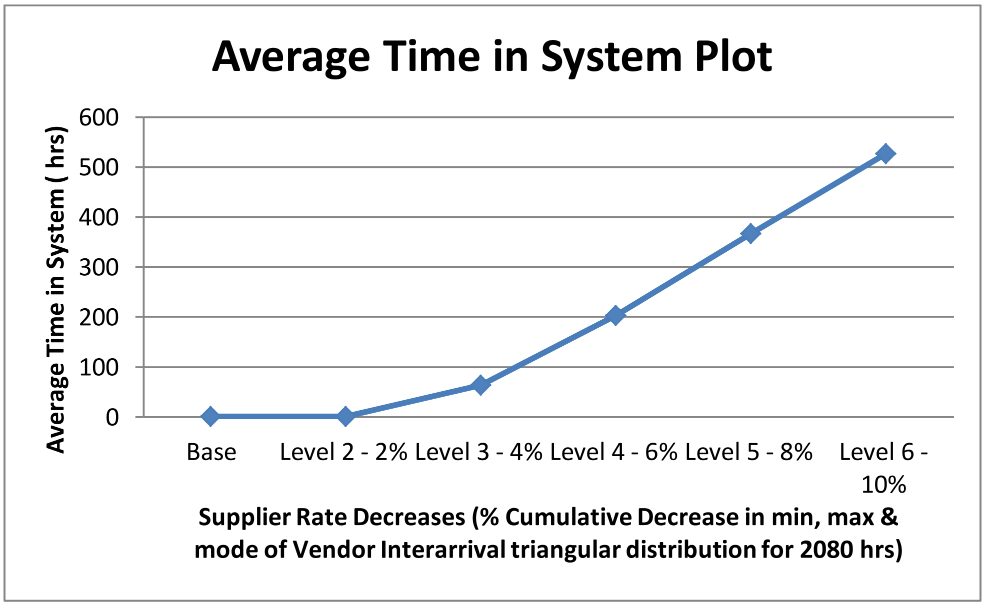


Figure 25 Plot of Average Time in System for supply rate decreases influence

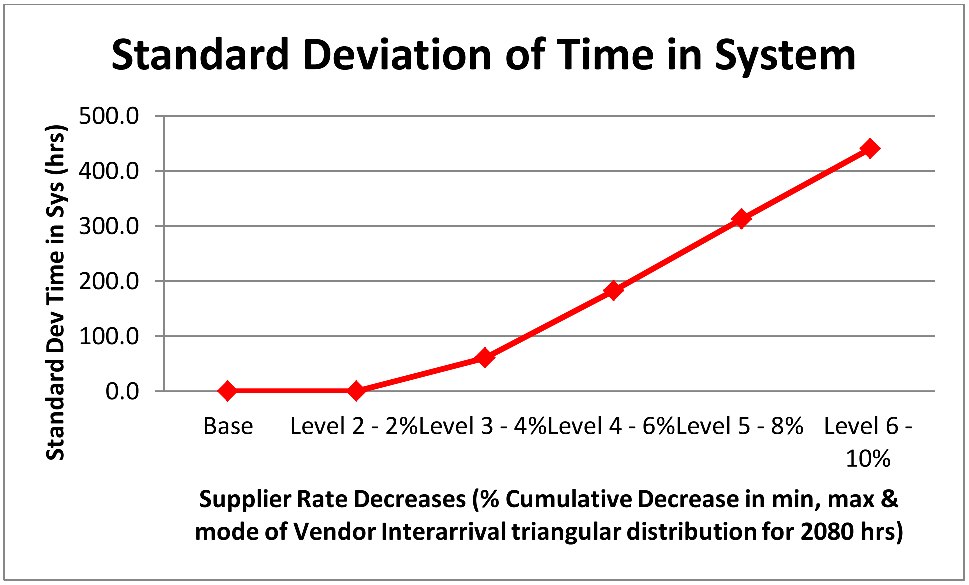


Figure 26 Plot of Standard Deviation of Time in System for supply rate decreases influence

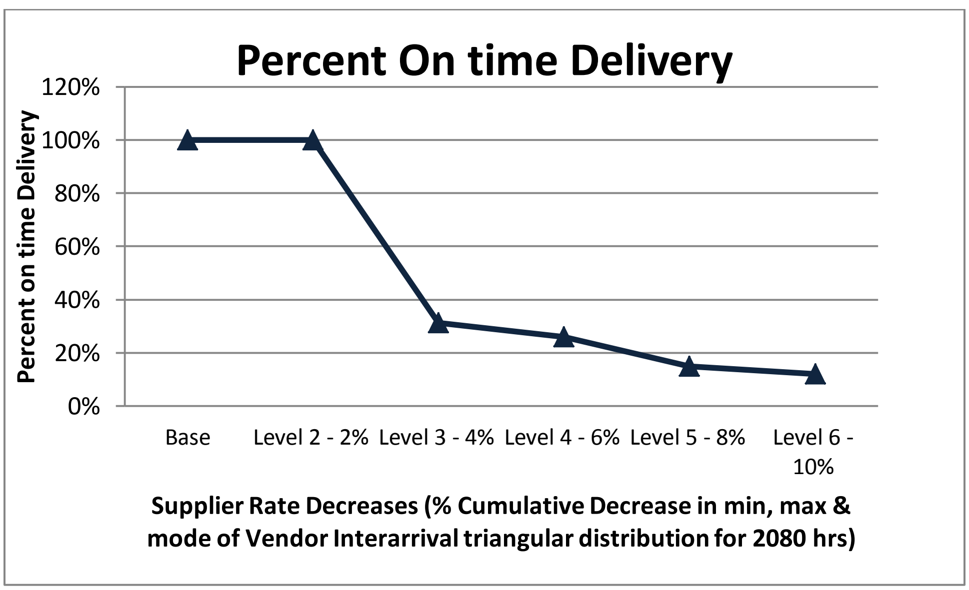


Figure 27 Plot of Percent On time Delivery for supply rate decreases influence

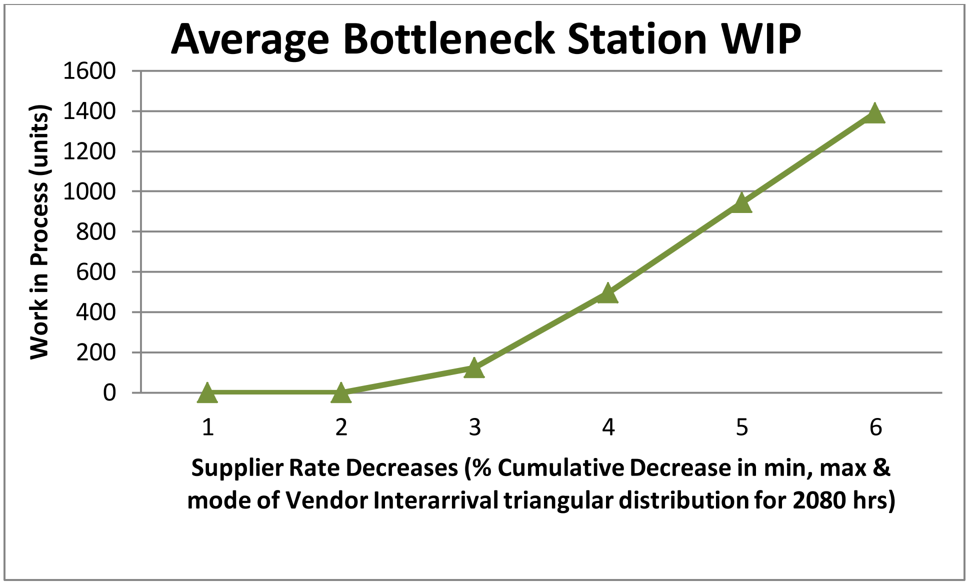


Figure 28 Plot of Bottleneck Station WIP for supply rate decreases influence

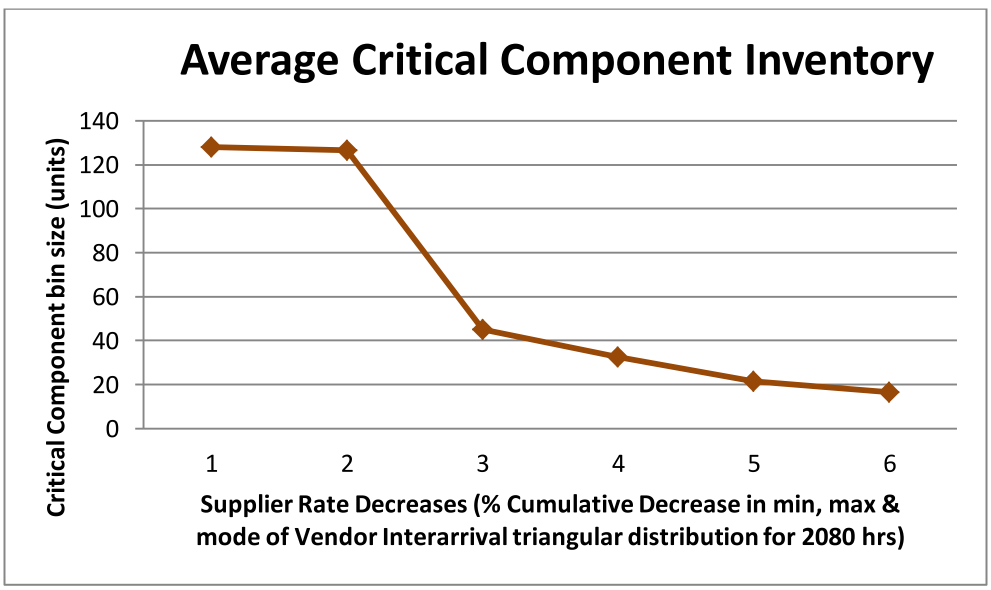


Figure 29 Plot of Critical Component Inventory for supply rate decreases influence

The Table 13 below shows a summary of paired t-test analysis comparing the base model result with each level result. The change in performance metrics from the base line scenario to the 2% level for bottleneck station WIP and Percent on time delivery is not statistically significant based on the results of t-tests. Also the standard deviation of the time-in-system performance metric increases to a higher value with each experiment level and this change indicates a higher level of disturbance in the time –in-system performance metric during the course of the simulation. Similar to the product customization influence, the standard deviation does not represent completely the characteristics of the response to the influence effects during the course of the simulation. Hence the performance metrics and the data collection methods are revised to show the response rate of the system with respect to the impact of the external influence effects.

Table 13 t- Test Results Summary for Diminished Supplies Influence

Performance Metric	Level 2 - 2%	Level 3 - 4%	Level 4 - 6%	Level 5 - 8%	Level 6 - 10%
Average Time in system	*	*	*	*	*
Standard deviation time in system	*	*	*	*	*
Percent on time delivery		*	*	*	*
Bottleneck Station WIP		*	*	*	*
Critical Component Inventory	*	*	*	*	*

The experiment levels for further study can still be selected from these results based on their statistical significance from the baseline scenario. The 2 % decrease in supply size does not show statistical significance across all the metrics. The next statistically significant level is the 4% level. From 6% to 8% levels, the metrics are linear and can be generalize with a slope. Also higher levels beyond 8% tend to show unacceptable increase from a practical perspective of in performance levels such as a 300 hour increase in average time-in-system metric for the 8% levels. The intermediary point is selected as the high level. Table 14 shows the low and high levels as well as the level change description for this influence.

Table 14 Diminished Supplies Influence Levels Selection

Influence Level Change Description	Low Level	High Level
Decreasing the percentage change in supplier lot size levels twice consecutively over a one year interval	4%	8%

Single Factor Analysis- Supplier Going Out of Business

The supplier going out of business is the extreme case scenario of diminishing supply where the supplier will not supply components after a certain point in the simulation. The experiment levels for this influence are varied from 0 hours of non-supply, which is the base model to 1500 hours of non-supply with a 250-hour increment between levels. A 250 hour period of no supply translates to about a month and half without a supplier. The experiment level is limited to 1500 hours no supply, because in a real world scenario, it is highly unlikely that an organization will wait for about 9 months to find an alternate supplier without any supply during the 9 months. Figures 30 to 34 are the plots of the resulting performance metrics average time-in-system, standard deviation of time-in-system, percent on time delivery, bottleneck station WIP, and critical component inventory respectively. The results plot for average time-in-system, standard deviation of time-in-system and bottleneck station WIP, show resilience to the effects of influence until 250 hours after which they show a more linear trend.

The percent on time delivery plot starts with a steep drop between the base and 750 hours of non-supply levels and stays relatively flat at near single digit percent on time delivery. This means the system is not able to maintain on time delivery of the production orders during the simulation time. The Table 15 below shows a summary of paired t-test analysis comparing the base model result with each level result. The performance metrics show a statistically significant change from the baseline scenario for all the experiment levels.

Table 15 t- Test Results Summary for Supplier Going Out of Business Influence

Performance Metric	Level 2 – 250 hrs	Level 3 – 500 hrs	Level 4 – 750 hrs	Level 5 – 1000 hrs	Level 6 – 1250 hrs	Level 7 – 1500 hrs
Average Time in system	*	*	*	*	*	*
Standard deviation time in system	*	*	*	*	*	*
Percent on time delivery	*	*	*	*	*	*
Bottleneck Station WIP	*	*	*	*	*	*
Critical Component Inventory	*	*	*	*	*	*

Like the results in the previous influences, the standard deviation of the time-in-system performance metric increases to a higher value with each experiment level and this change indicates a higher level of disturbance in the time –in-system performance metric during the course of the simulation. Similar to the previous influences, the standard deviation does not represent completely the characteristics of the response to the influence effects during the course of the simulation. Hence the performance metrics and the data collection methods are revised for this external influence too.

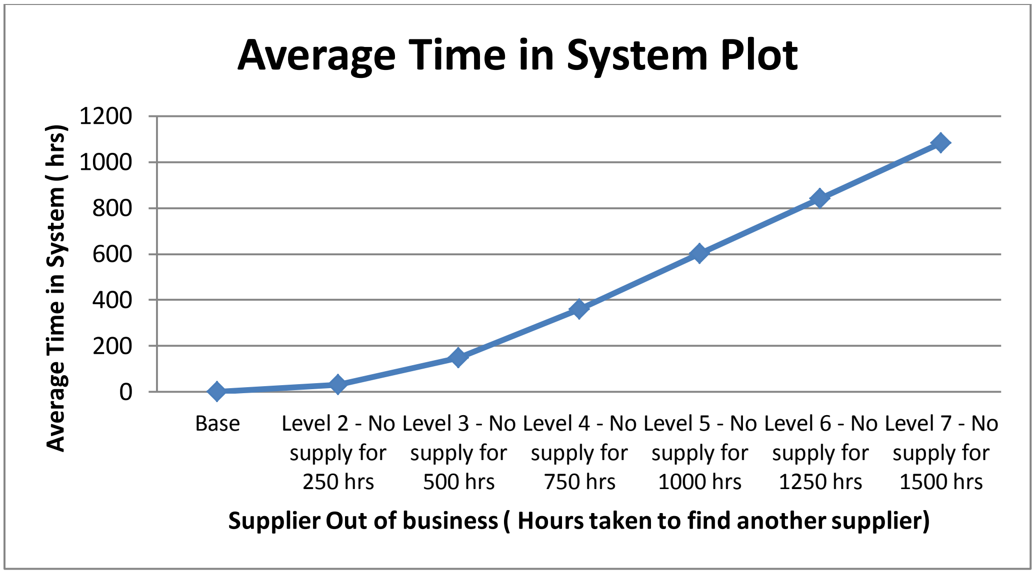


Figure 30 Plot of Average Time in System for Supplier Going out of Business Influence

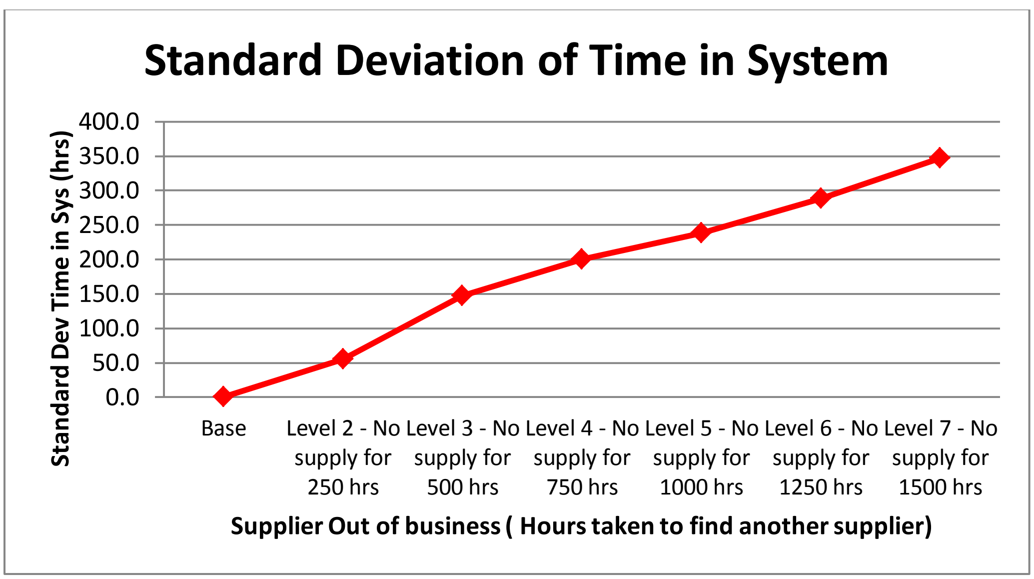


Figure 31 Plot of Standard Deviation of Time in System for Supplier Going Out of Business Influence

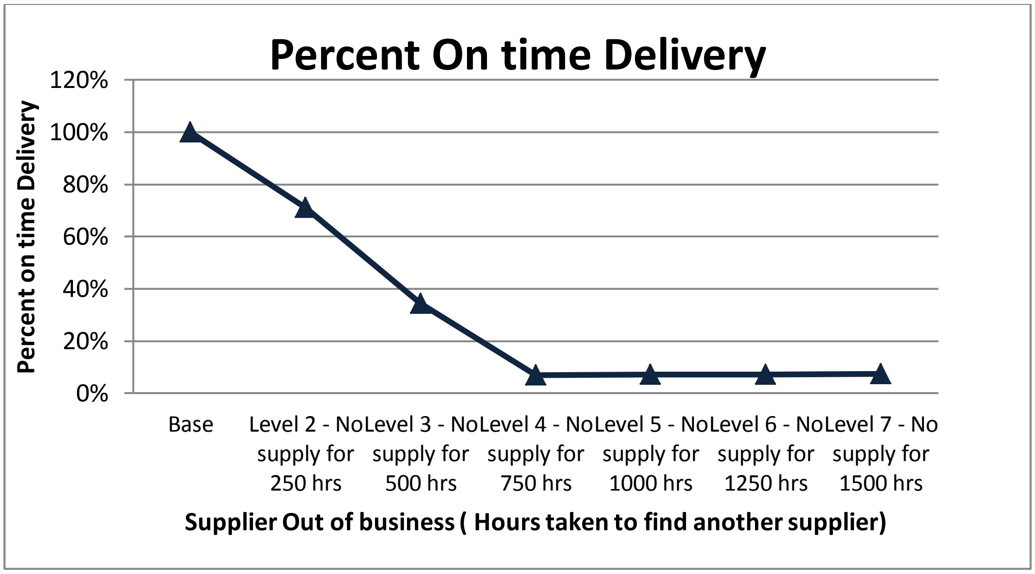


Figure 32 Plot of Percent On time Delivery for Supplier Going Out of Business Influence

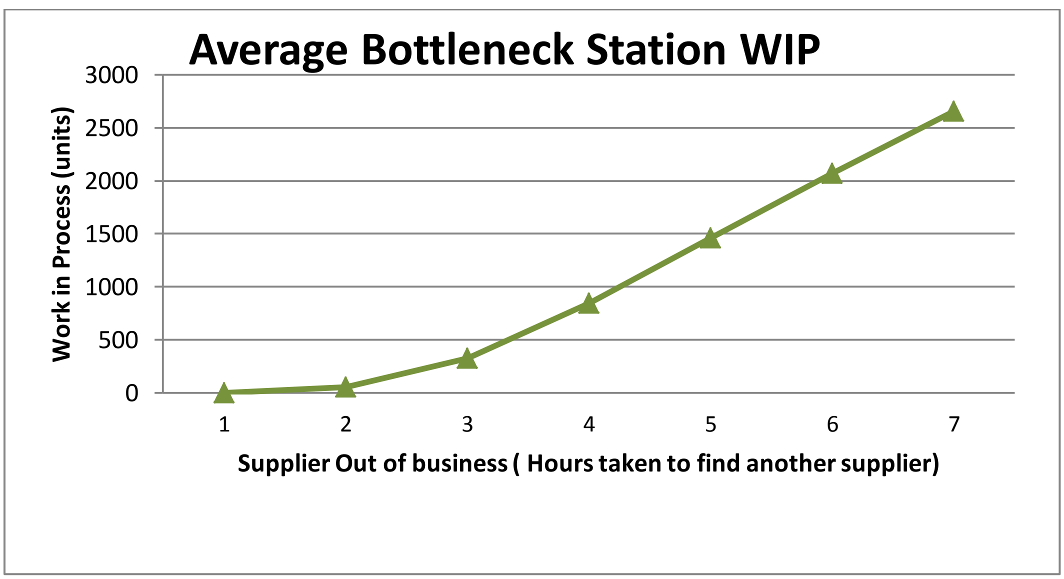


Figure 33 Plot of Throughput Rate for Supplier Supplier Going Out of Business Influence

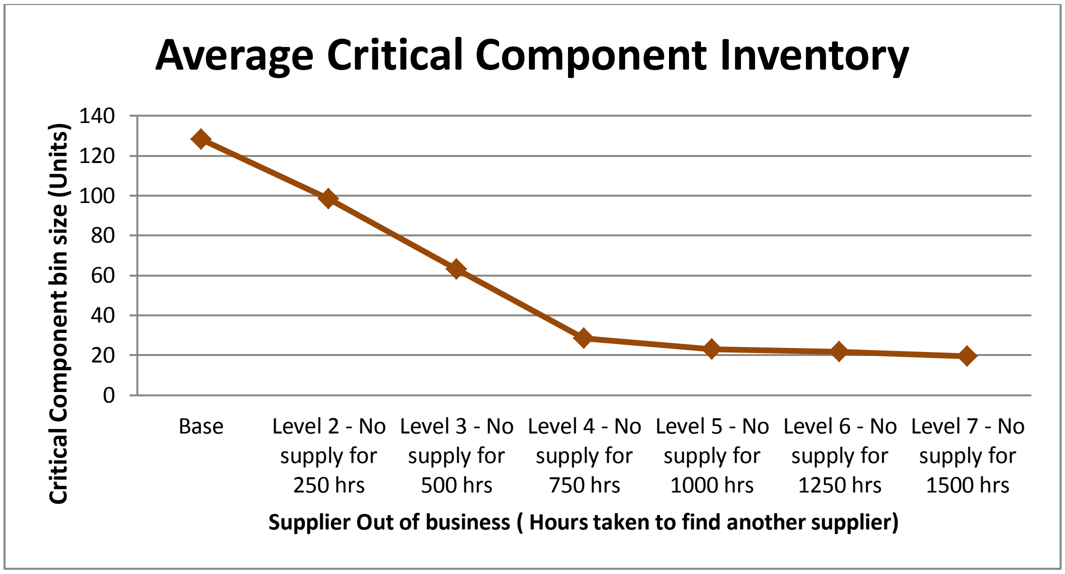


Figure 34 Plot of Bottleneck Resource Utilization for Supplier Going Out of Business Influence

In a practical scenario, an organization will not wait for more than 6 months to find a replacement supplier. The 6 months would be around 1000 hours in simulation time. Using the 1000 hours as the high level, an intermediary point is selected at the 500 hour level. The Table 16 provides a summary of the levels selected with a description for level change.

Table 16 Supplier Out of Business Influence Level Selection

Influence Level Change Description	**Low Level**	**High Level**
Supplier stops supplying at low and high levels	500 hours no supply	1000 hours no supply

Single Factor Analysis- Competitor Going Out of Business

The competitor going out of business influences are modeled by percent increase in the mode (most likely value in the triangular distribution) of the interarrival time distribution for orders with a percent change in the mode parameter and corresponding change in the minimum and maximum values so that the variance remains constant throughout the experiment. The variance is kept constant for each experiment level so that the influence effect is a shift in average effect instead of both a shift in average and variance between each level, which would be more complex to compare. The experiment levels are varied from a 0% decrease in mode of interarrival time distribution, to a 30% decrease as the highest level in 5% increments. A 30% decrease in order interarrival time corresponds to one of the three competitors for the case study organization being out of business. Hence the maximum experiment level was limited to 30% level. The order interarrival times for each level in increments of 5% decrease in order interarrival time is shown in Table 17 and is based on the data discussed earlier in Table 9 in section 3.6. The results plot (Figures 35 and 39) for average and standard deviation of time-in-system show a correleated linear increase with each level increment starting from the 5% level. Until 5% decrease in order interarrival time, the system attempts to be resilient and with levels beyond the 5% shows a linear increase. The plot of percent on time result shows the inverse trend of the time-in-system plots. The plot of bottleneck station WIP shows a marked increase in WIP from the 5% to 10% level and trends to a very slow increase for the remaining experiment levels. The bottleneck workstation in the case study organization is the testing station. With increase in orders entering the system, the WIP tend to accumulate at the two previous stations essentially starving the testing station. This effect explains the lack of marked change at the later levels. The critical component inventory results plotted in Figure 39 decreases with a linear trend for increasing experiment levels.

Table 17 Experiment level parameters for Competitor going out of Business Influence

	Order Inter-arrival Times (in hrs)			
% Decrease	**Min**	**Most likely**	**Max**	**Average**
0%	0.200	0.400	0.530	0.376
5%	0.180	0.380	0.510	0.356
10%	0.160	0.360	0.490	0.336
15%	0.14	0.340	0.470	0.316
20%	0.120	0.320	0.450	0.296
25%	0.100	0.300	0.43	0.276
30%	0.080	0.280	0.410	0.256

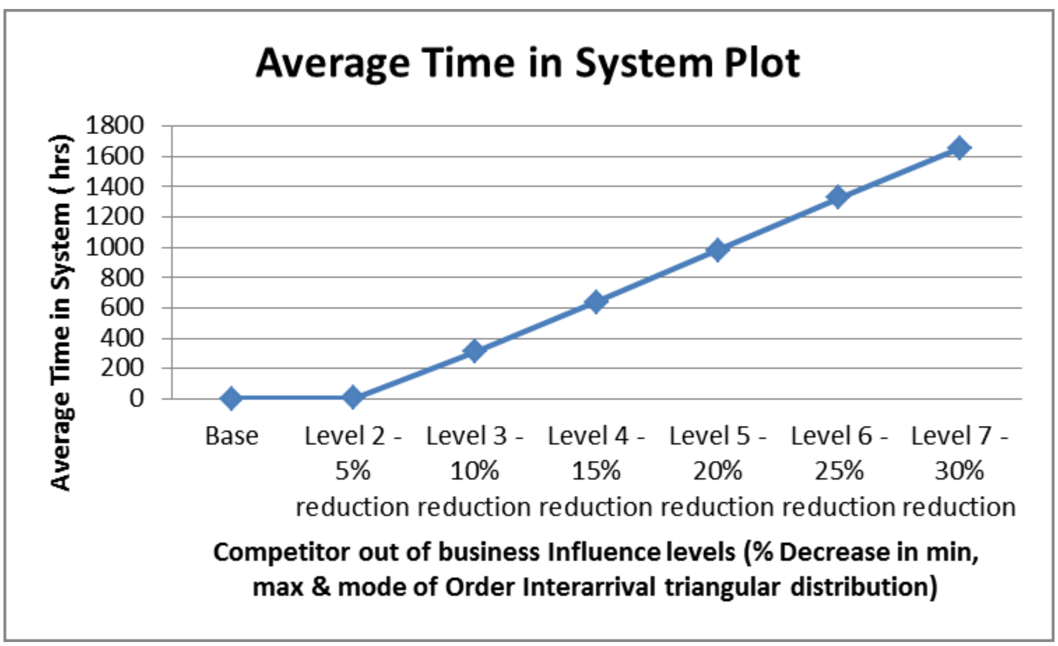


Figure 35 Plot of Average Time in System for Competitors Going Out of Business Influence

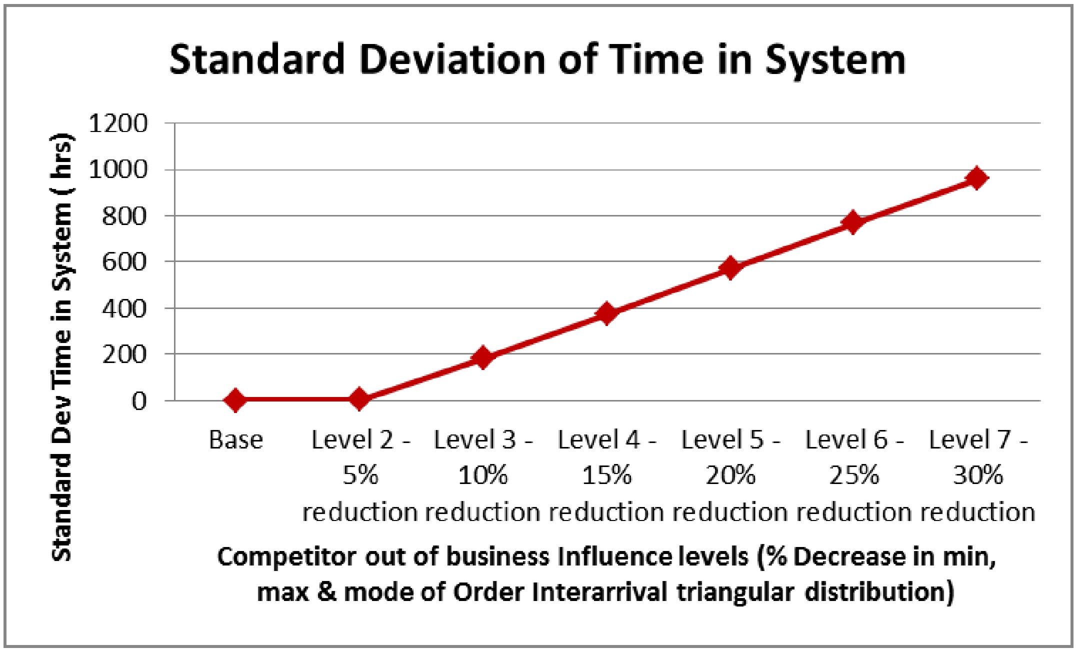


Figure 36 Plot of Standard Deviation of Time in System for Competitors Going Out of Business Influence

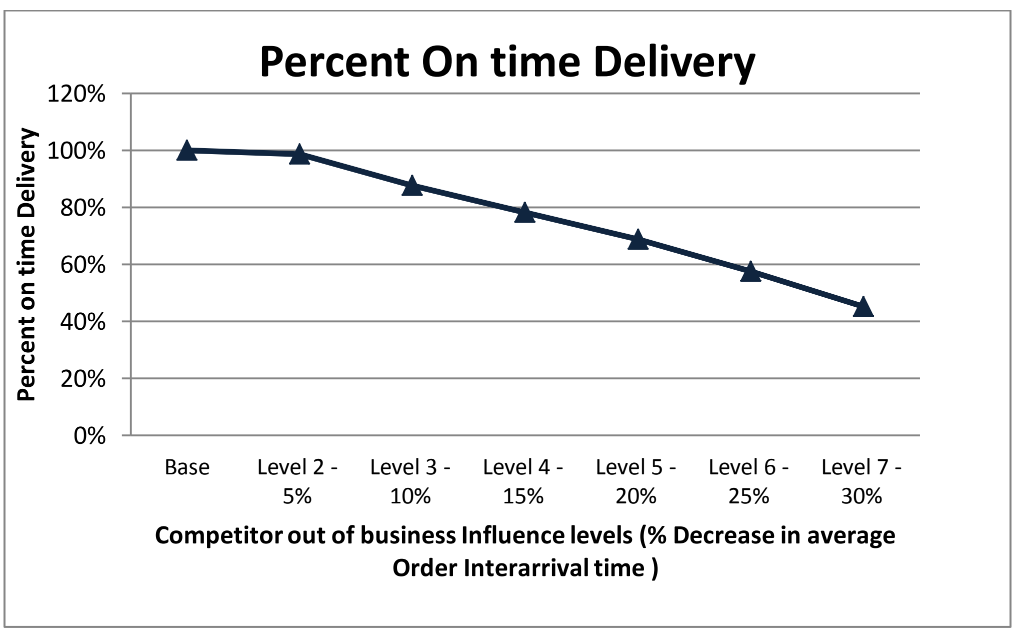


Figure 37 Plot of Percent On time Delivery for Competitors Going Out of Business Influence

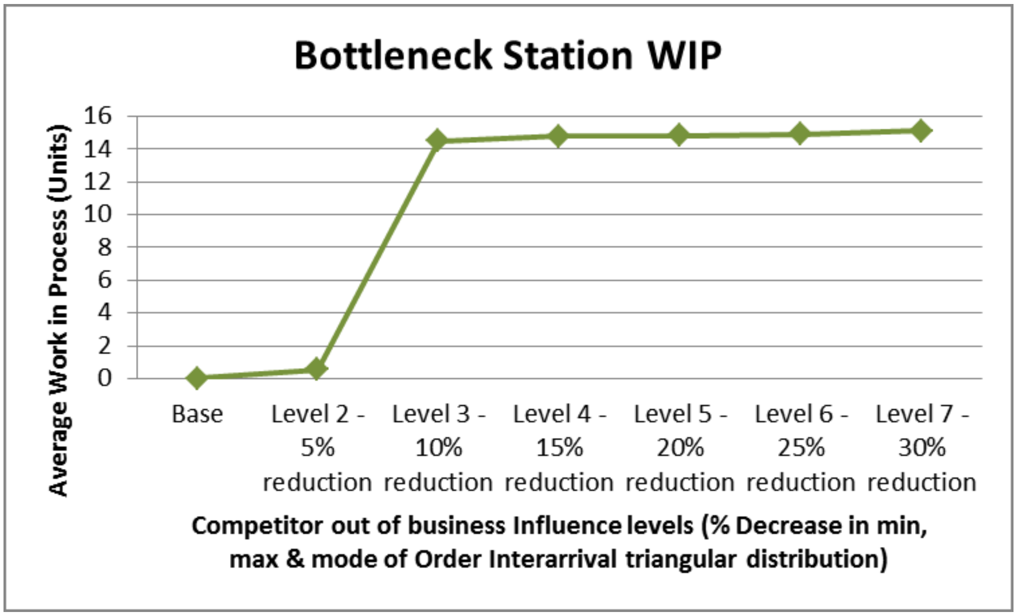


Figure 38 Plot of Bottleneck Resource Utilization for Competitors Going Out of Business Influence

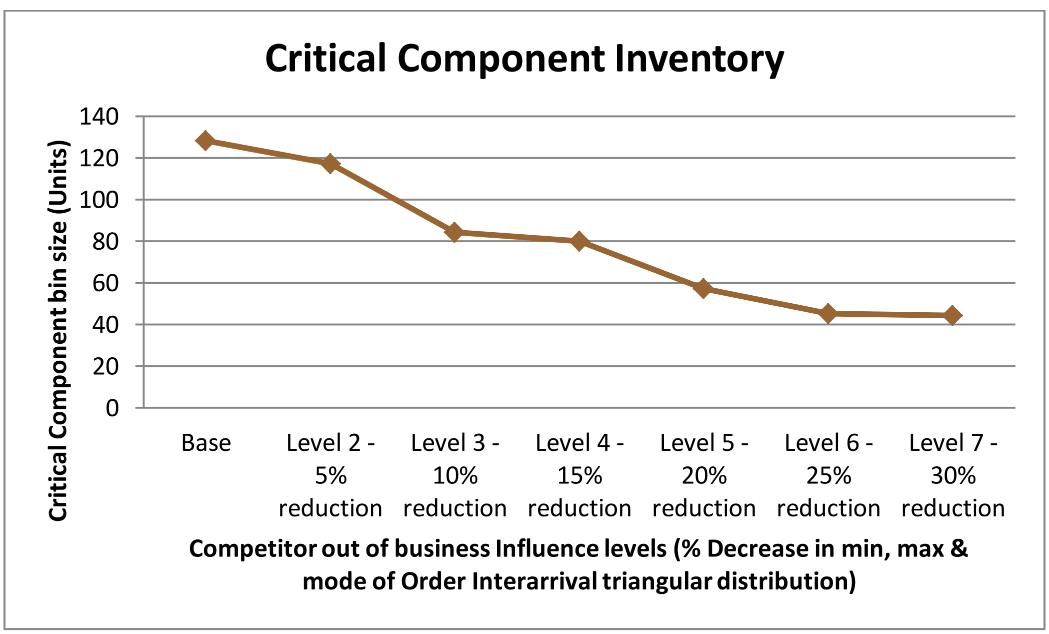


Figure 39 Plot of Percent On time Delivery for Competitors Going Out of Business Influence

The Table 18 below shows a summary of paired t-test analysis comparing the base model result with each level result. From the table, based on the time-in-system related performance metrics, the influence effect on the system for the 2% decrease in order interarrival time seems to be mitigated without any control action. Like the results in the previous influences, the standard deviation of the time-in-system performance metric increases to a higher value with each experiment level and this change indicates a higher level of disturbance in the time –in-system performance metric during the course of the simulation. Hence the performance metrics and the data collection methods are revised for this external influence.

Table 18 t- Test Results Summary for Competitor Competitors Going Out of Business Influence

Performance Metric	Level 2 - 5%	Level 3 - 10%	Level 4 - 15%	Level 5 - 20%	Level 6 - 25%	Level 7 - 30%
Average Time in system		*	*	*	*	*
Standard deviation time in system		*	*	*	*	*
Percent on time delivery		*	*	*	*	*
Bottleneck Station WIP	*	*	*	*	*	*
Critical Component Inventory	*	*	*	*	*	*

As discussed earlier, the case study organization is has three competitors in business and a loss in one competitor would results in a 25 % more increase in the frequency of customers placing orders on the system. Since the performance metrics except WIP tend to be linear after a 10% decrease in the interarrival times. The highest level considered is the 30% decrease in the order interarrival times. The intermediary level between 0 and 30% is considered as the low level for future experimentation. Table 19 shows a summary of the influence levels selected for experiments.

Table 19 Competitor Going Out of Business Influence Levels Selection

Influence Level Change Description	Low Level	High Level
Decrease the order inter arrival time	15%	30%

3.8.2 Preliminary Results Analysis.

The performance metrics selected for the preliminary experiments are based on statistical accumulator variables. Statistical accumulator variables collect information during the simulation such as total number of parts produced so far. These variables vary with simulation time. In the preliminary simulation experiments, the starting conditions for the simulation had very negligible impact on the time required to achieve steady state. However, with the application of the influence, the system exits from steady state and passes through a transient state where it tries to recover back to another steady state. The performance metric values obtained at the end of simulation is the cumulative average over the simulation time. These performance metrics do not represent the recovery from the transient state to another steady state period. The preliminary results were helpful to understand that the selected experiment level does impact the performance metrics statistically. This section discusses some of the drawbacks of using the existing performance metrics based on the preliminary results.

The time in system is the sum of the processing times as well as the queue times for each entity in the system. If the serial assembly system has "N" stations, then the time in system "TS_i" for an entity "i" is calculated as

$$TS_i = \sum_{j=1}^{N} (WQ_j + PT_j)$$

Where for the entity "i", WQ_j is the wait time at station "j" and PT_j is the processing time at station "j".

The "TS_i" is a statistical accumulator variable and the average of this variable over simulation time is the Average time-in-system performance metric used in the preliminary analysis.

$$\text{Average time in System} = \frac{\sum_{i=1}^{M}(TS_i)}{M} \quad \text{for each "}i\text{"}$$

Where for the entity "M" is the number of entities completed within a simulation time.

Figure 40 shows an example of a possible response plot of time in system (TS_i) for each entity exiting the system for the supplier out business external influence effect. Each point on the plot curve represents the time in system for an entity at the corresponding simulation time. The average of TS_i shown in the sample plot as a straight line does not show the system recovery characteristics. As the simulation time increases, the entire line corresponding to the average time in system will shift lower towards the base line when no external influence affects the system.

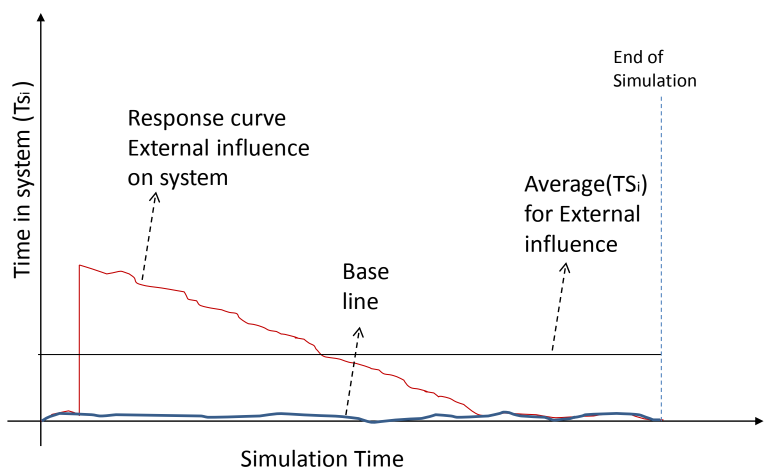


Figure 40 Example Plot for Entities Time-in-System Response

Customers define an acceptable lead time for the orders (time between order placement and receipt of the order) and if the time-in-system is greater than this standard lead time, then the order is defined as delayed. In the steady state simulation analysis, the percentage on time delivery is calculated as the number of orders that were delayed versus the total number of orders that exits the system. This performance metric in the current definition provides a lagging indicator of the system performance with respect to customer expectations and does not reflect the status of the current orders in the system at a given point in time. Hence, this performance metric is not used for the response rate analysis. The average work in process at the impacted stations and average impacted critical component inventory metrics also average across simulation time and does not reflect the response of the system to the influence effects.

3.8.3 Performance Metrics in Response Rate Analysis

As discussed in previous section, the performance metrics values estimated in the steady state analysis provides a snapshot of the system at the end of the simulation. At the end of the steady state simulation, the average values of the performance metrics may be skewed because it does not reflect if the system has recovered or in the process of recovery /not yet recovered. In addition, the standard deviation of the performance metrics in the output under the effect of external influences during the simulation period not only contains the variation of the normal base system but also the influence related variance. In order to address the research objectives better, the performance metrics and their definitions are redefined as follows.

Time in system for each entity:

The time in system is the sum of the processing times as well as the queue times for each entity in the system. If the serial assembly system has "N" stations, then the time in system T_i for an entity "i" is calculated as

$$TS_i = \sum_{j=1}^{N} (WQ_j + PT_j) \quad for\ each\ "i"$$

Where for the entity "i", WQ_j is the wait time at station "j" and PT_j is the processing time at station "j".

Work in Process at the impacted station(s)

An impacted station is defined as the station that is impacted by the external influences. The station impacted by the supplier related influence effects is the assembly station where the supply of component used at the station is affected. For response rate, the Work-in-Process is the number of orders waiting in the assembly process queue. This data collected for the Work in process will be the current number in the queue at the impacted station(s) and is collected every time an order exits the system.

Impacted Critical Component Inventory

Inventory size for the critical component related to the impacted station is collected for the response rate analysis. Since all the critical components are supplied at similar intervals and identical lot sizes, only one critical component is selected for the analysis. In addition, the supplier related influence affects impacts the PC board component. For the response rate analysis, the impacted critical component inventory data collected is the number in the inventory bin before picked by the order and is collected every time an order exits the system.

Data Collection and Variance Reduction

In the discrete event simulation, data is recorded for the three performance metrics when an entity exits the system. In order to reduce the hourly data points to daily data points, the performance metrics are averaged across 8-hour intervals. An 8-hour work schedule typically constitutes a regular manufacturing work shift. In order to separate the inherent variability of the performance metrics caused by the processing time distributions at various stations from the induced variability of the influence effects, four independent replications are run for each scenario. The last step in the data collection process is to smooth the plot by removing the short term variations and provide a long term trend of the performance metric. Some of the short term variations include the randomness of the inherent distributions used for generating the workstation processing times, order and supplier's interarrival times. Moving average method is used to smooth these short term variations and these are plotted to show the long-term trend for each performance metric. Each 8 hour average of the response data constitutes a day average of the performance metric. A 10-day average data point increment is used for the moving average plot.

3.8.4 Control Action Investment Metrics in Response Rate Analysis

A control action may require investment if it is to be implemented in a manufacturing system. This investment can be invested initially or over a period of time. The investment in control actions over a period is measured through a set of metrics collectively named "control action investment metrics". These investment metrics along with the other initial investments together would help a manager to decide the degree of mitigation required for each external influence effect. These metrics differ depending on the type of control action implemented. This study focuses on two control actions: Additional Supplier control action and Additional Resource control action.

In this study, additional supplier control action has one control action investment metric: Excess inventory measured across time using Arena process analyzer. Recall that the supplier enforces an annual usage contract where the supplier will deliver up to a maximum lot of 240 units per delivery and if the system has inventory unused at the end of the year, the remaining unused inventory will charged to the manufacturing organization. Hence, the excess inventory for each of the critical components is the control action investment metric to be estimated through simulation. Other one-time investments for the setting up the additional supplier include the tooling costs, engineering setup charge, procurement and material handling charge. The procurement and material handling charges are broken down to per component charge and added to the overall cost per unit component. In some cases, the initial tooling and engineering setup charges are small compared to cost of the component delivered, but it will be added as part of the investment costs in this study.

The second control action discussed in this study is the setting up of additional resources. The additional resources considered for this simulation study are the human resources. Recall from previous discussions that a floater resource is hired and utilized at any of the work stations. Unlike the existing workers at each station, this floater is being cross trained to be capable of assembling the product at any of the workstations. By increasing the number of floaters, the organization could mitigate the effects of an external influence such as competitor out of business. By increasing the cross trained workers, the capacity is split across the workstations instead of increasing capacity at individual work station by adding another dedicated resource. One potential control action investment metric is the utilization which could be used in measuring the capacity used by the floater. However, managers focus on increasing the utilization of a resource and lose sight of the other major performance metric. Also, because of the cross training of the floater resource, a considerable amount of time is spent in training. Hence, the control action investment costs include the salary for one or more floater resources, their training and other hiring costs.

There are two basic savings for all the control actions that mitigate the external influence effects: Additional opportunity costs and lost sales recovery costs. Additional opportunity costs reflect the increased sales due to the mitigation effect on the external influence by the control action. The lost sales recovery is cost recovered from the on-time delivery of orders to the customer which would have otherwise been late due to the external influence effects. In this study, the penalty for delayed delivery is cancellation of late orders from the customer. Recall that the case study organization is a startup with new products in the market. Delays in shipment sends speculation regarding product durability and customer cancel orders switching back to wired control of their applications instead of the wireless product manufactured by the organization. Since, there is a time line where these products must be sold before use because of shelf life of components such as batteries, cancelled orders results in a near complete loss of the product after manufacturing. The total net cash flow is the deduction of cash flow in from the cash flow out for each corresponding year.

In order to better relate to the manager regarding estimation of success or failure of a project, the net present value of the control action implementation cash flows is selected versus other discount cash flow methods such as Internal rate of return, and profitability index.. Using the investment metrics, and considering the control action investment as a mutually exclusive investment project in an organization, the net cash flows for each year (corresponding to 2000 hours of simulation time) is calculated. Net present value (NPV) is a popular discounted cash flow method applied by managers universally to evaluate the success/ failure of an investment because it assumes that the projected cash is reinvested at the company's required rate of return. Unlike any financial ratio or a return rate metric, the NPV calculates the projects value and in cases where there are more than one projects (like more than one control actions in this study), NPV could be added together. In scenario's where there are negative cash flows, other metrics such as the Internal Rate of Return might lead to more than one value. In such cases NPV provides a better estimate of the project's value over time. When an organization suffers a loss due to delayed orders from the effect of an external influence, the organization will have to declare a loss for the delayed orders. This study uses the recovery of this loss as the basis for using a cash flow analysis. Also the cash flow analysis captures the additional benefits of applying a control action such as ability to sell/ship more orders than the base line scenario after the external influence effect is mitigated. In order to tie in borrowing costs of the organization the discounted rate is applied and the present value of investment is estimated.

Discount rate used in NPV estimation is the rate of return earned on an investment if the investment was done in a financial market or another manufacturing project. If the organization has borrowed the control action investment, it would be the rate at which the funds were borrowed. For the purpose of this case study, the investment rate is selected as the LIBOR rate. LIBOR stands for London Interbank offered rate. This rate is the rate at which banks borrow unsecured loans from other banks in the London wholesale money market. The highest value for LIBOR rate in the last ten year period is 7.453% in May, 2000 (Source: www.bloomberg.com). The estimation of cash flows for additional supplier is shown below.

The following set of parameter definitions and calculations are used Consider the "*t*" to be time interval for which the cash flow is to be estimated. In this study, the cash flow is estimated at the end of every year. The control action investments cost metric for additional supplier control action is excess inventory for each critical component at the supplier location.

$EI_{cc}^{Base\ line}$ - The excess inventory count (which represents the inventory returned to the supplier by the system due to complete bin capacity) at the end of time period "*t*" for baseline scenario

$EI_{cc}^{Control\ action}$ - The excess inventory count at the end of time period "*t*" for control action application scenario

RC_{cc} – The unit cost for each critical component.

APC_{cc} – The annual procurement costs for each critical component for the time "*t*".

TDC_{cc} – The tooling and die costs for each critical component for the time "*t*".

PE_{cc} – The production engineering costs incurred by the supplier for each critical component for the time "*t*".

PC– The unit cost for each competed product.

HW– The Hourly Wage for cross trained worker (floater resources).

r – Number of floater used for the additional Resource Control Action

h – Number of working hours in time period "*t*" (h = 2000 hours in this study)

k – Discount rate (based on the LIBOR market rate) for the time period "*t*"

C– The customer penalty component for delayed orders. If a customer rejects the delayed orders completely then the value of C will be 100%.

NT_{CA} – Number on time after applying the Control Action for the time "*t*".

TC – One time training costs for one floater resource (r =1).

HC – Hiring Costs related to one floater resource

NT_{BL} – Number on time in Base Line scenario for the time "*t*".

ND_{EI} – Number not shipped on time (delayed orders) during the External Influence for the time "*t*".

ND_{CA} – Number not shipped on time during the Control Action application for the time "*t*".

TCO_t^{SCA} – Total Cash flow Out for additional Supplier Control Action.

TCO_t^{RCA} – Total Cash flow Out for additional Resource Control Action.

In this study, there was no delayed orders in base line, hence the NOT_{BL} is the same as total number completed by the system in time "*t*".

<u>Cash Flow Out Estimation</u>

If the additional supplier control action is applied to one critical component only, where "*cc*"=1, then the Total Cash flow Out (TCO_t^{SCA}) for the time period "calculated as

$$TCO_t^{SCA} = [(EI_1^{Control\ action} - EI_1^{Base\ line}) * RC_1 + APC_1 + TDC_1 + PE_1]$$

If the control action is applied to "*n*" critical components, then

$$TCO_t^{SCA} = [\sum_{cc=1}^{n}(EI_{cc}^{Control\ action} - EI_{cc}^{Base\ line}) * RC_{cc} + APC_{cc} + TDC_{cc} + PE_{cc}]$$

The Total cash flow for additional Resource Control Action (TCO_t^{RCA}) for the time period "*t*" is estimated as follows

$$TCO_t^{RCA} = (HW * h + HC + TC)$$

Cash Flow In Estimation

The Total Cash flow In is calculated through two components: the Additional Opportunity Costs (AOC) and Lost Sales Recovered (LSR).

The Additional Opportunity Costs (AOC) is calculated as

$$AOC = [(NT_{CA} - NT_{BL}) * PC$$

The Lost Sales Recovered (LSR) is calculated as

$$LSR = [(ND_{EI} - ND_{CA}) * C$$

The Total Cash flow In for the time period "t", TCI_t, is the sum of AOC and LSR.

The net present value is estimated as follows.

$$NPV = \sum_{t=0}^{n} \frac{[TCI_t - \sum_{t=0}^{n}(TCO_t^{RCA} + TCO_t^{SCA})]}{(1+k)^t}$$

Where "n" number of cash flow periods.

The variables $EI_{cc}^{Base\ line}$, $EI_{cc}^{Control\ Action}$, NT_{CA}, NT_{BL}, ND_{EI} and ND_{CA} are collected at the end of each time period "t" for "n" periods using ARENA Process Analyzer.

3.9 Experimental Design for Response Analysis

The experimental matrix for the response analysis is a nested design consisting of two sets. Each set represents an experiment level of the external influences. In order to mitigate each level of the external influence effects, one or more control actions are applied. These control actions may consist of several controllable factors of applicability. For example, in this case study, the competitor out of business influence effect may require additional supplier as well as additional resource to mitigate the influence effect. The additional supplier may contain several controllable factors such as lot size, delivery interval etc. The additional resource control action may have one or more controllable factors such as number of resources, scheduling methods of the resources etc. Each set (level) of external influence consists of applying all the factors corresponding to both the control actions, finding the significant factors and their interactions using regression analysis. An optimal setting for the control actions is found by minimizing the response variables (performance metrics). Based on the solution from optimization, the control action investment costs are obtained mitigating the effects of that particular level of external influence. A generic experimental design is shown in Figure 41.

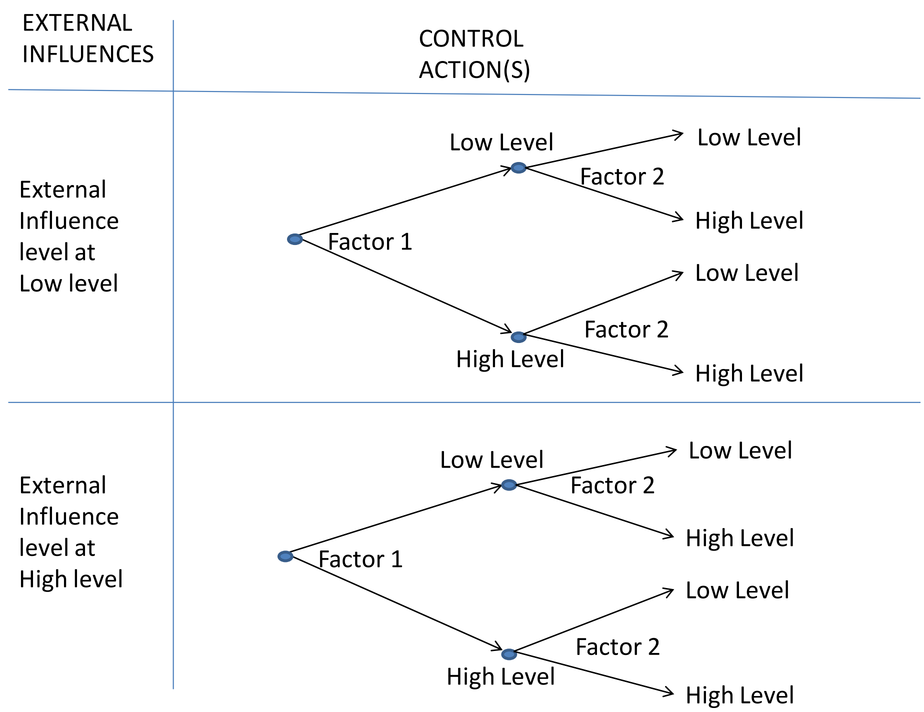


Figure 41 Generalized Experimental Design for Response Analysis.

The preliminary experiments show that the external influences can be modeled in a simulation model and for each increment in parameter change; the average of the performance metrics at the end of each simulation time is statistically significant from the base line performance metrics. Selection of the experiment levels for external influence was discussed in the preliminary results section 3.8.1. The Table 20 provides a summary of a 2-level experimental design setup for influence effects.

For each influence level of the external influence, the experiments are run for 20,000 hours of simulations and the response plots are plotted for the three selected performance metrics (Time-in-system, Bottleneck Workstation WIP and Impacted critical component inventory). Based on the results from this experiment run, a potential "meta" performance metric such as slope, peak value of the metric etc.is selected based on the shape of the response curves. The potential control actions shown in Table 20 are applied to mitigate the effects of the corresponding levels of external influences. Based on the responses and practical limits set by real world scenarios, two levels of control actions are selected and an experimental design is setup for the two varying levels of control action application on the system for each level of external influence.

Table 20 Experimental Design for Application of Control Actions on the External Influences

		Influence Experiment Levels		**Potential Control Actions for each influence level**	
External Influence	**Description of level change**	**Low Level**	**High Level**	**Low Level**	**High Level**
Supplier out of Business	No supply for a certain period	500 hours	1000 hours	Additional Supplier	Additional Supplier
Diminished Supplies over time	Two consecutive level reductions in supply lot size by the % level over a one year interval	4%	8%	Additional Supplier	Additional Supplier
Competitor out of Business	Increase in order interarrival time by a percentage	15%	30%	Additional Supplier & Resource	Additional Supplier & Resource
Product Customization	Proportion of custom orders vs. standard orders in the system	30%	50%	Additional Resource	Additional Resource

For this experiment setup the data for control action investment metrics for the corresponding control action is also collected and the net present value is calculated as discussed in section 3.8.4

of this study. The net present value (NPV) is calculated for the 10 year period (20,000 hours of simulation time) for each level. Each control action will have one or more controlling factors. Based on the previous discussions, the controllable factors selected for the additional supplier control action are supplier lot size and supplier delivery interarrival time and for the additional control resource control action the factor is number of floater resources.

The experimental design analysis will yield prediction functions for the statistically significant factors and their interactions of the control action(s) for the NPV and the "meta" performance metric selected from the response plots. The two prediction functions are optimized by minimizing the "meta" performance metric and maximizing the NPV. The constraints are for the optimizations are discussed for each analysis in the further sections. The final results will provide the significant control actions; control action factors and the optimized setting for each factor that will help mitigate the corresponding level of external influence.

CHAPTER IV

ANALYSIS AND INTERPRETATION OF RESULTS

This chapter presents the results of the investigation into the impact of each external influence individually and the experimental design results of the application of control action(s) in mitigating the effects of each external influence. The chapter is divided into four major sections: 1) Analysis of external influences, 2) Summary of external influences results, 3) Application of control actions 4) Analysis and results with respect to research objectives. The first section discusses the results of each external influence effects on the manufacturing system. The analysis in this section helps to address the first research question and also to define the experiment levels for the next set of analysis involving the application of control actions. The second section is discusses the identification of controllable factors for one or more control actions, application of the factors in an experimental design and discuss the results of the analysis with respect to the managerial aspects of the study. The chapter concludes with a summary of the application of control actions with respect to addressing the research objectives of this study.

4.1 Analysis for External Influence Effects

4.1.1 Results Analysis for Supplier Going Out of Business Influence Effect

In this study, the supplier going out of business influence effect stops the supply of one of the critical component to the system. As recalled in earlier discussions about the supply of the PC board component used in the assembly of the product to the second workstation is stopped for 500 or 1000 hours at the beginning of the simulation after a warm-up period of 80 hours. The supply is resumed after 500 or 1000 hours since it is highly likely that a manufacturing system will replace the supplier with another supplier. The response plots are plotted with the simulation time on the x-Axis and the Day Average value of the performance metric on the y-axis. Recalling the definition of day average in section 3.8.3, a day average is a 10 day moving average of performance metrics across simulation time. A moving average plot reduces the short term (day to day) variations and provides a long term trend (Law and Kelton, 2000) which helps to understand of the response characteristics better. The simulation results of the three performance metrics which estimate the impact of no supply for the two periods. The performance metrics for both periods of non-supply recover back to the base line scenario. Figure 42 provides a moving average plot of the time in system through the simulation time of 20,000 hours.

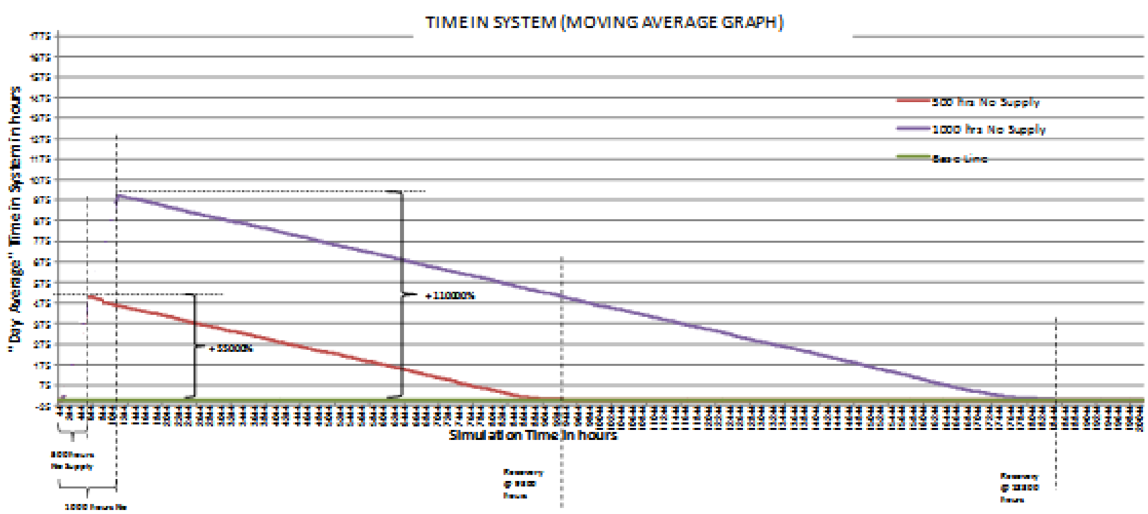


Figure 42 Time in System (Moving Average) Plot for Supplier Out of Business Influence Effect

The time in system plots show a linear recovery for both of the no supply scenarios. Table 21 shows a summary of the time in system performance metric. The slopes of the response plots for both the curves are similar. The ratio of recovery time and the maximum value between two levels is 2:1 approximately and this corresponds to the ratio of the two no supply durations. The rate of recovery in both levels (500 and 1000 hours no supply) depend on two parameters. The first parameter is the remaining capacity utilization at the workstations, primarily, the impacted station, which is the assembly work station that is starved from the PC board component. Since the influence effect directly impacts this station, it becomes the primary bottleneck station. In the base line scenario, the utilization of the assembly workstation is 68.5%. When supply resumes, the remaining 31.5% along with the remaining utilizations percentages for the preceding stations determine the recovery rate. Once the assembly workstation starts to recover, the next bottleneck station will be the testing station and the rate of recovery in the final stages depends on the testing station capacity.

Table 21 Time in System Analysis Summary for Supplier Out of Business Influence Effect

Performance Metric	**Influence Levels (hrs.)**	**Maximum Value**	**Recovery Time**	**Recovery Slope** (Time in System/Simulation Period)
Time in System	500	496.9 hrs	8800 hrs	0.0565
	1000	993.8 hrs	17300 hrs	0.0574

The second parameter is the resumed supply size and interval. The work in process at the impacted station (assembly station) shows a series of minor WIP bubbles. A WIP bubble is defined as a higher number of WIP than the baseline in a processing station queue. In a plot of WIP at certain simulation time intervals, a WIP bubble is identified by the gradual increase and decrease in the number of orders in queue before a processing station. An example of two large WIP bubbles is marked in the Figure 43.

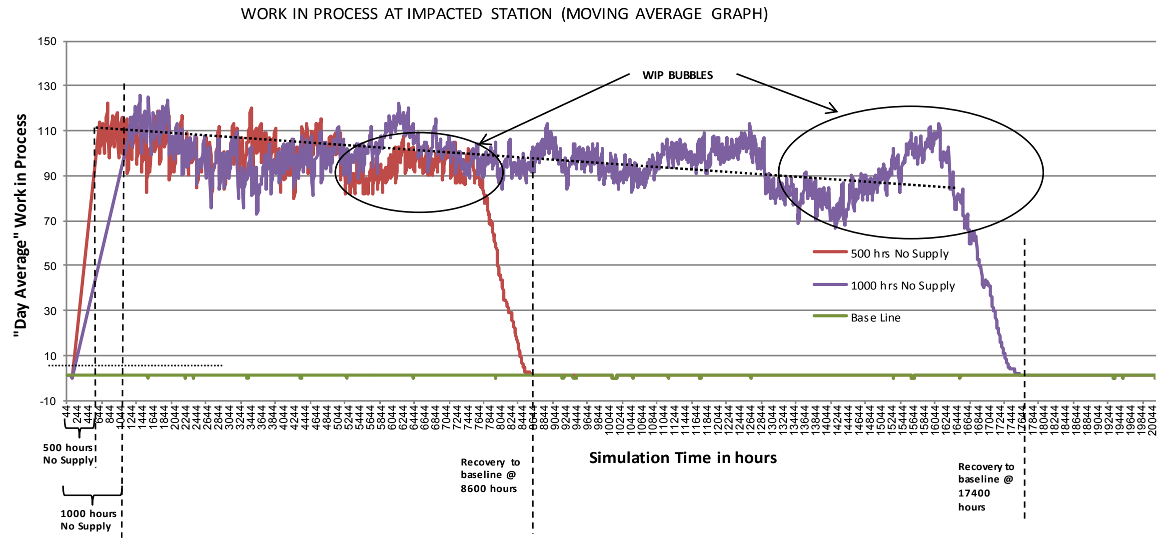


Figure 43 WIP (Moving Average) Plot for Supplier Out of Business Influence Effect

The WIP increases to about 110 units in both cases and shows a gradual recovery trend with minor WIP bubbles. For both the 500 hours as well as the 1000 hours of non-supply, the decreasing slope at the end of a final large WIP bubble starts a steeper recovery trend back to normal. In addition, the overall trend (indicated by the dotted line in the Figure 43) points to the slow recovery phase until the final sharp recovery slope. Since the two levels uses the same random number streams for generation of orders and processing times, the plots show comparable WIP bubbles between the two levels. Table 22 provides a summary of the plot. Similar to the time-in-system, the ratio of recovery time and the maximum value between two levels is 2:1 approximately and this corresponds to the ratio of the two no-supply hours.

Table 22 Bottleneck Station WIP Analysis of the Supplier Out of Business External Influence Effect.

Performance Metric	**Influence Levels (hrs.)**	**Average Maximum Value**	**Recovery Time**	**Recovery Slope** (Metric/Simulation Period)
Bottleneck Station WIP	500	110	8100 hrs	Varied
	1000	110	16400 hrs	

The critical component inventory (PC Board component supplied to the second workstation) shows three phases in Figure 44. The first phase is a trend that has high variance in inventory consumption, but the average trend follows a straight line parallel to the base line except the inventory level is closer to zero. The second phase is the gradual recovery slope back to the base line inventory level where the excess inventory starts to build gradually. In the third phase, the WIP in the bottleneck station start to decline sharply corresponding to the sharp recovery in inventory levels back to the base scenario.

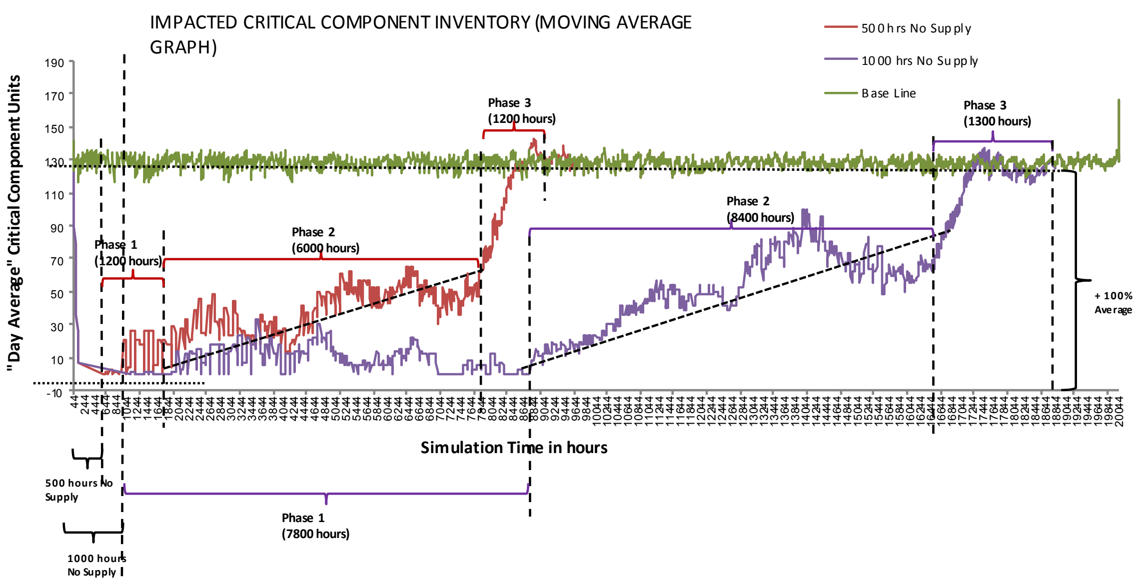


Figure 44 Critical Component Inventory (Moving Average) Plot for Supplier Out of Business Influence Effect

In the 500-hour no supply scenario, the Time in system, work in process, and inventory response plots show recovery back to baseline scenario at about 9000 hours. With 500 hours of no supply and at an order entry rate of 2.7 units / hour, the system would have required approximately 1350 units of inventory in stock in order to maintain the base line scenario. But the system starts with an inventory of 240 units for each component and hence requires about 1100 units. The average supply rate is 2.82 units per hour which is 0.12 unit / hour greater than the average order entry rate. With the recovery at about 9000 hours for all three metrics, the excess inventory used to recover is approximately 1080 hours. In the 1000-hour no supply scenario, the recovery time for the system to reach baseline scenario is could be determined from the excess inventory rate of 0.12 unit/hour. This lag in recovery is due to the queue in the bottleneck station. Table 23 provides a summary of the different recovery phases for both the 500-hour as well as the 1000-hour non-supply scenarios. The table shows that the last recovery phase is very similar for both scenarios. The ratios of recovery time and the maximum value between two levels is 6.5:1 for recovery in phase 1, 5:4 in phase 2 and 13:12 in phase 3 approximately.

Table 23 Inventory Analysis Summary for Supplier Out of Business Influence Effect

Performance Metric	**Influence Ends (hrs.)**	**Recovery Time for Phase I**	**Recovery Time for Phase 2**	**Recovery Time for Phase 3**
Critical Component Inventory	500	1200	6000	1200
	1000	7800	8400	1300

Comparing the results of the three performance metrics for 500 hours of no supply, the complete recovery back to the base line performance metric values occurs between 8400 and 9300 hours after the start of the influence. For the 1000 hours of no supply, the complete recovery occurs between 17400 and 18300 hours after the start of influence. The time-in-system is the lagging recovery performance indicator compared to the other two performance metrics and has simple response curve characteristics that could be easily related across the two levels of the external influence. Even though the critical component inventory level shows a complete recovery back to baseline models after an extended period of time, from a manager's perspective the recovery in phase 1 for both levels with inventory values above zero is the desired level. Any excess inventory impacts the manufacturing system's overall financial bottom line.

4.1.2 Results Analysis for Diminished Supplies over Time Influence Effect

The diminished supplies over time influence reduces the supply lot size of the critical components in two consecutive stages. The first decrease in supply lot size occurs from start of simulation (after warm up period) until 2080 hours and the second decrease occurs after 2080 hours and will remain in effect until the end of simulation. The two selected levels plotted in Figure 45 are 4% and 8% decreases in supplies. For both levels, the system resists the effect of the external influence for certain period (about 2600 hours and 500 hours for 4% decrease and 8% decrease levels respectively). The time-in-system response plot for 4% decrease shows a linear increase after the resilient phase of about 2600 hours and has a positive slope of 0.104 average hour time in system per simulation hour increase. The response for this level suggests that for less than two consecutive decreases in supply lot size, the effect is a simple linear response. However the response plot for 8% decrease level has two phases of response after the resilient phase. In the first phase, between 500 and 2100 hours of simulation time, the system follows a positive slope of 0.03 average hour time-in-system/ simulation hour increment and in the second phase the slope increases to 0.019 average hour time in system per simulation hour increase. This two phase increase in slope in the 8% decrease level corresponds to the two consecutive decreases in the supply lot size within a 2000 hour interval. Based on the analysis of the response plots for time-in-system for the two levels, it could be concluded that for lower levels of diminished supply influences, the response will be linear with a single after the resilient phase. It could also be concluded that the impact a single 4% decrease in supply lot size to the system does not impact the system.

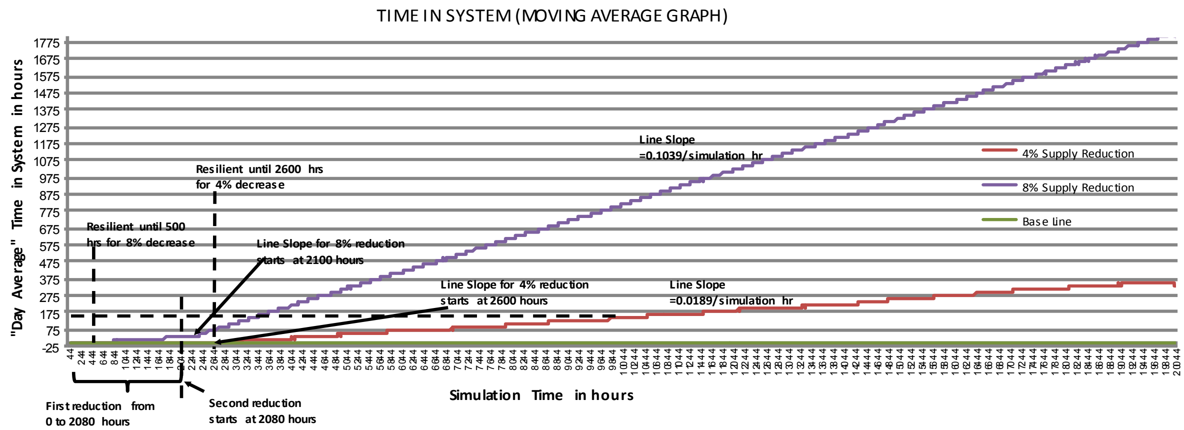


Figure 45 Time in System (Moving Average) plot for Diminished Supplies over Time Influence Effect.

The work in process moving average for 4% decrease and 8% decrease in supply lot size levels show similar trends with three phases as shown in Figure 46. The first phase is the resilient phase where the WIP levels correspond to the baseline values for a certain period (2700 hours in case of 4 % cumulative decrease and 500 hours in case of 8% cumulative decrease). Beyond the resilient phase, the WIP levels rises with a positive slope of 0.3 units/ simulation hour and 0.6units/simulation hour for 4% decrease and 8 % decrease levels respectively. The rate of increase in WIP for the 8% decrease level is twice the rate of increase for the 4% decrease level. The last phase, which is a flat line trend after the positive slope increase, includes the work in process levels to remain higher than the base levels with averages (100% and 89%) above base line for 4% and 8% cumulative lot size decrease. Although it is anticipated that the WIP average in the third phase for 8% level would be higher than 4% level, the results indicate an 11% difference between the two levels from the base line. The WIP metric is defined as the number in queue at the second workstation (assembly workstation) recorded at every time an order exits the system. In the simulation model, before every station a kitting logic is in place where an order processed from previous station is held until at least one of each component are available in the respective component bins. With higher cumulative percentage decrease in supplier lot sizes, the number in component bins are at near empty levels for considerable amount of time, triggering the bill of materials logic which holds the orders in a separate queue instead of the workstation queue. Recalling from earlier modeling discussion, an order is not released in to a workstation until the bill of materials logic verifies that all the components are available. The effect of this logic causes a decrease in average WIP levels recorded at the station.

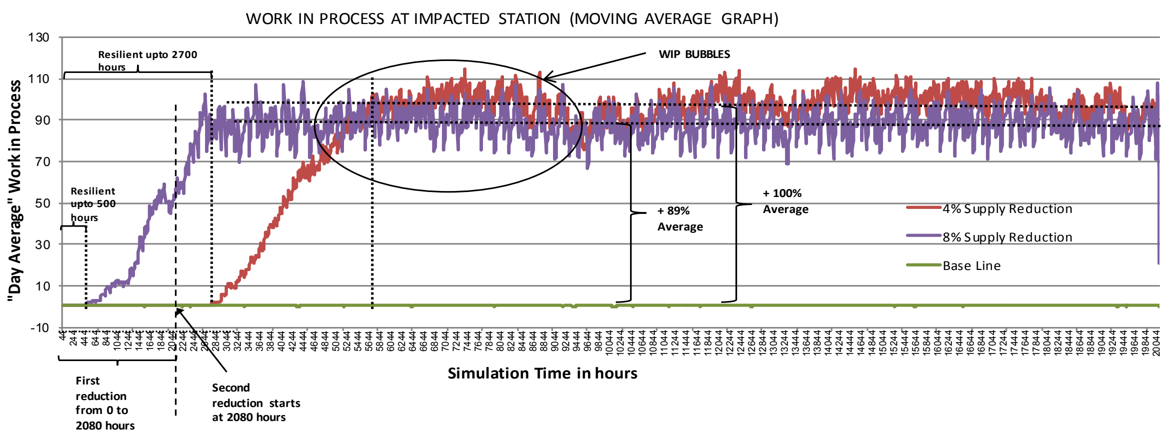


Figure 46 Bottleneck station WIP (Moving Average) Plot for Diminished Supplies over Time Influence Effect.

Figure 47 shows the critical component bin inventory size for the base line, 4% and 8% cumulative lot size reductions. The inventory response plot for 4% cumulative supply reduction shows a resilience phase of about 2400 hours before the bin levels start to decrease to zero. The 8% supply reduction response plot shows a similar trend as the previous experiment level without the resilience phase. The two experiment levels provide a manager the ability to gauge the response time required to initiate a control action to mitigate the effect of the diminishing supplies external influence after the start of the influence.

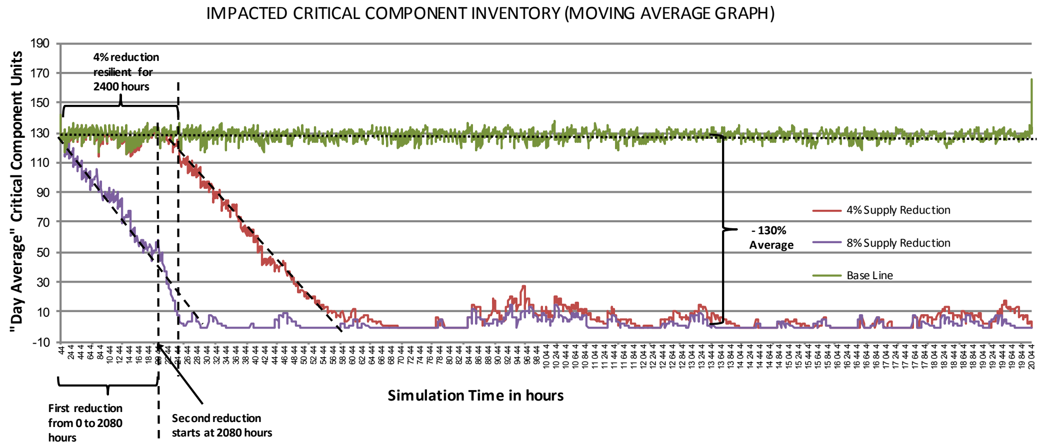


Figure 47 Critical Component Inventory (Moving Average) plot for Diminished Supplies over Time Influence Effect.

4.1.3 Results analysis for Competitor Out of Business Influence Effect

The competitor out of business influence effect impacts a system by a sudden surge in demand. With more customers placing orders into the manufacturing system, the interarrival time between each customer decreases. Each customer places an order of size one. The experimental levels are varied by changing the interarrival time parameters of the order interarrival time distribution in the simulation. Two selected experiment levels are used for this influence: 15% and 30% decrease in interarrival times. Figure 48 shows the response plot for the moving average time in system. The response plots are linear with a positive slope of 0.107 and 0.276 hour/simulation time respectively for the 15% and 30% decrease in inter arrival times. The ratio of the slopes for 30% decrease over 15% decrease in order interarrival times is 2.6:1. Similar to the supplier out of business influence effect, the rate of recovery depends on two system parameters: remaining capacity from the base line and the supply lot size. Compared to the baseline, the remaining capacity of the resources and the inventory left in the system bin is utilized for completing the surge in orders. However, as the orders increase the excess capacity and inventory is used immediately leading to the positive slope.

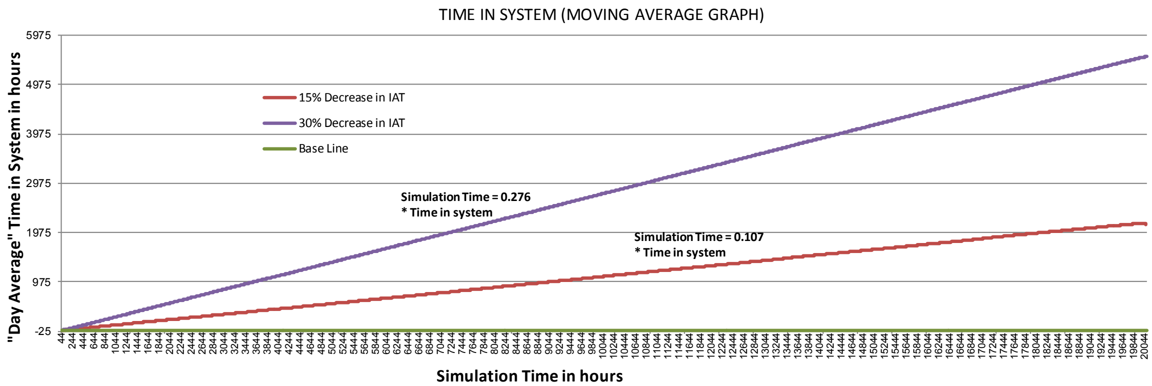


Figure 48 Time in System (Moving Average) plot for Competitor out of business Influence Effect.

Figure 49 shows the moving average WIP response plots for the two experiment levels apart from the base line. The response plot for the 15% decrease in inter arrival time shows an increasing trend followed by a recovery trend. The peak point on the plot where the recovery trend starts cannot be objectively defined and the recovery duration extends beyond the simulation period. The response plot for the 30% decrease in inter arrival time also follows a positive slope trend as the 15% level except the trend continues to increase over simulation time and the trend line falls below the 15% trend line. With higher number of orders entering the system due to the decrease in inters arrival time; the accumulation of higher WIP at first station affects the number in queue in the following stations.

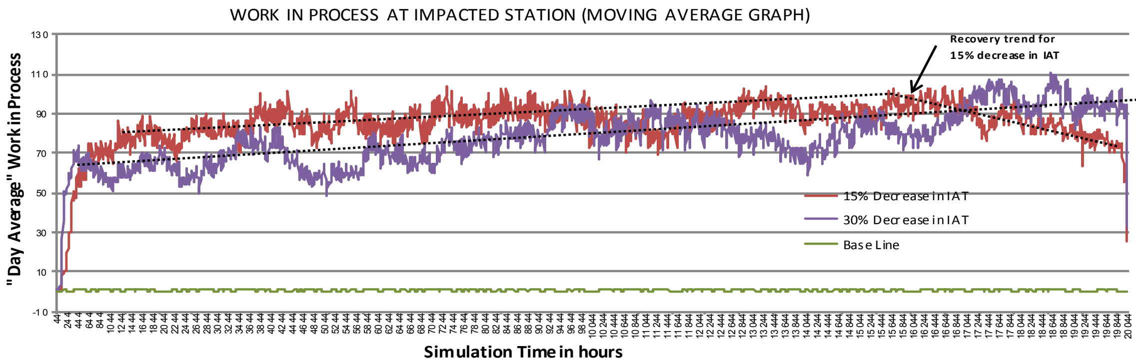


Figure 49 Bottleneck Station WIP (Moving Average) plot for Competitor out of business Influence Effect

Figure 50 shows the moving average response plots for the two levels of decrease in inter arrival time along with the base line. Both levels exhibit similar trends up until 8000 hours of simulation time after which the 15% decrease in inter arrival time exhibits a series of saw tooth phenomenon of inventory supply and deplete cycle. The 30% decrease in inter arrival time shows a flat trend in inventory levels hovering between 90 and 120 units after 8000 hours before finally depleting to lower levels. Due to high number of orders in the system, the orders wait for the critical components bin to be filled. When available, the orders are grouped with the critical components and enter the workstation queue. Again due to capacity constraints, the order gets delayed as WIP in the queue. The critical component inventory does not drop to zero at any point in time because of the capacity constraint. The WIP bubbles in Figure 49 and the corresponding inventory usage response plot in Figure 50 explains this phenomenon graphically.

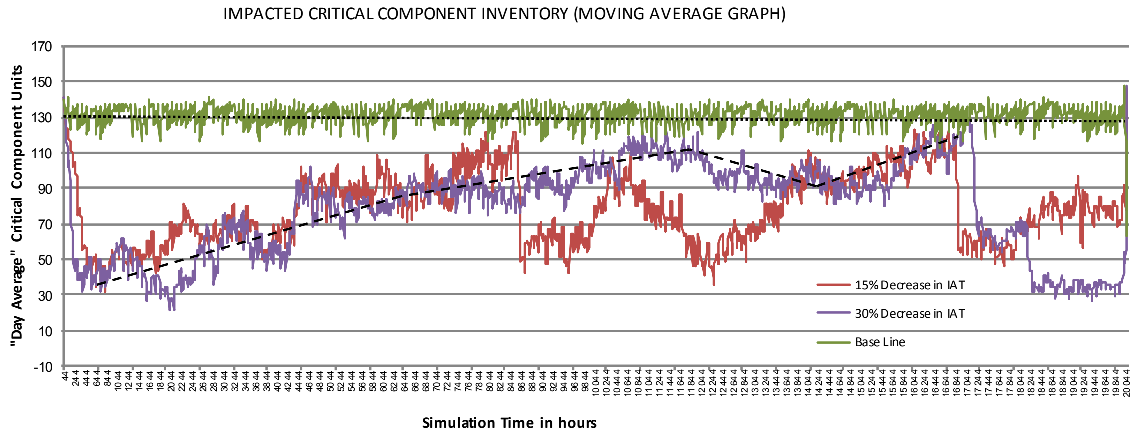


Figure 50 Critical Component Inventory (Moving Average) plot for Competitor out of business Influence Effect

4.1.4 Results Analysis for Product Customization Influence Effect

The product customization influence effect involves introducing a certain percentage of custom products along with the standard products. The custom products have 25 % higher labor hours than the standard products. Apart from the higher labor hours, a set uptime of 0.90 hour is applied at every workstation, whenever the product type switches to another. The experiment levels for this influence effect involve two levels: 30% and 60% of customized products. The Figure 51 shows the moving average time in system response plots. The response plots for both the experiment levels show a linear positive slope. The slope of the time-in-system for the 30% and 60% customization levels are 0.44 and 0.51 hour per simulation hour increment respectively. With each switch from a standard product type to custom product type (and vice versa), the workstation adds a setup time of 0.9 hours along with its regular processing times. As the proportion (experiment level), the number of switches from one product type to the other also increases, resulting in a higher waiting time for the products.

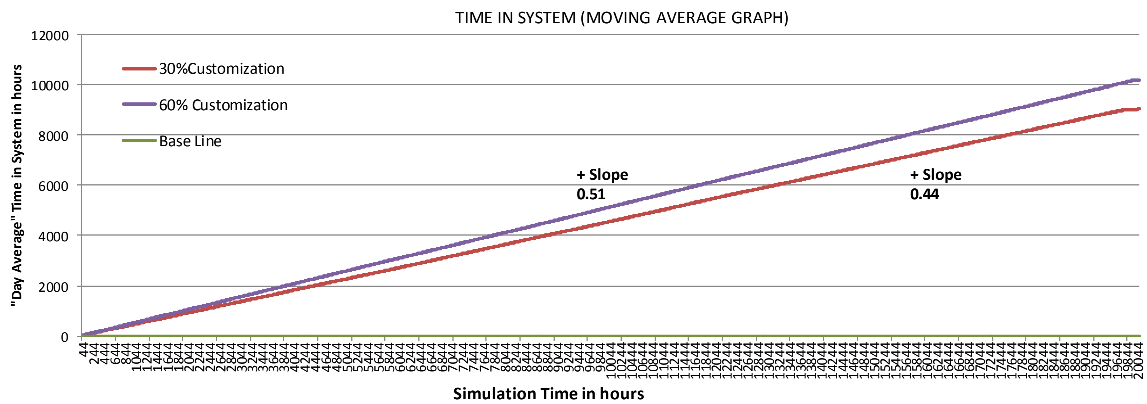


Figure 51 Time in System (Moving Average) Plot for Product Customization Influence Effect.

The bottleneck station WIP shown in Figure 52 follows the same trends as the time-in-system response plots for both experiment levels. The ratio of slope change between 30% custom products in the system vs. 60 % custom products entering the system is about 0.85 for both the time-in-system response as well as the bottleneck station WIP.

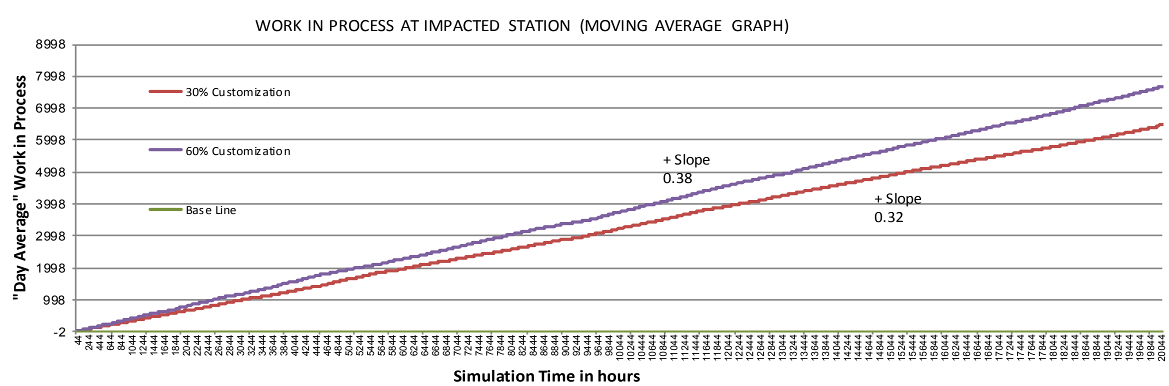


Figure 52 Bottleneck WIP (Moving Average) Plot for Product Customization Influence Effect.

The critical component usage drops as the levels increase, due to the increase in WIP in the system from the response plots in Figure 53. Since the custom products differ from the standard products by a change in processing times, there is no constraint on the supplier.

However, due to processing time increase and the frequency of use in setup time with level increase, the response plots show a shift in only the average (shown as dotted trend line in Figure 52) from the base line plot.

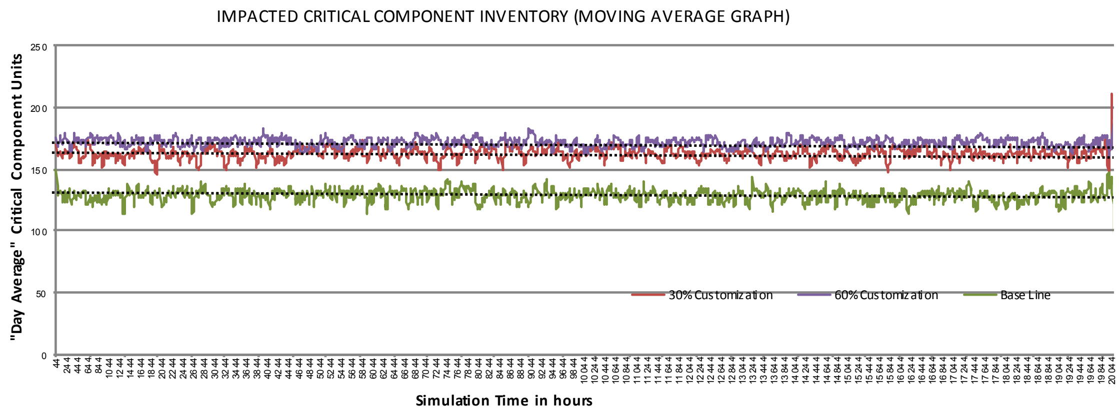


Figure 53 Critical Component Inventory (Moving Average) Plot for Product Customization Influence Effect.

4.1.5 Summary of External Influence Effect Analysis

The response characteristics of the time-in-system could help a manager in making managerial decisions regarding the application of control actions that could help to mitigate the effect of external influences. The influences related to the supplier (supplier out of business and diminished supplies over time) offer the manager time to react to the onset of the influence effects and this phase where the system resists to deviate from the baseline performance metric is called as the resilient phase. A resilient phase is important if a manager is reactive in applying a control action to mitigate the effects of the influences. This study focuses on the application of control actions proactively to mitigate the influence effects. The impact of the raw material inventory reduction or no supply on a system depends on the safety stock in the system, and the consumption rate dictated by the manufacturing systems capacity. Also, a manager has to decide on the application length of a control action. A control action can be applied short-term to mitigate the occurrence of one instance of an external influence effects. A high probability of multiple occurrences of the same external influence over time might force a manager to look for a long-term control action. Earlier in the study, a customer lead time parameter was introduced which is the maximum acceptable lead time for a customer. This customer lead time is used to measure the number of orders that were shipped over a certain period (simulation time). Hence before implementing a control action, a manager should consider based on the results of the external influence effects should consider the minimum reaction time required to initiate a control action, the acceptable level of performance metrics required to satisfy a customer, and the application time length of control actions (short term vs. long term).

The time in system performance metric provides a standard measure that could be used to compare the system recovery rate across different influence effects. For the remaining performance metrics such as work in process and critical component inventory, it was assumed in the study that the metrics corresponding to bottlenecks stations will provide a better representation of the system. However, the bottleneck station changes depending on the type of influence effect. In case of the external influence effects related to the supplier, the bottleneck station is the second station (assembly station) linked to the impacted critical component. In case of the competitors going out of business, the bottleneck station is the station with the highest processing time which is the testing station. Recall that the testing station does not have any critical components and hence the critical component supplied to the previous station was considered as s representation for the analysis. These drawbacks show that the time-in-system performance metric to be considered as the only manufacturing system response metric for the rest of this study.

The time-in-system performance metric considered is a response plotted over simulation time. In order to describe the response curve quantitatively, two “meta” performance metrics are defined. These meta-performance metrics help to signal whether the influence can recover individually without control action and to quantify the degree to which a control action if applied would mitigate the influence effects. The first meta -performance is the "Influence Risk Slope" noted by the symbol β.

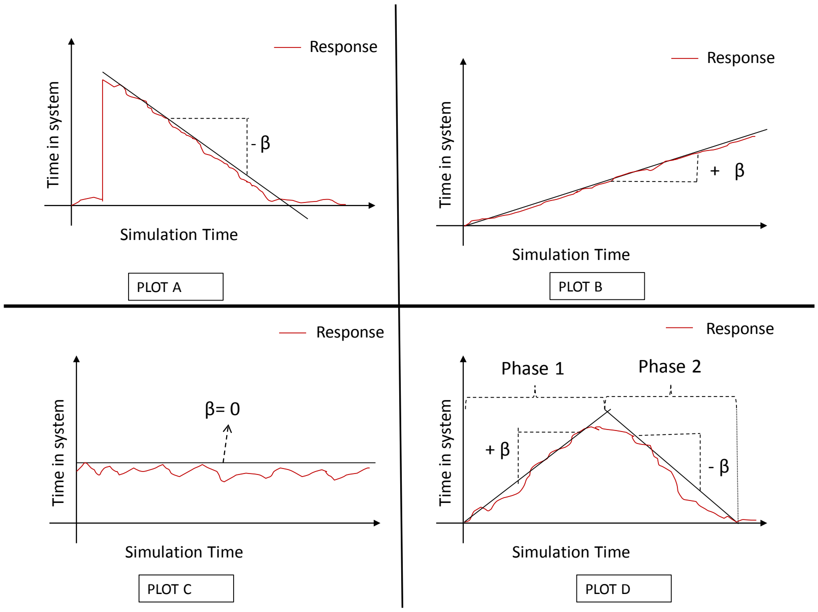


Figure 54 Illustrations for Different "Beta" Slopes

The Quad plot in Figure 54 shows four different scenarios for the value β. When responses are linear, β is calculated as the slope of two points on the line. However, in cases where the variability is more pronounced such as Plot C and Plot D, β is calculated more as a long-term trend. The case study plots for individual influences did not show a time in system response plot that fits the profile of the response plot shown in Plot D of Figure 54. However, the responses of other performance metrics have shown a similar profile. An example for such as plot would be bottleneck station WIP metric under the supplier out of business influence effects. In this type of plot (Plot D), there are two slopes a positive slope that signals an influence risk followed by a negative slope although the recovery point (peak time in system value has shifted considerably from the start time of influence. Based on the results from the influence effects, such recovery of performance metrics occurs when the influence effect recedes and the system returns to base line scenario. A peak value of the time in system metric is defined as the highest value recorded for the response throughout the simulation period. If the slope is monotonically positive, then the system does not recover. If the slope of the response curve is zero or positive, there is no recovery over the simulation period and a negative slope means there is a recovery. For a control action to be effective, the slope must be negative. A reference point used along with the slope on the response line corresponds to the location of the peak value of time in system.

Based on the results for each individual influence shown in the response, the methodology for estimating the influence risk slope is estimated as follows.

Influence Risk Slope of the response line, $\beta = \frac{(y_1 - y_2)}{(x_1 - x_2)}$

The points (x_1, y_1) and (x_2, y_2) vary sometimes depending on the type of the influence. Hence, the following list provides the positions of the two points for each external influence considered in this study.

The time-in-system response output for supplier out of business influence effect corresponds to the plot A in Figure 54, and the points (x_1, y_1) and (x_2, y_2) are defined as follows.

x_1 $- Simulation\ \ time\ at\ peak\ value\ of\ the\ time\ in\ system\ response$

y_1 $- Peak\ value\ of\ time\ in\ system\ response$

x_2 $- Simulation\ time\ at\ which\ recovery\ occurs$

y_2 $- Time\ in\ system\ value\ at\ which\ recovery\ occurs$

The time-in-system response output for competitor out of business influence diminished supplies over time influence, and product customization influence effects corresponds to the plot B in Figure 54, and the points (x_1, y_1) and (x_2, y_2) are defined as follows.

x_1 $- Time\ at\ the\ start\ of\ the\ external\ influence$

y_1 $- Value\ of\ time\ in\ system\ response\ at\ influence\ start$

x_2 $-$ $End\ of\ simulation\ time$

y_2 $-$ $Peak\ value\ of\ time\ in\ system\ at\ the\ end\ of\ simulation$

The simulation time at which recovery of a response curve back to base line occurs is determined graphically and verified by moving average method. The response plots provide an approximate range of simulation time at which the recovery occurs. Moving average values of time-in system metric with an interval corresponding to 320 hours of simulation is obtained starting at this range. The 320 hours corresponds to about eight work weeks with 40 hour per week of the system operating. Based on the response plots of time in systems in this case study, the system reaches back to steady state without disturbance in less than 320 hours. The recovery point occurs when the moving average value drops to or below the average time in system value of the base line scenario. The simulation time corresponding to the time-in-system value at which the recovery occurs is selected. Figure 55 shows an example of determining recovery point. For illustration purposes an interval of 5 values instead is used instead of 320 values. In the example, the moving average for the values of "y" starting from point (x_{18}, y_{18})until point (x_{22}, y_{22}) has a value below the baseline average value. The point $(x_{18}, y_{18})$is considered as a recovered point.

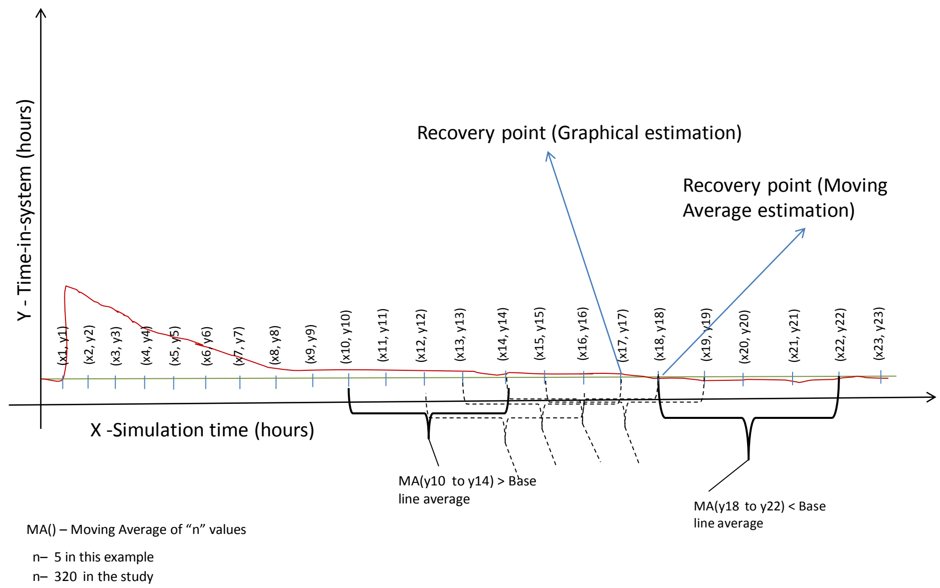


Figure 55 Illustration of Recovery point determination

For the supplier out of business influence effect, the peak value occurs a few hours after the influence ends and the time in system starts to recover towards baseline levels. In case of all the diminished supplies over time and customer out of business influence effects, the time in system response continues to increase with a positive slope over simulation period and the peak time in system value will be the time at the end of the simulation. In case of the product customization external influence, the slope is zero and the average of time in system value for the influence has shifted parallel to the base line levels. In summary, the response plots for each individual external influence effects help a manager to determine if the system can recover from the influence effect without control actions.

4.2 Application of Control Actions

The controls actions are applied to the manufacturing system to mitigate/exploit the effects of the external influences. This section discusses the results for two control actions selected in this study are adding another supplier and adding additional resource along with the external influence effects that are mitigated/exploited by them. This section is organized into three parts that addresses the research questions: Adding additional supplier, adding additional resource and adding both additional supplier and resource simultaneously. Each part starts with a discussion of the selection of control action factors, continues with the selection of the experimental levels for each control action, analyzing the design of experiments to obtain prediction equations for each response variables, optimizing the time-in-system and net present value prediction equations for appropriate control action factors to find the best levels of control action application(s) to mitigate/exploit a particulate level of external influence effect.

4.2.1 Additional Supplier Control Action

An additional supplier control action is applied where a manager brings in one or more suppliers along with the existing supplier base. The supply lot size and the delivery frequency depend on the type of contract established with the new suppliers by the manager. These suppliers are enlisted for either short-term or for the long term. It would make more practical sense to add additional suppliers for critical components. Critical components are defined in this study as products that have custom specifications and usually available through one vendor. One of the issues faced by the organization is the size of the organization compared to its suppliers which tilts the negotiating balance of power in the favor of the suppliers. The suppliers because of the custom nature of the components attempt to hedge the risk of carrying high inventory enters into a contract with the manufacturer. Based on this contract, the new suppliers will supply up to a maximum fixed lot size at a certain frequency and the manufacturer will buy back the remaining inventory at the end of each year. The additional supplier control action can be applied to three of the four external influences mentioned in this study: Supplier out of business external influence, Diminished supplies over time and Competitor out of business. The additional supplier control action can be applied by having one or more suppliers, increasing the supply lot size of the critical components and/or by decreasing the interarrival time between each supply lots. For the purpose of this research, the addition of one supplier is considered for this control action because a supplier with adequate capacity will be able to mitigate the effects of external influences. The new supplier will be capable of matching the supply criteria in terms of volume and supply frequency. The preliminary results of external influences effects considered in this study indicate that it is possible to mitigate the effects of the external influences with one additional supplier with a lot size of no greater than that of the existing supplier (240 units/delivery). In addition, with the organization fitting the profile of a small to medium scale manufacturer having fewer resources, the components being unique custom designed and the probability of excess left over inventory to be bought back year-end at more than one supplier locations is high. For each external influence, the control action is applied through the factors supply lot size and interarrival times using a design of experiments matrix. The statistically significant factors and their interactions are determined through the analysis of variance method and a prediction equation is determined for the peak time-in-system response variable. The peak time in system (y_{PTIS}) value is defined as the maximum value of the time in system value(TS_i) for any entity "i". If 'n' represents the last entity at the end of simulation then the peak value of the time in system (y_{PTIS}) is the maximum value of the time in system response over the range of i= 1 to n and is expressed mathematically as follows.

$$y_{PTIS} = Max_{\,i=1\ to\ n}(TS_i)$$

In order for the influence to be fully mitigated, the peak time-in-system value must fall below the customer required lead time. Recall earlier in the study, we defined customer required lead time as the acceptable time-in-system value agreed with the customer. An optimal setting for the two control action factors (supply lot size and Supply Interarrival time) is found based on the response variable peak time-in-system and net present values by solving the prediction equations. In order for a manager to justify the cost benefit of applying additional supplier control action in mitigating/exploiting an external influence effect, a control action investment metric component inventory size is considered in the analysis. Excess inventory is defined as the total amount of unused component inventory at the end of the simulation period. In any supplier/customer, relationship there exists a balance of power concerning purchasing contract negotiations. For a small startup manufacturer such as the case study organization, the balance of negotiating power shifts to supplier where the supplier dictates terms such as delivery lot size, delivery interval, and demand per year. This excess inventory is considered to evaluate the net present value of the investment.

One factor analysis is conducted by keeping the factor levels for the external influence under consideration constant and varying the control action factors delivery lot size and supplier interarrival time individually. The one-factor analysis levels considered for the control action factor delivery lot size are 240, 120, 60, 30 and 15 units. The maximum lot size supplied by the existing supplier is 240 units and the lot size is reduced by half for each experiment level. The one-factor analysis levels considered for the control action factor supplier interarrival delivery time is in Table 24. Apart from the average being reduced at each level the variance is also reduced. It is a more practical assumption that as the average supply delivery interval is reduced the variance will also be reduced proportionally. The level 2 in Table 24 is the supplier interarrival time for the existing supplier during the base line scenario. The level above is double the average value of the supplier interarrival time and the spread is also increased by two. The level below is half the value of the supplier interrival time and spread is reduced by half.

Table 24 Supplier Interarrival Time Levels for the Additional Supplier Control Action

Levels	Triangular distribution parameters for Supplier Interarrival time (Hours)			Average Supplier order Interarrival Time (Hours)	Variance of Supplier order Interarrival Time
	Minimum	Mode	Maximum		
1	160	170	180	170	16.67
2	80	85	90	85	4.17
3	40	42.5	45	42.5	1.04

As outlined in the previous sections, the supplier supplies the components at a lot size no larger than a specified value at an interval based on the triangular distribution. Although the delivered lot size is dependent on the available remaining bin size set by the manufacturing system, the annual supply quantity will remain the same every year. If the case study organization uses less than the negotiated demand number, it will be forced to buy the excess inventory from the supplier at the end of each year. The excess inventory is considered as lost sales. This excess inventory forms the basis for a manager to decide the cost of mitigating the effects of an external influence using the additional supplier control action. A manager has the option to renegotiate with the additional supplier, the supply terms (supply lot size, and delivery frequency) or terminate the services at the end of each contract year. The right to exercise this option depends on the intensity of external influences and the probability of the external influences reoccurring.

4.2.1.1 Supplier Out of Business

The two levels of external influence considered for this analysis are no supply for 500 hours and no supply for 1000 hours. This represents the situation where the supplier goes out of business and it takes the organization some time to replace the existing supplier. The 500 hours and 1000 hours represent the time it takes for a manager to find the replacement supplier. The additional supplier control action in this case would step in to fill the gap left by the bankrupt/lost supplier even though, the additional supplier might not supply at the same terms as the existing supplier. By adding an additional supplier, an organization will have two suppliers: existing supplier with baseline supply parameters and the additional supplier whose supply parameters is to be determined in this study for various influences. Experimental design is conducted to find the appropriate supply parameters for the additional supplier. For each level, one factor analysis is performed by varying each of the two control action factors: Supplier average interarrival time and Supply lot size. Based on the results from this analysis, two levels are selected for each factor and a design of experiments is conducted with four replications for each of the two response variables: Peak value of time in system response and net present value. The analysis is done separately for the two levels of supplier out of business external influence.

<u>No Supply for 500 hours</u>

Two sets of one factor analysis were conducted and the average response across four simulation replications was plotted. The first set of graphs starting from Figures 56 to 60 has the response curve for time in system obtained by keeping the supply lot size constant and varying the average supply interarrival times. The levels for supply inter arrival times are based on the Table 19. By varying keeping one control action factor constant and varying the other factor in a two level experimental setup, the level of mitigation that occurs is assessed. It also helps the manager to determine if the lowest and the highest levels selected help in mitigating the effects of the external influence. In Figure 56, the response plot for average supply interarrival time of 85 hours and 42.5 hours cannot be plotted since the response overlaps with the base line scenario. This overlapping of the responses indicates that the control action has completely mitigated the effects of the external influence with an influence risk ratio of zero and the peak value of time in system coinciding with the average time in system of the base line system. Similarly, in Figure 57, the response plot for average supply interarrival time of 42.5 hours coincides with the base line scenario. In addition, the influence risk slopes for the different levels plotted in each graph is similar across varying levels.

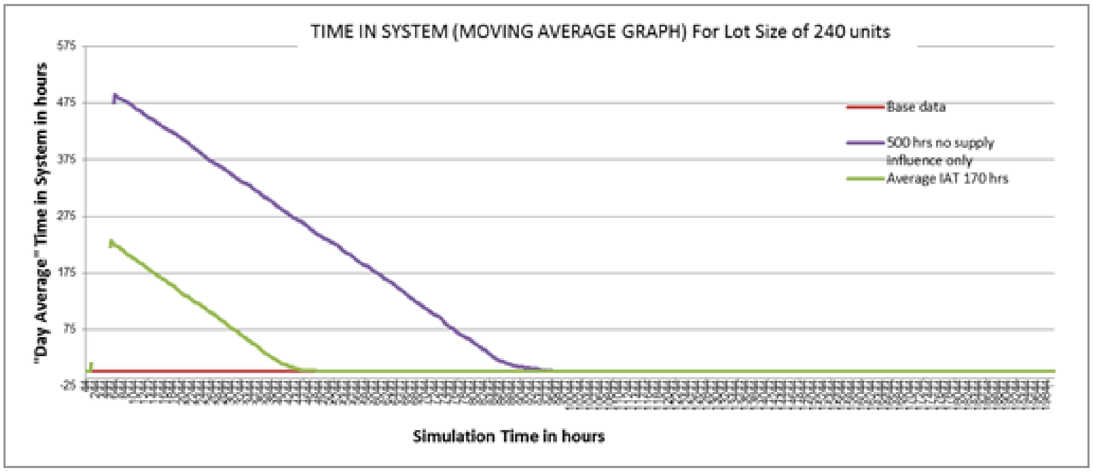


Figure 56 500 Hours No supply with Lot Size of 240 units and Varying Supply IAT

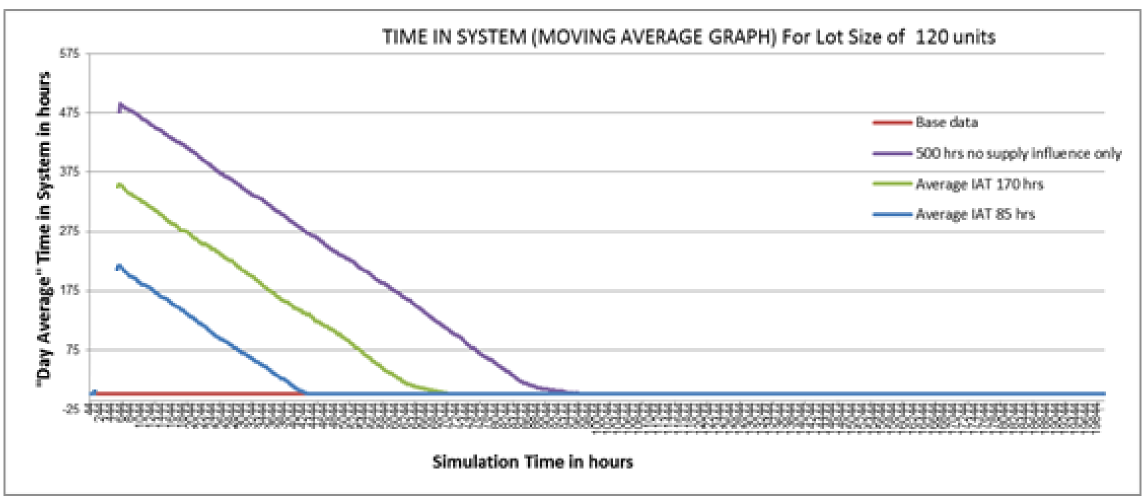


Figure 57 500 Hours No supply with Lot Size of 120 units and Varying Supply IAT

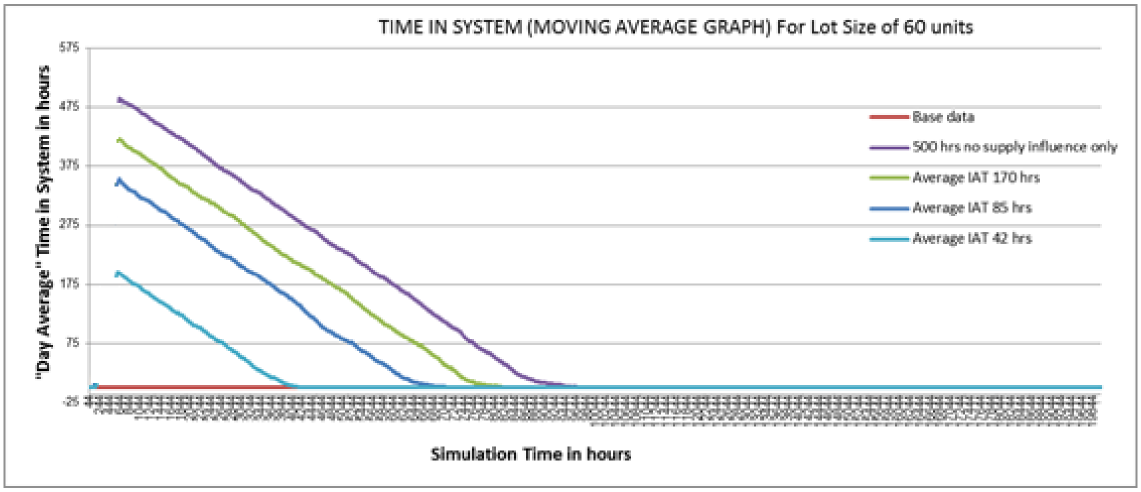


Figure 58 500 Hours No supply with Lot Size of 60 units and Varying Supply IAT

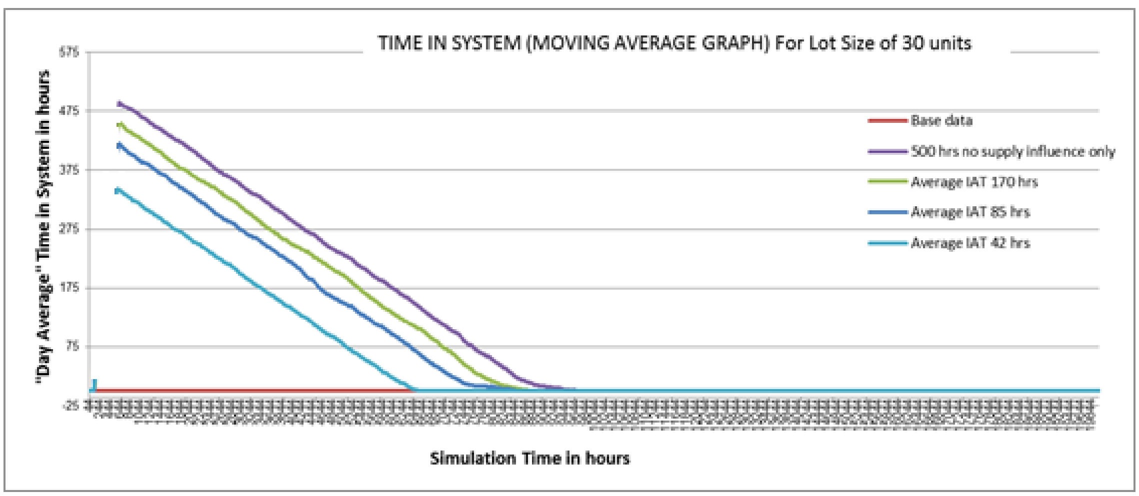


Figure 59 500 Hours No supply with Lot Size of 30 units and Varying Supply IAT

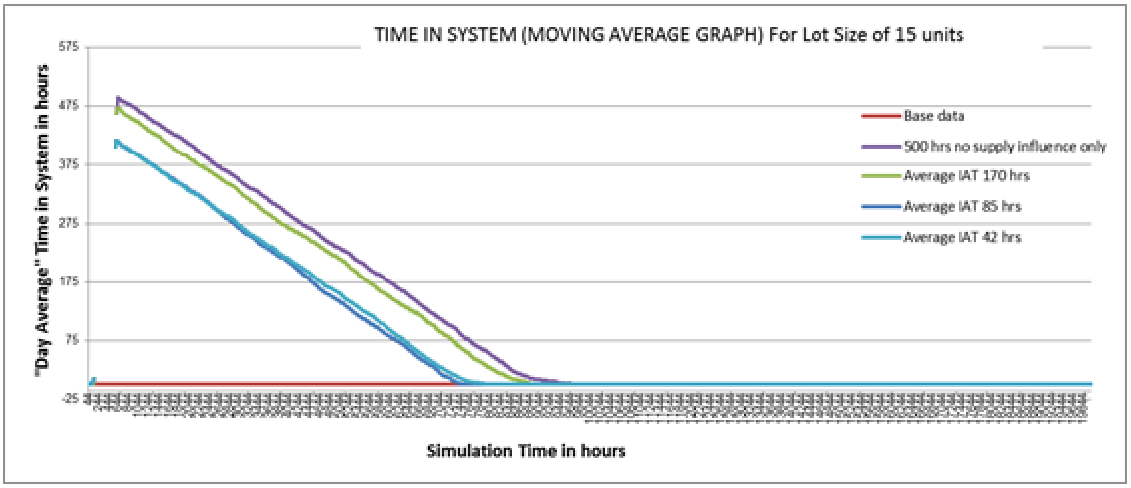


Figure 60 500 Hours No supply with Lot Size of 15 units and Varying Supply IAT

From the above plots, since the influence slopes are almost the same and the peak values change proportionally, the experiment levels selected for average supply interarrival time are 170 hours and 42.5 hours In addition, the plots show that at 170 hours of supply interrival time the mitigating does not occur at any levels, selecting this as a high level would give the manager an option to limit the investment in control actions. The option to limit investments occurs when the customer relaxes the standard lead value and accepts to receive a certain percentage of delayed orders from the manufacturer. The second set of graphs starting from Figures 61 to 63 has the response curve for time in system obtained by keeping the lot size constant and varying the average supply interarrival times. The levels for supply lot sizes are 240 units, 120 units, 60 units, 30 units and 15 units. In Figures 62 and 63, the response plot for supply lot size of 240 units overlaps with the base line scenario. Similarly, in Figure 62, the response plot for supply lot size of 240 units and 120 units cannot be plotted since the response overlaps with the base line scenario.

In addition, the influence slopes for the different levels plotted in each graph is similar across varying levels. However, the response plot for supply lot sizes of 15 and 30 units at constant average supply interarrival time of 42.5 hours seems to overlap with graphically different slopes which means that there is very minimal influence mitigating effect with the smaller supplier lot sizes at lower supplier interarrival times. The average supply rate for the bankrupt supplier was around 2.8 units/ hour. At low levels of supply size especially at 15 and 30 units and with the lowest level of supplier average interarrival time of 42.5, the supply rate falls far below the levels of the bankrupt supplier (0.35 and 0.7 units/hour respectively). Although not significant enough to be selected for the lower levels, a manager can keep his options open for limited investment in an additional supplier. The net present value at these levels might make a manager decide what percentage of orders can be shipped delayed vs the investment cost to mitigate the influence. Based on the graphs, the supplier lot size change seems to have a more mitigating effect than the supplier interarrival level changes in mitigating the 500 hour no supply influence effects.

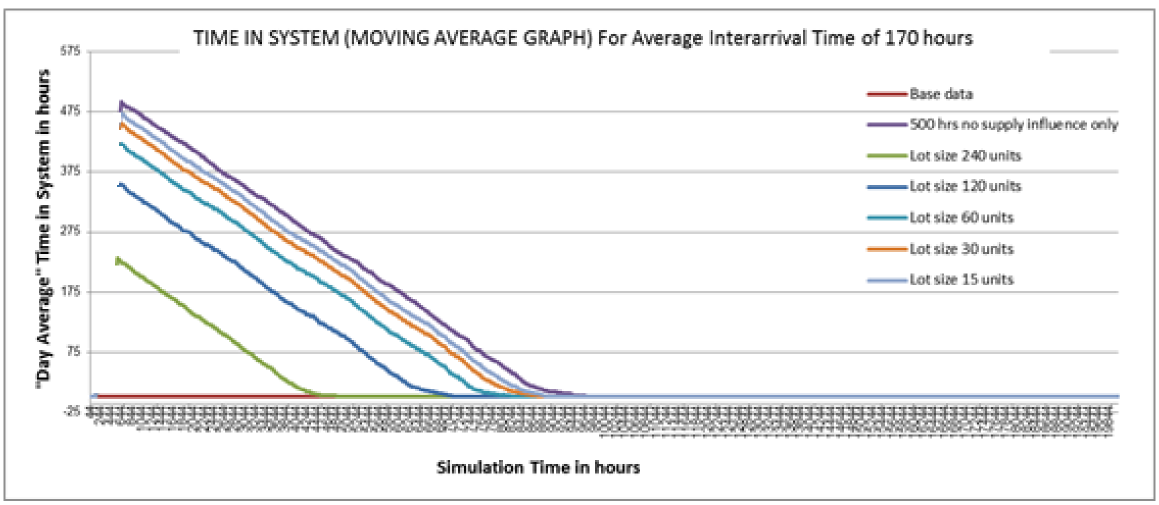


Figure 61 500 Hours No supply with Average Supply IAT of 170 hrs and Varying Lot Size

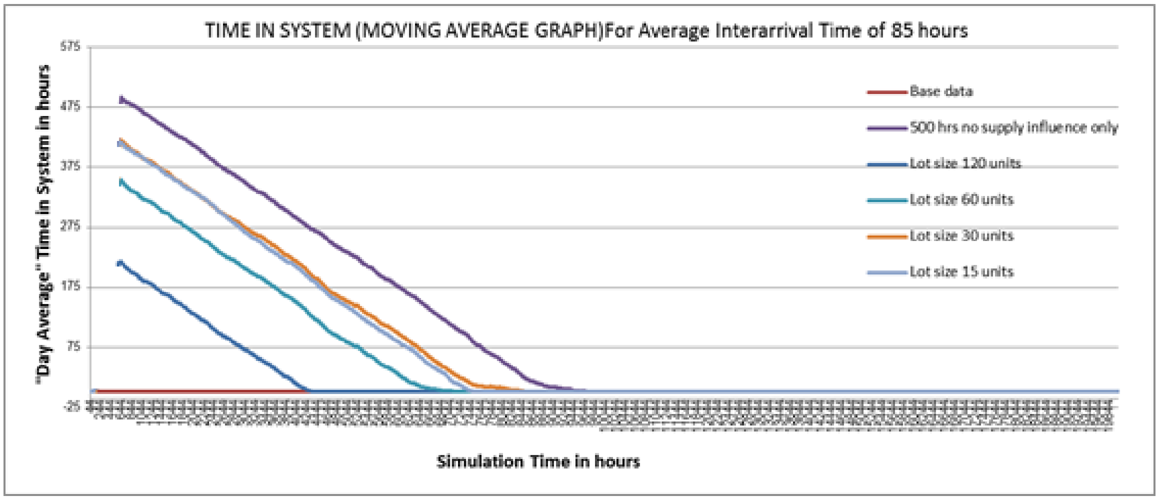


Figure 62 500 Hours No supply with Average Supply IAT of 85 hrs and Varying Lot Size

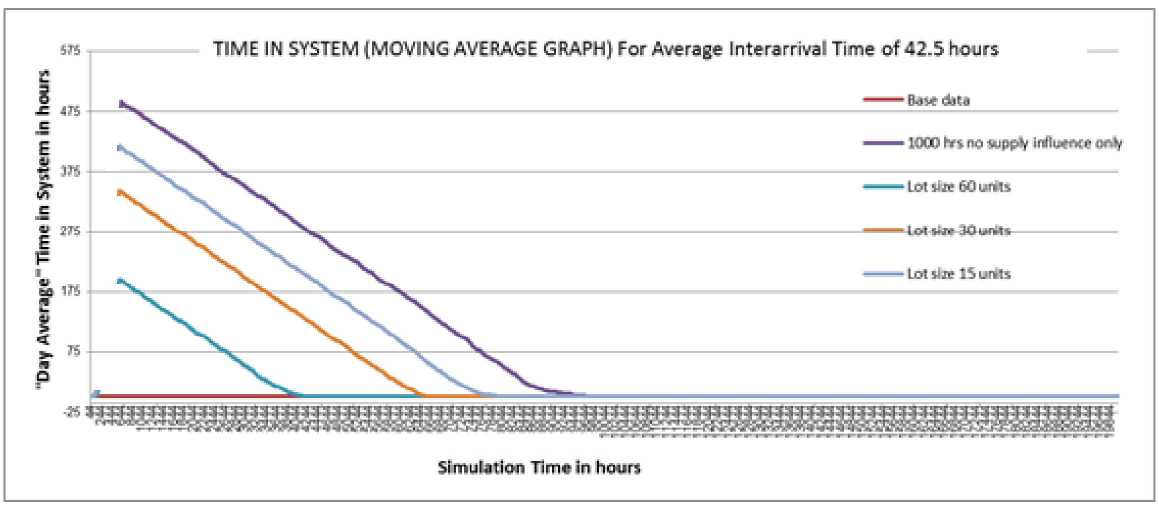


Figure 63 500 Hours No supply with Average Supply IAT of 42.5 hrs and Varying Lot Size

Based on the above results, the high and low levels considered for additional supplier lot size factor are 120 units and 15 units respectively. Even though a supply lot size of 240 units from an additional supplier mitigates the effects of the influence, this level contributes to extremely high excess inventory. The current supplier supplies 240 units in lot size and any additional supplier supplying the same lot size would contribute to a much higher inventory levels especially at lower levels of external influence effects.

The estimated effects, coefficients for the prediction equation and analysis of variance results for the design of experiments using Minitab Release 15 statistical software are in Appendix C. The results for design of experiments consist of two tables: Estimated effects and coefficients and the analysis of variance table. The p (2 tails) values for the interactions and their effects are less than 0.05 indicate with 95 % confidence the true value of the response will fall within the predicted interval. The R-Sq and adjusted R-sq values which are used to measure the model strength are closer greater 99% which indicates a good fit of the data to the equation. Based on the results, the coefficients of the statistically significant factors and their interactions are used to create a prediction equation for the response variable $\hat{y}_{PTIS}$ is as follows.

$$\hat{y}_{PTIS} = 485.271 - 5.04038 * x_{LS} + 0.106174 * x_{SIAT} + 0.0228465 * x_{LS} * x_{SIAT}$$

$$\hat{y}_{NPV} = -54168 + 42086.2 * x_{LS} + 1503.05 * x_{SIAT} - 273.876 * x_{LS} * x_{SIAT}$$

Where,

$\hat{y}_{PTIS}$ – Predicted response variable for peak value time in system

$\hat{y}_{NPV}$ – Predicted response variable for peak value time in system

x_{LS} – Supply lot size factor

x_{SIAT}- Supply average interarrival time.

Based on the results and graphical analysis, the factor settings for x_{LS} and x_{SIAT} are 120 units and 42.5 hours. The data summary for the design of experiments with the average response variables across four replications is shown in the Table 25.

Table 25 DOE Experiment Table Summary for 500 hours No supply

Experimental Factors			Response Variables			
Additional Supplier Lot Size	**Additional Supplier Interarrival Time**	**Supply Rate (Units/ hour)**	**Net Present Value ($)**	**Net loss not recovered ($)**	**Influence Risk Slope**	**Peak Time in System (Hours)**
0	**0**	**0**	($5,660,790)	($5,660,790)	-0.056	496.9
15	**170**	**0.08**	$105,829	($5,554,961)	-0.059	485.97
15	**42.5**	**0.35**	$331,538	($5,329,252)	-0.056	428.74
120	**170**	**0.71**	$505,138	($5,155,652)	-0.057	366.17
120	**42.5**	**2.82**	$2,544,588	($3,116,202)	0	1.45

Recalling the earlier definition of control action investment metrics, these metrics assist in measuring the investment costs for a control action. In case of the additional supplier control action, the excess inventory remaining at the supplier location at the end of each year is a variable control action investment metric. This metric is obtained through ARENA Process analyzer using the settings (x_{LS} and x_{SIAT} are 120 units and 42.5 hours) over one year intervals. Using the NPV calculating spreadsheet shown in Appendix D and the ARENA Process Analyzer data (APPENDIX E) the NPV is calculated for each levels of the experiment. In addition, the additional supplier control action ensures that the orders are not delayed. From NPV data in Table 25, the NPV increases as the mitigation of external influence through the control action increases. Without the control action, the net loss for the organization because of the influence is $5,660,790. However, with the investment through control action, the net loss is mitigated by about 55%. With the existing system constraints and the loss of a supplier for a period of 500 hours, the application of control action was able to recover only 55% of loss.

This cash flow analysis extends over a span of 10 years which is equivalent to 20,000 hours of simulation time. One of the advantages of NPV is that with a net cash flow data across 10 years, the NPV could be calculated for any number of intermediary years. This flexibility would help a manager to evaluate the additional supplier contracts at the end of each year and decide on the renewal or extension based on the influence changes.

Table 26 Net Cash Flow for 500 hours Supplier Out of Business with Additional Supplier Control Action

<table>
<tr><th>Year</th><th>Net Cash Flow</th><th>NPV 5 year</th><th>NPV 10 year</th></tr>
<tr><td>Year 1</td><td>$ (1,600.00)</td><td rowspan="5">$3,663,281.05</td><td rowspan="10">$2,544,588.38</td></tr>
<tr><td>Year 2</td><td>$ 935,366.00</td></tr>
<tr><td>Year 3</td><td>$ 1,266,753.00</td></tr>
<tr><td>Year 4</td><td>$ 1,257,053.00</td></tr>
<tr><td>Year 5</td><td>$ 1,249,582.00</td></tr>
<tr><td>Year 6</td><td>$ 37,026.00</td><td></td></tr>
<tr><td>Year 7</td><td>$ (430,571.00)</td><td></td></tr>
<tr><td>Year 8</td><td>$ (427,461.00)</td><td></td></tr>
<tr><td>Year 9</td><td>$ (425,426.00)</td><td></td></tr>
<tr><td>Year 10</td><td>$ (422,304.00)</td><td></td></tr>
</table>

Table 26 shows the net cash flow and the NPV for two different periods for the selected factor settings. The NPV is a positive value and hence the manager might be convinced that the settings for this control action will return a positive return on investment as well as mitigate the effects of the control action. However, the net cash flow turns negative from the sixth year of implementing the control actions even though the NPV shows a positive value. In order to maximize the value of the control action investment, it would be prudent for the manager to terminate the services of the second supplier making the control action a short term control action or to renegotiate for low supply quantities and /or increased supply frequencies. If the chances are high that the supplier might go out of business again, the manager could decide on the option to continue with the additional supplier control action.

No Supply for 1000 hours

Similar to 500 hours of no supply level, two sets of one factor analysis was conducted and the average response across four simulation replications was plotted. The set of graphs starting from Figures 64 to 68 has the response curve for time in system obtained by keeping the lot size constant and varying the average supply interarrival times. This analysis would help to determine the high and low levels for both the control action factors. The levels for supply inter arrival times are identical to 1000 hours of no supply level and are based on the data in Table 19. Recall that the average interarrival times listed in the Table are 170 hours, 85 hours and 42.5 hours. Similar to 500 no supply level, in the 1000 hours no supply level, the response plot for average supply interarrival time of 85 hours and 42.5 hours cannot be plotted since the response overlaps with the base line scenario as shown in Figure 64. In addition, the response plot for average supply interarrival time of 42.5 hours coincides with the base line scenario (Figure 65). The extra supply more than enough covers the lost supplier. This overlapping of the responses indicates that the control action has completely mitigated the effects of the external influence with an influence risk ratio of zero and the peak value of time in system coinciding with the average time in system of the base line system. In addition, the influence risk slopes for the different levels plotted in each graph is similar across varying levels. The overall trend follows the similar path as the 500 hours of no supply influence effects except the slope of the line is different for the 1000 hours no supply level. Based on the previous discussions, the recovery slope for 500 hours of no supply and 1000 hours of no supply levels are similar. A manager can extrapolate the recovery point given the direction, value of the influence risk slope and the starting point of the influence. Also selecting a level that would be similar to the existing supplier would incur high investment costs due to excess inventory.

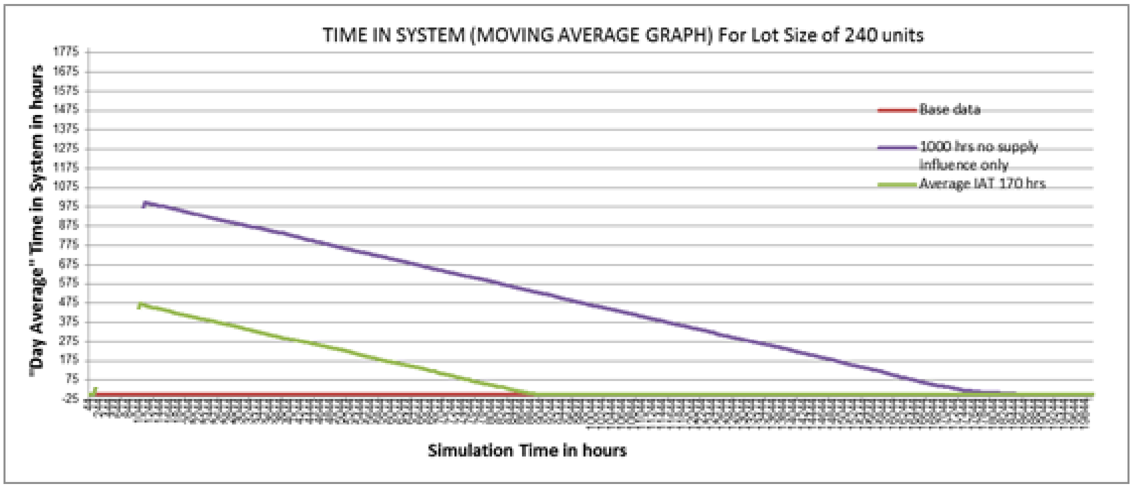


Figure 64 1000 Hours No supply with Lot Size of 240 units and varying Supply IAT

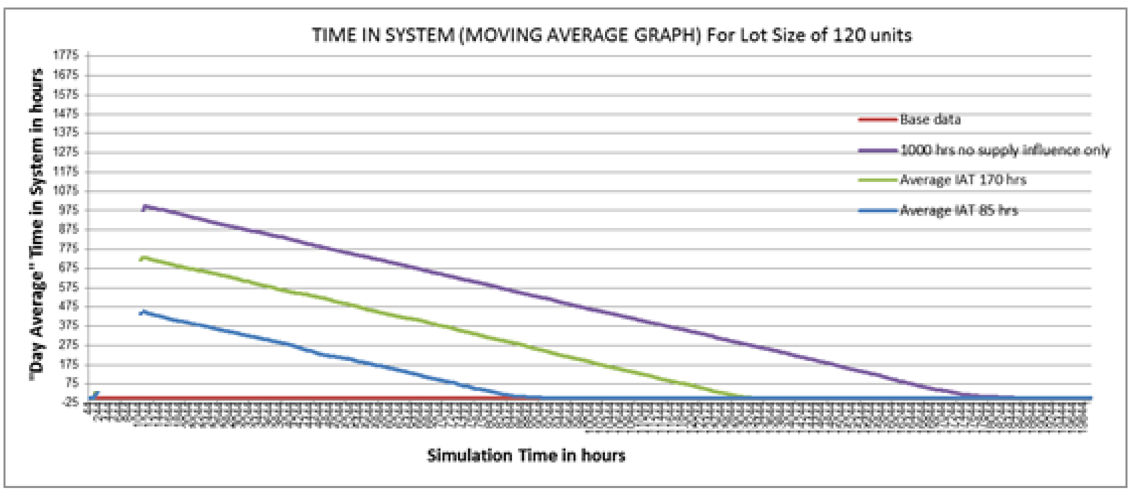


Figure 65 1000 Hours No supply with Lot Size of 120 units and Varying Supply IAT

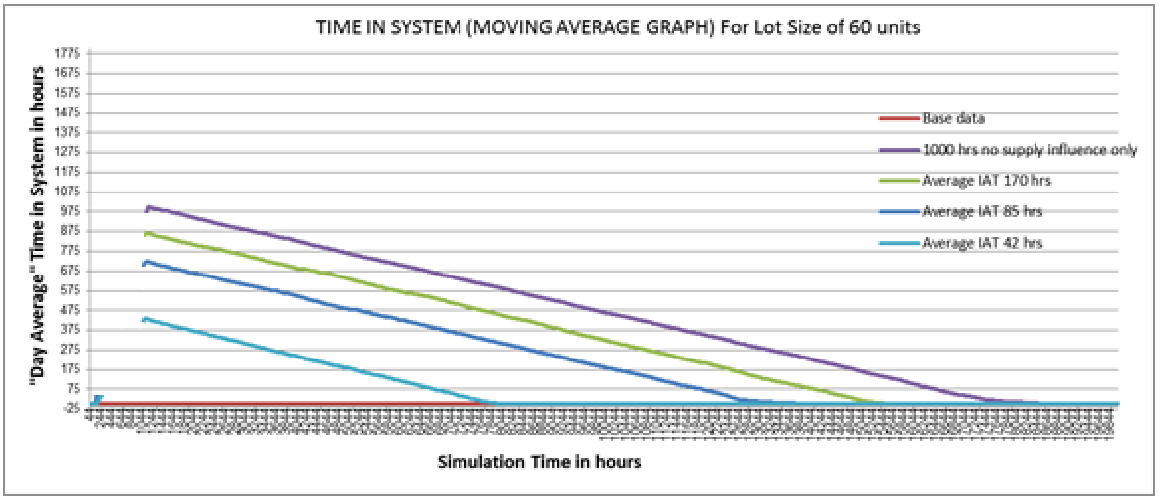


Figure 66 1000 Hours No supply with Lot Size of 60 units and Varying Supply IAT

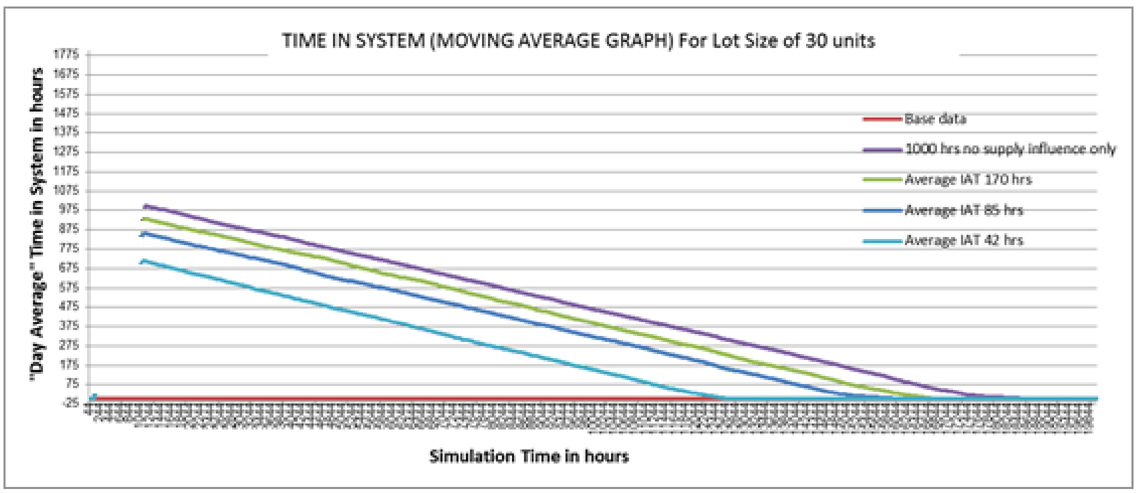


Figure 67 1000 Hours No supply with Lot Size of 30 units and Varying Supply IAT

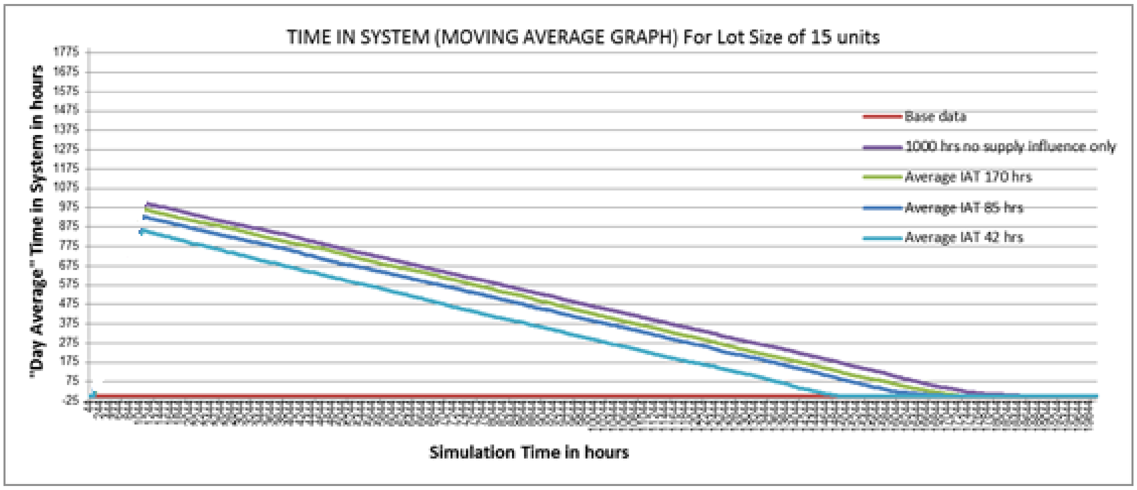


Figure 68 1000 Hours No supply with Lot Size of 15 units and Varying Supply IAT

The next set of graphs starting from Figures 69 to 71 has the response curve for time in system obtained by keeping the maximum supply lot size constant and varying the average supply interarrival times. In a practical scenario, a manager would want to understand varying which control action factor provides a faster result; in other words which control factor provides the significant impact in mitigating the external influence effects. The levels for supply lot sizes are 240 units, 120 units, 60 units, 30 units and 15 units. For the 1000 hours no supply level, the response plot for supply lot size of 240 units overlaps with the base line scenario as in Figures 70 and 71. In Figure 71, the response plot for supply lot size of 240 units and 120 units cannot be plotted since the response overlaps with the base line scenario. In addition, the influence risk slopes for the different levels plotted in each graph is similar across varying levels. However, the response plot for supply lot sizes of 15 and 30 units at constant average supply interarrival time of 42.5 hours seems to overlap with different slopes which means that there is very minimal influence mitigating effect with the smaller supplier lot sizes at lower supplier interarrival times. The influence risk slopes seem to be similar through graphical estimation between the 500 hours and 1000 hours of no supply.

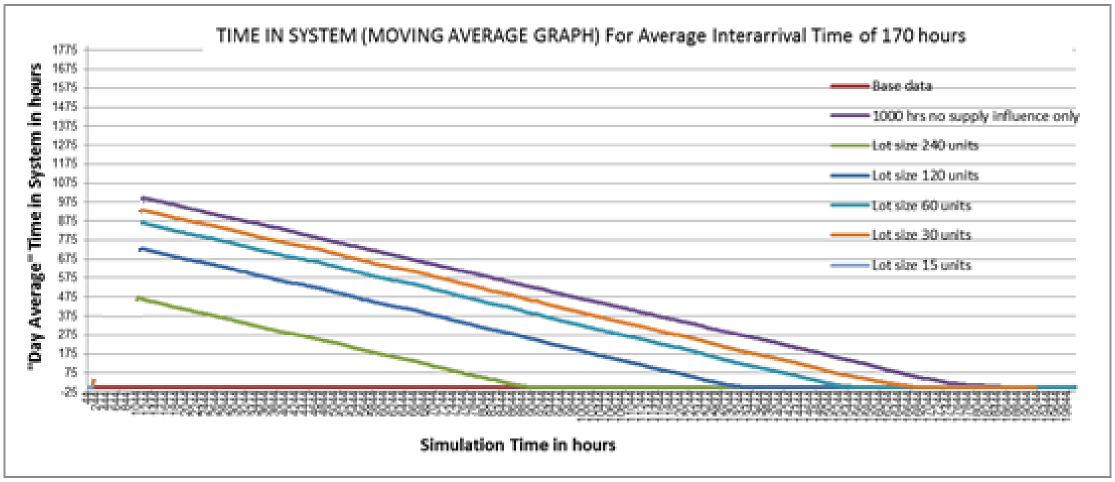


Figure 69 1000 Hours No supply with Average Supply IAT of 170 hrs and Varying Lot Size

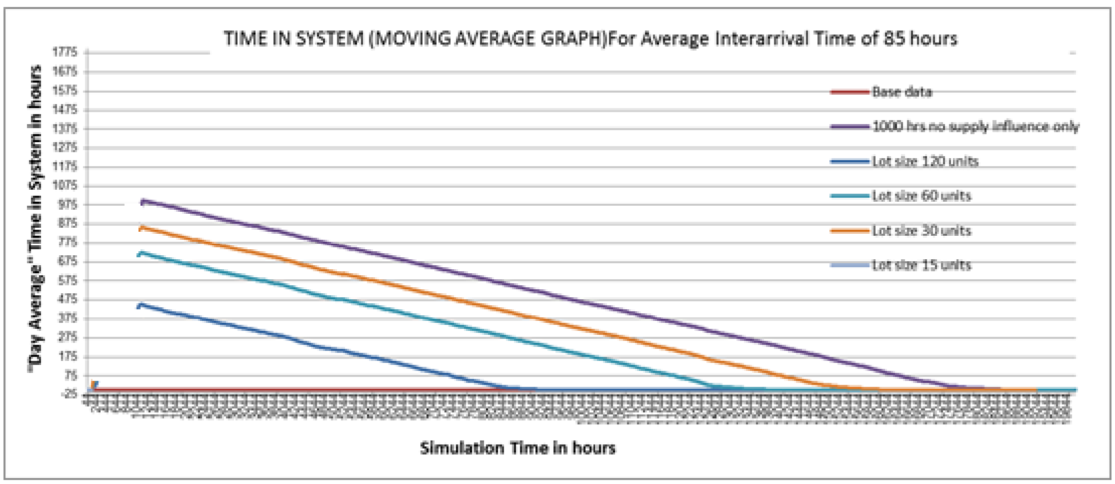


Figure 70 1000 Hours No supply with Average Supply IAT of 85 hrs and Varying Lot Size

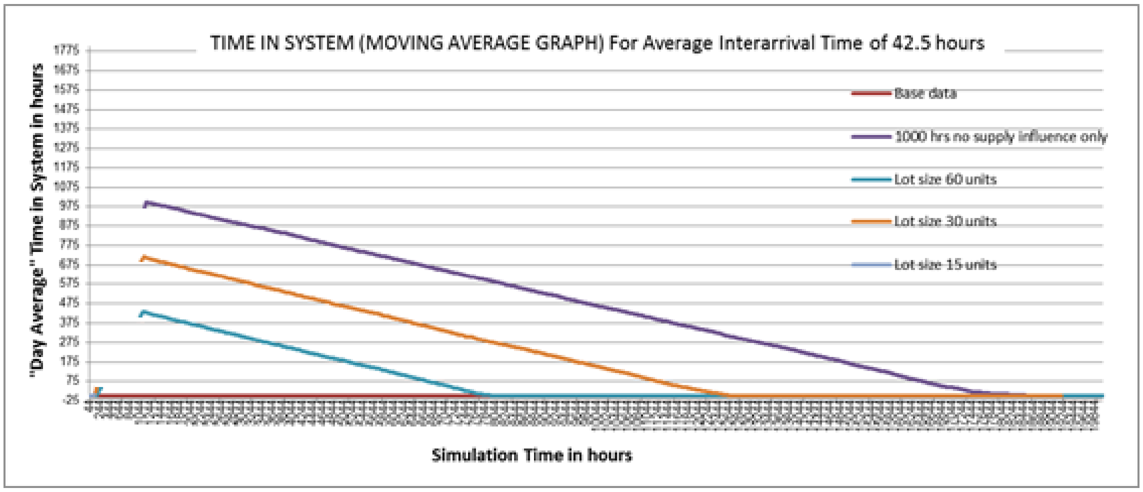


Figure 71 1000 Hours No supply with Average Supply IAT of 42.5 hrs and Varying Lot Size

The plots show that at higher level of supply lot size and varying the supply interarrival times, the change in peak value of time in system between each level of supply interarrival time is proportionate. The plots for lower level of supply interarrival show a similar response with change in supply lot size. With either the supplier lot size at low levels or the supply interarrival time at high levels, the system seems to respond slower to the control actions. However, with the lower supply size and higher time in system, the Based on the above results, the high and low levels considered for supplier lot size factor are 120 units and 15 units respectively.

Based on the Minitab results attached in Appendix C, the coefficients of the statistically significant factors and their interactions are used to create a prediction equation for the response variable $\hat{y}_{PTIS}$ is as follows.

$$\hat{y}_{PTIS} = 882.601 - 9.40405 * x_{LS} + 0.782460 * x_{SIAT} + 0.0419781 * x_{LS} * x_{SIAT}$$

$$\hat{y}_{NPV} = -1093649 + 56517.7 * x_{LS} + 6898.36 * x_{SIAT} - 351.069 * x_{LS} * x_{SIAT}$$

Based on the results and graphical analysis, the factor settings for x_{LS} and x_{SIAT} are 120 units and 42.5 hours. The predicted $\hat{y}_{PTIS}$ using this solution is 1.458 hours and $\hat{y}_{NPV}$ for 10 year is $6,475,641, which is below the customer required time in system.

The data summary for the design of experiments with the average response variables across four replications is shown in the Table 27. The net loss due to the influence effect is $9,761,367 which is about 1.7 times more than the 500 hours of no supply influence effect. The net loss recovered is 66% and the unrecoverable influence effect loss is about the same as the 500 hours of no supply influence.

Table 27 DOE Experiment Table Summary for 1000 hrs No Supply

Experimental Factors			**Response Variables**			
Additional Supplier Lot Size	**Additional Supplier Interarrival Time**	**Supply Rate (Units/ hour)**	**Net Present Value ($)**	**Net loss not recovered ($)**	**Influence Slope**	**Peak Time in System (Hours)**
0	**0**	**0**	($9,761,367)	($9,761,367)	-0.05740	993.8 *
15	**170**	**0.08**	$216,648	($9,544,719)	-0.05876	981.60
15	**42.5**	**0.35**	$819,933	($8,941,434)	-0.05534	801.55
120	**170**	**0.71**	$1,370,119	($8,391,248)	-0.05850	743.48
120	**42.5**	**2.82**	$6,475,641	($3,285,726)	0	1.45 **

This cash flow analysis extends over a span of 10 years which is equivalent to 20,000 hours of simulation time. This worksheet is the identical in format to the worksheet described for the 500 hours of no supply influence with additional supplier control action. NPV is calculated for the additional supplier control action setting (supply lot size of 120 units and average supplier interarrival time of 42.5 hours) when 1000 hours of no supply is affecting the system and shown in Table 28

Table 28 Net Cash Flow for 1000 hours Supplier Out of Business with Additional Supplier Control Action

Year	Net Cash Flow	NPV 5 year	NPV 10 year
Year 1	$ (1,600.00)	$4,191,203.65	$6,475,641.38
Year 2	$ 616,406.00		
Year 3	$ 1,263,753.00		
Year 4	$ 1,260,053.00		
Year 5	$ 1,259,782.00		
Year 6	$ 1,267,026.00		
Year 7	$ 1,256,629.00		
Year 8	$ 1,265,139.00		
Year 9	$ 1,267,174.00		
Year 10	$ 648,096.00		

A positive NPV might be an incentive to convince a manager that the settings for this control action will return a positive return on investment as well as mitigate the effects of the control action. The net cash flow stays positive until tenth year of implementing the control actions. It would be prudent for the manager at the end of ninth year to terminate the services of the second supplier making the control action a short term control action or to renegotiate for low supply quantities and /or increased supply frequencies. The NPV of the investment in a control action investment helps a manager to relate the control actions to mitigate the effect of an external influence and also meet the customer expectations.

4.2.1.2 Diminished Supplies over Time

In the diminished supplies over time influence, a supplier reduces the delivery lot size by a certain percentage twice over one year interval and the reduced lot size remains constant for the rest of the simulation. Based on the preliminary results discussed in section 3.8.2 and the results of the one factor response analysis of this influence the two influence levels selected are 4 percent cumulative decrease over time and 8 percent cumulative decrease over time. For this influence effect, a one-factor analysis is performed for each level of the influence by varying the two control action factors: Supplier average interarrival time and Supply lot size individually. Based on the results from this analysis, two levels are selected for the experimental design in the application of control action. Each experiment level is run for four replications for the Peak value of time in system response variable. The analysis is done separately for the 4% and 8% decrease in supplier lot size external influence effects.

4 percent cumulative decrease in supplier lot size

Two experimental sets of single factor analysis were conducted, one for each control action factor and the average responses for time-in-system values were plotted. The levels for supply inter arrival times are based on the Table 19 and the levels for supplier lot size were 240, 120, 60, 30 and 15 units. The response plot for average supply interarrival time of 170 hours, 85 hours and 42.5 hours can be plotted, but no difference can be seen because the responses overlaps with the base line scenario. This overlapping of the responses indicates that the control action has completely mitigated the effects of the external influence at 4 percent diminished supplies level with an influence risk slope (recovery slope) of zero and the peak value of time in system coinciding with the average time in system of the base line system. Similarly, the response plots for average supply interarrival time of 170 hours, 85 hours and 42.5 hours for fixed supply lot sizes coincides with the base line scenario. In addition, the influence slopes for the different levels plotted in each graph is similar across varying levels.

Based on the above plot results, it is not possible to select the high and low experiment levels for the control action factors graphically. Closer analysis of the raw data reveals that for a supplier lot size of 15 units and an average supply interarrival time of 170 units, there is an increase in the peak time in system value above the customer-required value of about 2.25 hours. Hence, an experimental design is formed using the levels 120 units and 15 units for the supplier lot size factor and levels 170 hours and 42.5 hours respectively for average supplier interarrival time. A lot size of 240 units though mitigates the effects of the influence, contributes to extremely high inventory left over inventory at the additional supplier. The current supplier supplies a lot size of 240 units at an average interarrival time of 85 hours and any additional supplier supplying the same lot size would contribute to a much higher inventory levels especially at lower levels of external influence effects.

The estimated effects, coefficients for the prediction equation and analysis of variance results for the design of experiments using Minitab Release 15 statistical software are in Appendix C. The results for design of experiments consist of two tables: Estimated effects and coefficients and the analysis of variance table. The p (2 tails) values for the interactions and their effects are less than 0.05 indicate with 95 % confidence the true value of the response will fall within the predicted interval. However, the R-Sq and adjusted R-sq values for both the $\hat{y}_{PTIS}$ and $\hat{y}_{NPV}$ are 64% and 75% for NPV response variable and 57% and 47% for the Peak time-in-system response variable. A lower number indicates that the data is not a good fit the equation. The reason for this degree of unfit compared to previous experiments is that the 4% influence level did not reach critical level to be mitigated by the control actions effectively and profitably. Based on the results, the coefficients of the statistically significant factors and their interactions are used to create a prediction equation for the response variable $\hat{y}_{PTIS}$ is as follows.

$$\hat{y}_{PTIS} = -0.5318 + 0.01674 * x_{LS} + 0.04682 * x_{SIAT} - 0.0004 * x_{LS} * x_{SIAT}$$

$$\hat{y}_{NPV} = 3467250 - 5751.70 * x_{LS} + 3908.60 * x_{SIAT} - 182.580 * x_{LS} * x_{SIAT}$$

Based on the results and graphical analysis, the factor settings for x_{LS} and x_{SIAT} are 15 units and 42.5 hours respectively.

The data for the design of experiments with the average response variables across four replications is shown in the Table 29. From Table 29, it is obvious that more than two levels of supplier interarrival time especially at lower supplier lot size of 15 have closer NPV values. The similarity in values is the reason for the poor unfit of the experiment model to the data. The predicted $\hat{y}_{PTIS}$ using this solution is 1.458 hours and the10 year$\hat{y}_{NPV}$ is $7,472,630, which is below the customer-required time in system (2.25 hours).

Table 29 DOE Experiment Table Summary for 4 percent Cumulative Decrease in Supply Lot Size

Experimental Factors			Response Variables			
Additional Supplier Lot Size	**Additional Supplier Interarrival Time**	**Supply Rate (Units/ hour)**	**Net Present Value ($)**	**Net loss not recovered ($)**	**Influence Slope**	**Peak Time in System (Hours)**
0	**0**	**0**	($8,602,042)	($8,602,042)	0.1040	327.36
15	**170**	**0.08**	$7,686,415	($915,627)	-0.0018617	6.67
15	**42.5**	**0.35**	$7,472,630	($1,129,412)	-2.8516E-05	1.45
120	**170**	**0.71**	$6,321,413	($2,280,629)	-2.5013E-05	1.40
120	**42.5**	**2.82**	$5,070,116	($3,531,926)	-2.8516E-05	1.45

Because of the small decrease in lot size, a smaller supply rate is needed to mitigate this influence effect. High supply rate in terms of lower inter arrival time and/or high lot size will tend to negate the effect of the control action. With a smaller lot size of 15 and higher interarrival time of 170 hours, the loss due to the influence effect is recovered by 89.4%.

Appendix E has the data obtained from ARENA Process analyzer and used for calculating NPV for four replications. Similar to the application of additional supplier control action in case of the supplier out of business external influence the control action investment metric selected for this scenario is the excess inventory remaining at the supplier location at the end of each year is a variable control action investment metric. This metric is obtained through ARENA Process analyzer using the optimum settings (x_{LS} and x_{SIAT} are 15 units and 42.5 hours) over one year intervals. In addition, the additional supplier control action ensures that the orders are not delayed. The number of orders that were delayed when diminished supplies over time influence effect was acting alone on the system was also recorded at intervals of 2000 hours (one year). This metric will provide the manager an estimate of the potential lost sales recovered due to the application of the control actions. This cash flow analysis extends over a span of 10 years which is equivalent to 20,000 hours of simulation time.

Table 30 Net Cash Flow for 4% Diminished Supply with Additional Supplier Control Action

Year	Net Cash Flow	NPV 5 year	NPV 10 year
Year 1	$(1,600.00)	$3,430,695.21	$7,472,630.98
Year 2	$(36,854.00)		
Year 3	$446,717.00		
Year 4	$1,379,227.00		
Year 5	$1,536,056.00		
Year 6	$1,546,027.00		
Year 7	$1,534,157.00		
Year 8	$1,547,745.00		
Year 9	$1,544,992.00		
Year 10	$1,542,900.00		

Table 30 shows that NPV for both 5 year and 10 year period is a positive value and hence the manager might be convinced that the settings for this control action will return a positive return on investment as well as mitigate the effects of the control action. However, the net cash flow remains negative at the beginning year apart from the initial investment. The reason for the negative cash flow for the first year is because the system has built in inventory already to cope up with the 4% level decrease in supply lot size. Also the diminished supplies influence calls for two consecutive decreases in supply lot size over a period of two year interval. The first decrease of 4% in year one was not enough to impact the system and shows in as the negative cash flow for the first year. For this influence, with the additional supplier control action at low levels the NPV seems to increase with time. The slow reduction in supply size is filled by a low fill rate.

8 percent Cumulative Decrease in Supplier Lot Size

In the next 8 % decrease in supplier size experiment level, the supply lot size is decreased 8% twice over a one year time interval. The two additional supplier control action factors applied for mitigating this influence effect are supplier lot size and average interarrival supply time. The experimental levels selected for the supplier lot size factor are 240 units, 120 units, 60 units, 30 units and 15 units. The experiment levels for supply inter arrival times are identical to 4% diminished supplies level and are (170 hours, 85 hours and 42.5 hours). The two sets of one factor analysis were conducted and the average time in system response was plotted. In the first set of analysis, the response curve for time in system is obtained by keeping the lot size constant and varying the average supply interarrival times. The plots for average supply interval of 170 hours and 85 hours with a constant supplier lot size of 15 units is shown in Figure 72. All levels of the supply lot size control action factor except 15 units level have an influence risk slope β of zero (response overlaps with the base line scenario) for all levels of average supply interarrival times. Similarly, all levels of the average interarrival supply time control action factor except 170 hour level have an influence risk slope β of zero for all levels of supplier lots size which is shown in Figure 73. These responses indicate that the control action has completely mitigated the effects of the external influence with an influence risk ratio of zero and the peak value of time in system coinciding with the average time in system of the base line system.

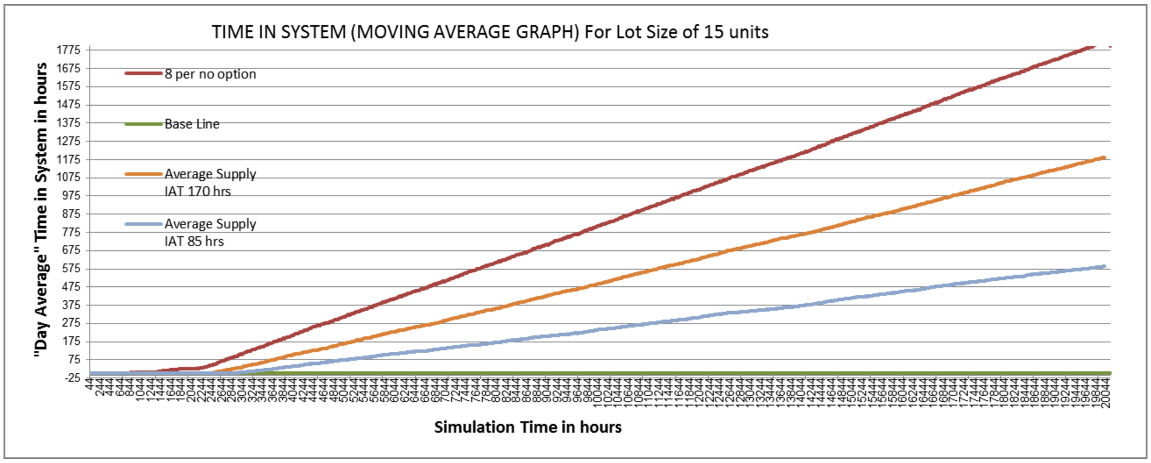


Figure 72 8 % Decrease In Supply Lot Size With Lot Size Of 15 Units And Varying Supply IAT

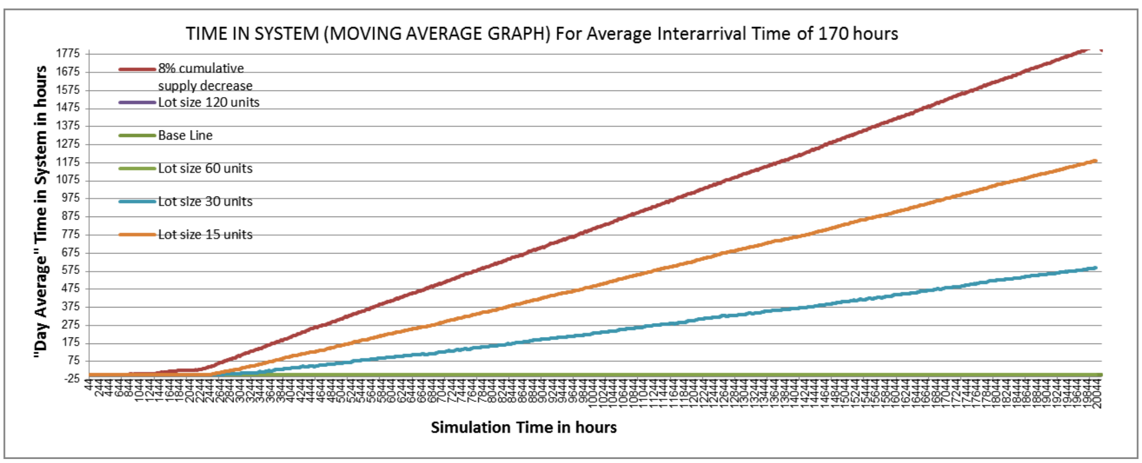


Figure 73 8 % Decrease In Supply Lot Size With Average Supply IAT Of 170 Hrs And Varying Lot Size

Based on the above results, the high and low levels considered for supplier lot size factor are 120 units and 15 units respectively. The high and low experimental levels considered for average the supply interarrival time are 170 hours and 42.5 hours. The response variables for time-in-system indicate that there is very little impact from the effect of lot size supply size of 120 units with respect to change in interarrival times. As discussed earlier in the modeling of this influence (section 3.6.3), the supply lot size decreases to 204 units per delivery. This corresponds to a supply rate of about 2.4 units/hour. The order is generated at an average of 2.7 orders/hour. To complete the gap, a supply rate of 0.3 units/hour of supply is required. The level of additional supplier lot size 15 units and additional supplier interarrival time of 42.5 is adequate to complete the gap in supply. The diminished supplies for 8% decrease in supply time influence correspond to a decrease in supply lot size to about 204 units per delivery. The design of experiments was analyzed using Minitab Release 15 statistical software and the results showing estimated effects, coefficients for the prediction equation and analysis of variance are attached in Appendix C. Based on the results, the coefficients of the statistically significant factors and their interactions are used to create prediction equation for the response variable $\hat{y}_{PTIS}$ and $\hat{y}_{NPV}$ are as follows.

$$\hat{y}_{PTIS} = -456.903 + 3.806 * x_{LS} + 10.785 * x_{SIAT} - 0.0895 * x_{LS} * x_{SIAT}$$

$$\hat{y}_{NPV} = -529659 + 40959.2 * x_{LS} + 1105.29 * x_{SIAT} - 247.359 * x_{LS} * x_{SIAT}$$

The data for the design of experiments with the average response variable is shown in the Table 31.

Table 31 DOE Experiment Table Summary For 8 % Decrease In Supply Lot Size

Experimental Factors			**Response Variables**			
Additional Supplier Lot Size	**Additional Supplier Interarrival Time**	**Supply Rate (Units/ hour)**	**Net Present Value ($)**	**Net loss not recovered ($)**	**Influence Risk Slope**	**Peak Time in System (Hours)**
0	**0**	**0**	($9,260,557)	($9,260,557)	0.0190	1815.06
15	**170**	**0.08**	$3,368,129	($5,892,428)	0.0599575	1205.23
15	**42.5**	**0.35**	$3,593,839	($5,666,718)	-0.0000285	1.45
120	**170**	**0.71**	$3,767,439	($5,493,118)	-0.0014492	1.08.
120	**42.5**	**2.82**	$5,806,889	($3,453,668)	-0.0000285	0.91

Based on the results and graphical analysis, the factor settings for x_{LS} and x_{SIAT} are 120 units and 42.5 hours. The predicted $\hat{y}_{PTIS}$ using this solution is 1.458 hours and $\hat{y}_{NPV}$ for 10 year is $5,806,889, which is below the customer required time in system. The net loss not recovered is still negative which means that despite the recovery due to application of the control action, the loss due to effect of the external influence on the system is not completely recovered.

This solution is different from the manual estimation results that predicted that an additional supplier with a lot size of 15 units and average supply interarrival time of 42.5 was enough to mitigate the influence effects. Since the gap estimated is 0.3 units/hour and the supply lots size of 15 and supply IAT of 42.5 will be able to feed the demand, the variations in delivery due to random number generation will force the second supplier to be able to not meet the demand. Besides, the solution set obtained through optimization also provides additional inventory which also improves the base line scenario.

Table 32 Net Cash Flow For 8% Diminished Supply Influence Level With Additional Supplier Control Action

Year	Net Cash Flow	NPV 5 year	NPV 10 year
Year 1	$(1,600.00)	$3,170,885.98	$5,806,889.23
Year 2	$300,266.00		
Year 3	$992,553.00		
Year 4	$1,019,753.00		
Year 5	$996,382.00		
Year 6	$1,012,326.00		
Year 7	$996,229.00		
Year 8	$1,011,339.00		
Year 9	$1,007,674.00		
Year 10	$1,008,996.00		

From Table 32, the NPVs for 5 year and 10 year are both positive with increase in values as time progresses. The net cash flow shows that the system stabilizes after year 3. Both the 4 % and 8% follow a similar trend with NPV increasing over time.

4.2.1.3 Competitor Out Of Business

In the competitor out of business influence effect, the number of orders (orders of size one) entering the system increases through a decrease in the supplier interarrival time. The application of additional supplier control action for the previous influences involves adding a supplier to one critical component (PC Board). Since an order increase requires increase in the entire critical components inventory, additional suppliers are added for all the components. This change also increases control action investment costs. There are two levels considered for this influence: 15 % decrease and a 30% decrease in order interrrival time. By keeping the influence level constant, a single-factor analysis is performed for each level of the influence by varying the two control action factors individually: Supplier average interarrival time and Supply lot size. Based on the results from this analysis, two experiment levels are selected for each control action factor and a design of experiments (2 factors x 2 levels) is conducted with four replications for the two response variables: Peak value of time in system response and net present value. The analysis is done separately for the two levels of the competitor out of business external influence.

15% Decrease in Order Interarrival Time

Two sets of one factor analysis were conducted and the average response across four simulation replications was plotted. The first set of graphs starting from figures 68 to 72 has the response curve for time in system obtained by keeping the supply lot size constant and varying the average supply interarrival times. The experiment levels for supply inter arrival times are based on the Table 19 and the levels for supply lot sizes are 240 units, 120 units, 60 units, 30 units and 15 units. In Figure 68, the response plot for average supply interarrival time of 85 hours and 42.5 hours is not visible since the response overlaps with the base line scenario. This overlapping of the responses indicates that the control action has completely mitigated the effects of the external influence with an influence risk ratio of zero and the peak value of time in system coinciding with the average time in system of the base line system. The response plot for supply interarrival time of 170 hours at 240-unit lot size shows a small increase and recovers over time with a negative influence risk slope. In Figure 74 where the supply lot size is 120 units and the average supply IAT is varied across the three levels, the response plot for average supply interarrival time of 42.5 hours coincides with the base line scenario. For a supply lot size of 15 units, there is no recovery over time with the influence risk slopes being positive across all level changes in average supplier interarrival time.The plots in Figures 74 to 78 (varying the Interarrival times over Supply lot size) for the time-in-system response variable indicate that at the control action mitigates at all levels of change in supply arrival times.

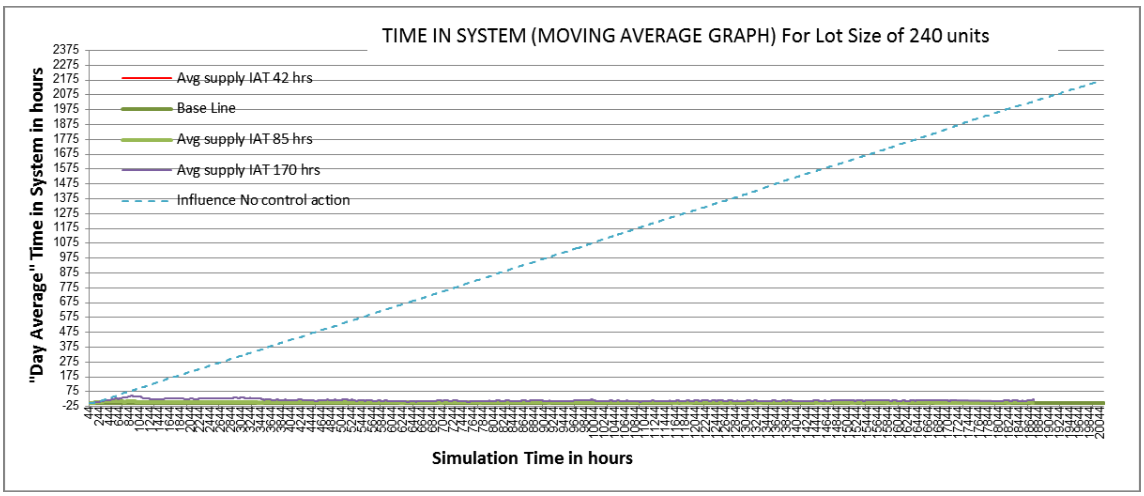


Figure 74 15% Decrease In Order IAT With Lot Size Of 240 Units And Varying Supply IAT

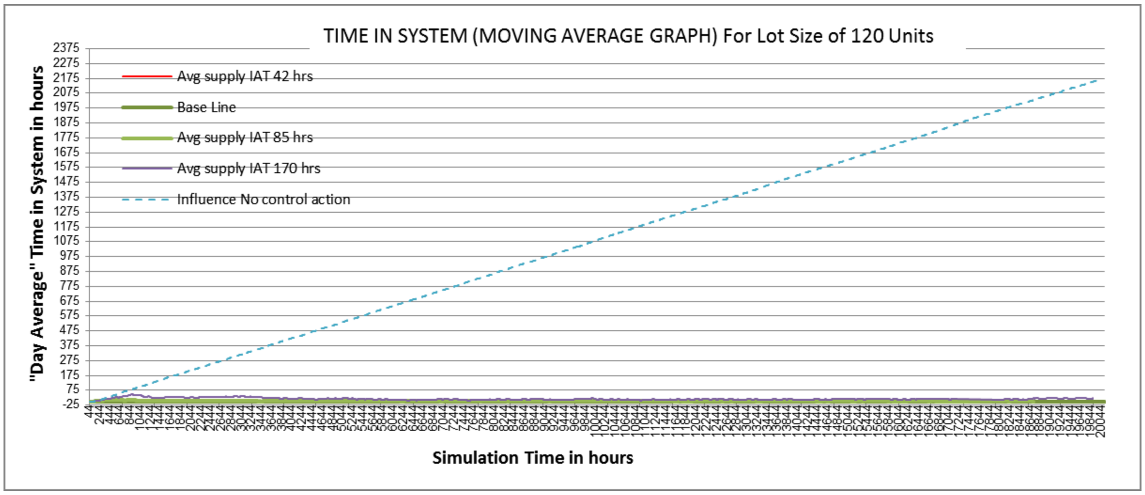


Figure 75 15% Decrease In Order IAT With Lot Size Of 120 Units And Varying Supply IAT

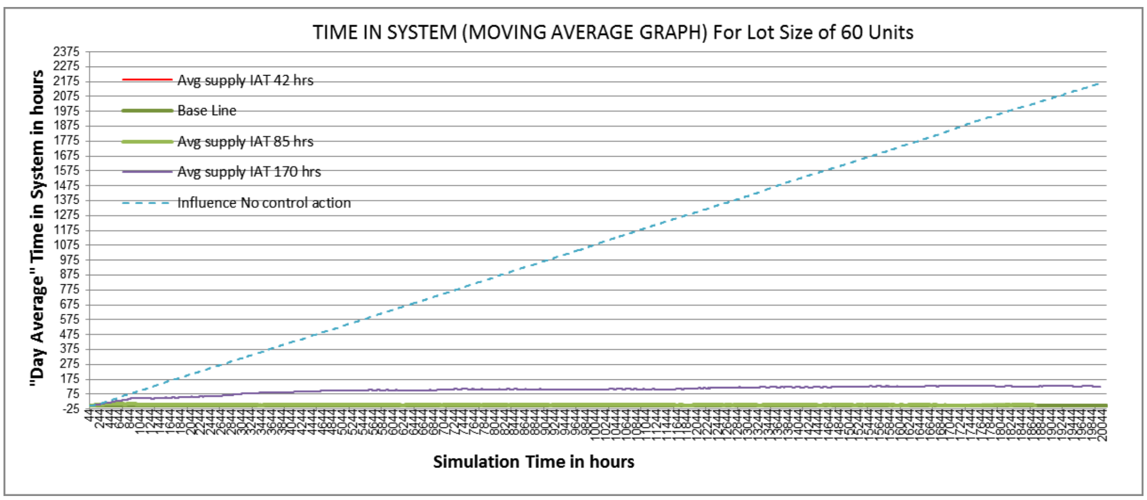


Figure 76 15% Decrease In Order IAT With Lot Size Of 60 Units And Varying Supply IAT

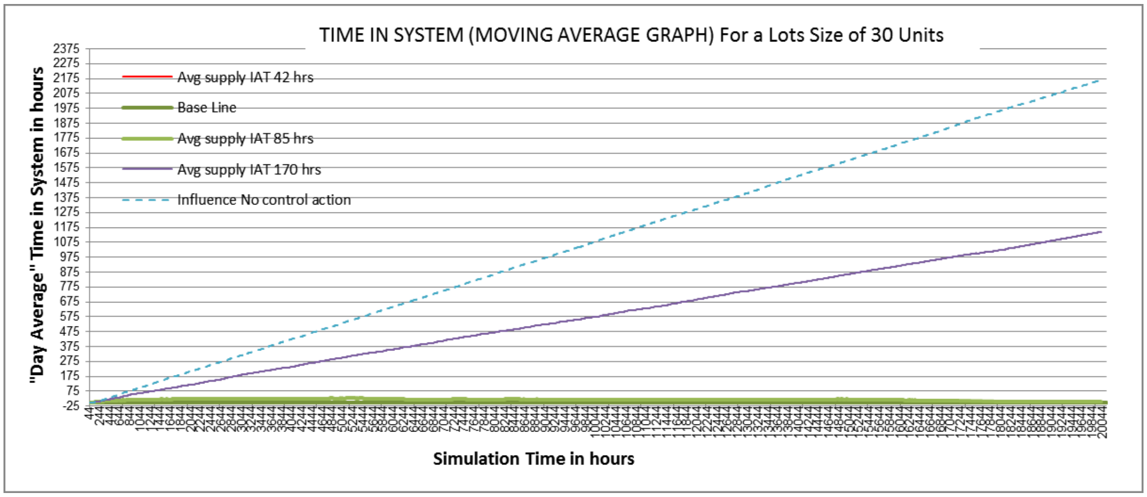


Figure 77 15% Decrease In Order IAT With Lot Size Of 30 Units And Varying Supply IAT

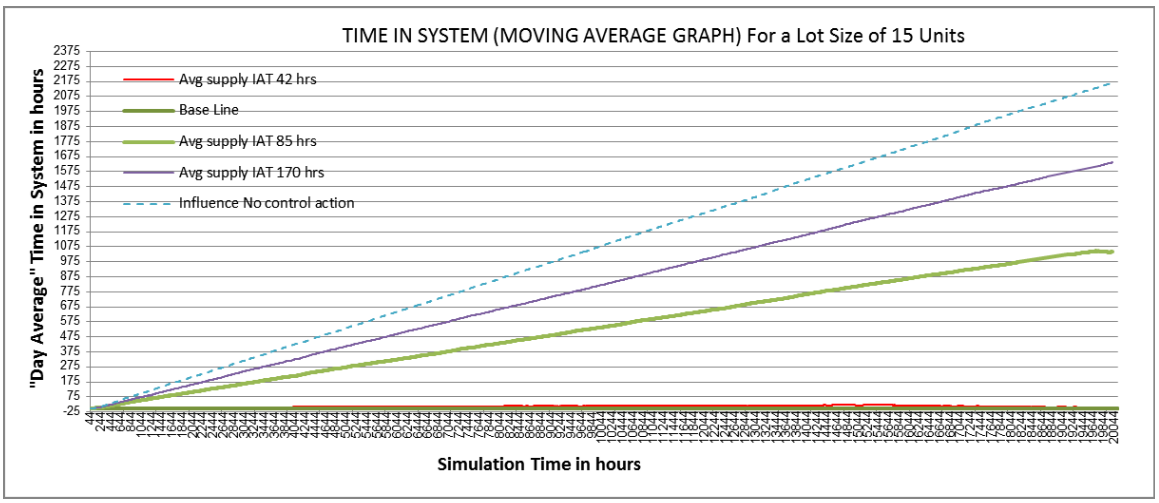


Figure 78 15% Decrease In Order IAT With Lot Size Of 15 Units And Varying Supply IAT

In the second set of graphs shown in Figures 79 to 81, the response curve for time in system obtained by keeping the lot size constant and varying the average supply interarrival times. In Figure 79, the response plot for supply lot size of 240 units coincides with the base line scenario. Similarly, in Figure 80, the response plot for supply lot size of 240 units and 120 units cannot be plotted since the response overlaps with the base line scenario. In addition, the influence risk slopes for the different levels plotted in each graph is similar across varying levels.

However, the response plot for supply lot sizes of 15 and 30 units at constant average supply interarrival time of 42.5 hours seems to overlap with graphically different slopes which means that there is very minimal influence mitigating effect with the smaller supplier lot sizes at lower supplier interarrival times. The influence risk slopes are proportional to the previous levels of the control factors and this indicates a linear reduction slope from positive to zero. In this scenario the slope will not be negative during mitigation since the time-in-system for starts at zero when influence starts and hence will follow a path towards zero until it overlaps with the base line.

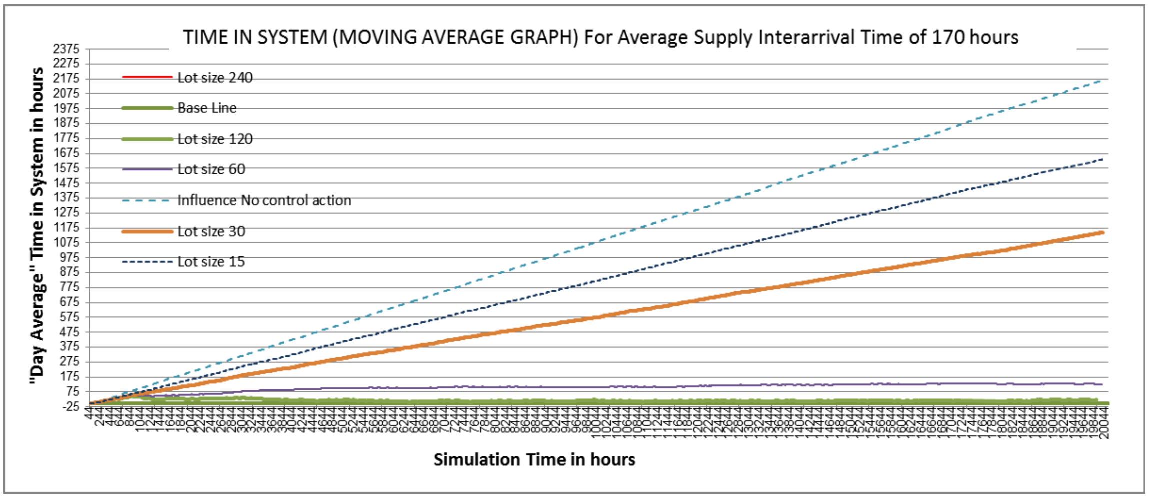


Figure 79 15% Decrease In Order IAT With Average Supply IAT Of 170 Hrs And Varying Lot Size

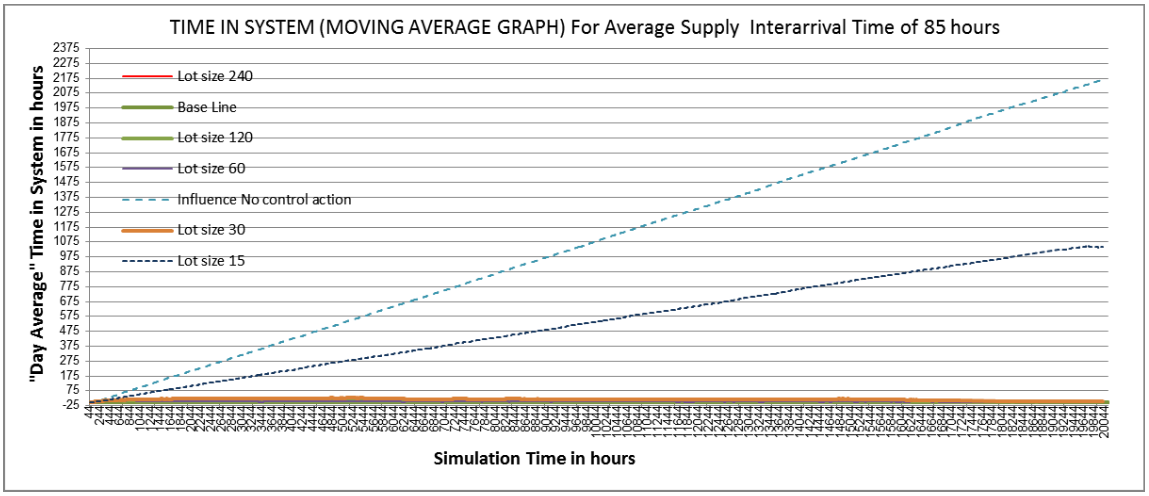


Figure 80 15% Decrease In Order IAT With Average Supply IAT Of 85 Hrs And Varying Lot Size

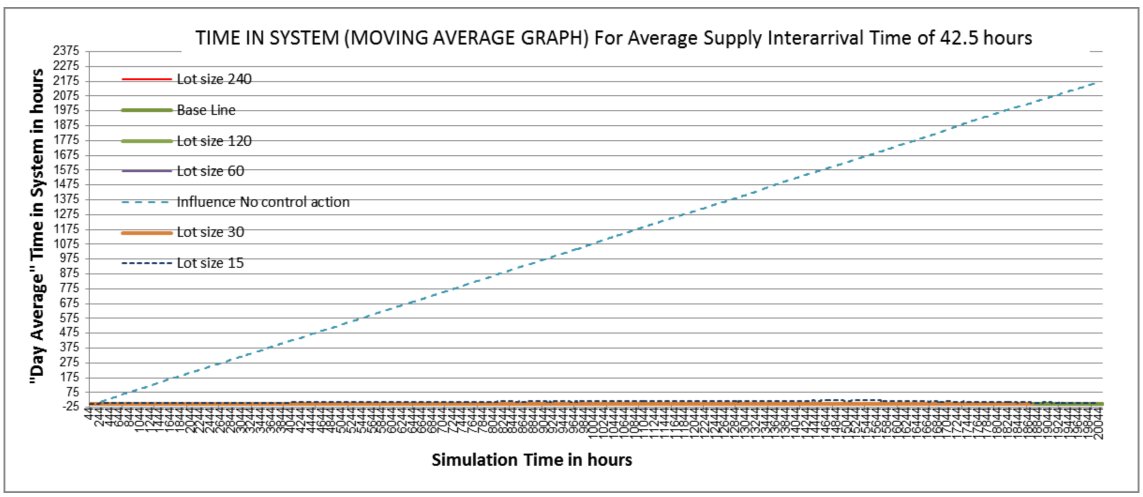


Figure 81 15% Decrease In Order IAT With Average Supply IAT Of 42.5 Hrs And Varying Lot Size

Based on the above results, the effective range for high and low experiment levels considered for supplier lot size factor are 120 units and 15 units respectively. Although higher lot sizes contribute mitigation of the external influence, it also results in extremely high excess inventory. The high and low levels considered for the average supplier interarrival time factor are 170 hours and 42.5 hours respectively. The data for the design of experiments with the average response variable is shown in the Table 33.

Table 33 Experiment Summary For 15 % Decrease In Order IAT

Experimental Factors			Response Variables			
Additional Supplier Lot Size	**Additional Supplier Interarrival Time**	**Delivery Rate (Units/ hour)**	**Net Present Value ($)**	**Net loss not recovered ($)**	**Influence Risk Slope**	**Peak Time in System (Hours)**
0	**0**	**0**	($11,526,523)	($11,526,523)	0.1070	2148.72 *
15	**170**	**0.08**	($5,635,630)	($17,162,153)	0.0818	1620.22
15	**42.5**	**0.35**	($4,395,488)	($15,922,011)	0.0031	62.59
120	**170**	**0.71**	($1,285,648)	($12,812,171)	0.0018	37.39
120	**42.5**	**2.82**	$510,787	($11,015,736)	0	1.69 **

Based on the Minitab results attached in Appendix C, the coefficients of the statistically significant factors and their interactions are used to create prediction equations for the response variable $\hat{y}_{PTIS}$ and $\hat{y}_{NPV}$ are as follows.

$$\hat{y}_{PTIS} = -557.5950 + 4.4916 * x_{LS} + 14.1197 * x_{SIAT} - 0.1137 * x_{LS} * x_{SIAT}$$

$$\hat{y}_{NPV} = -20163 + 12943.3 * x_{LS} - 27075.1 * x_{SIAT} + 25.185 * x_{LS} * x_{SIAT}$$

Based on the results and graphical analysis, the factor settings for x_{LS} and x_{SIAT} are 120 units and 42.5 hours. The predicted $\hat{y}_{PTIS}$ using this solution is 1.69735 hours and $\hat{y}_{NPV}$ for 10 year is $510,787, which is below the customer required time in system. For previous influences, since one supplier was added as a control action, the response variable was selected as excess inventory. Hence for the successful mitigation of the competitor out of business influence effect, the application of additional control action is expanded to include all the critical components used by the system. Even though this influence level sees an increase in number of orders, the additional supplier control action is applied to all the critical components. Also the number of orders is not enough to justify the investment costs associated with the addition of suppliers. NPV is calculated for the additional supplier control action setting when 1000 hours of no supply is affecting the system.

Table 34 Net Cash Flow For 15 % Decrease In Order IAT For Competitor Out Of Business Influence With Additional Supplier

<table>
<tr><th>Year</th><th>Net Cash Flow</th><th>NPV 5 year</th><th>NPV 10 year</th></tr>
<tr><td>Year 1</td><td>$(1,600.00)</td><td rowspan="5">$2,422,812.52</td><td rowspan="10">$510,787.36</td></tr>
<tr><td>Year 2</td><td>$504,184.00</td></tr>
<tr><td>Year 3</td><td>$962,240.50</td></tr>
<tr><td>Year 4</td><td>$963,183.50</td></tr>
<tr><td>Year 5</td><td>$950,727.25</td></tr>
<tr><td>Year 6</td><td>$(262,394.00)</td><td></td></tr>
<tr><td>Year 7</td><td>$(723,608.00)</td><td></td></tr>
<tr><td>Year 8</td><td>$(728,294.25)</td><td></td></tr>
<tr><td>Year 9</td><td>$(720,457.25)</td><td></td></tr>
<tr><td>Year 10</td><td>$(737,047.25)</td><td></td></tr>
</table>

Table 34 shows the net cash flow for the optimal settings (120 units supply lot size and 42.5 Supply interarrival time) and the NPVs for 5 and 10 year periods. The additional opportunity costs for the first year recorded under additional cash flows is positive for this setting. Due to the increase in number of orders and the system trying to recover, the number orders shipped was greater than the baseline scenario. The NPV of the control action investment is decreases with increase in time. The system adds on the excess inventories beyond the five year period point that it requires either additional resource with corresponding increase in demand in order to make more or to renegotiate the inventory reduction with the supplier.

In the supplier related influence effects, the system was starved of components and the number of orders shipped will come back to the base line scenario but will not increase beyond. In this influence the number of orders entering the system increases and with additional materials and at least 30% more utilization (bottleneck station capacity), the number of orders shipped/sold should increase contributing to excess revenue. However, since the additional supplier is added for all the other critical components the net cash flow is lowered and hence the NPV is less compared to the other influences and the additional supplier control actions. The NPV estimation in the control action investment in mitigating the effects of competitor going out of business influence effect helps a manager to relate the impact of system wide implementation vs. localized implementation of a control action in mitigating the influence effects.

<u>30% decrease in Order Interarrival Time</u>

The 15% decrease in interarrival time of orders was able to sustain with existing resources and with increase in component inventory from the suppliers. However, in order to completely mitigate the effects of a 30 % decrease in interarrival time between orders, additional resources is necessary along with additional suppliers. The mitigation of this competitor out of business level using two control actions together is discussed in the future section.

4.2.2 Additional Resource Control Action

The additional resource control action can be applied to two of the four external influences mentioned in this study: Competitor out of business external, and Product customization influence effects. A resource in this study is defined as a skilled person capable of assembling the product at different workstations. The additional resource control action can be applied by having one or more floater resources to assist at workstation. Each workstation has one dedicated resource trained to perform jobs particular to the workstations. A floater resource is defined as a resource that is cross trained across all the four workstation tasks. Instead of adding/ increasing dedicated resources with excess capacity at each station, a cross-trained worker resource can pick up the additional workload at any workstation, thereby easing the capacity constraints at different workstations. A cross trained worker acts as the flexible capacity buffer for each work station. Cross training helps a manager to reduce the overhead costs to a minimum compared to hiring additional dedicated workers at each workstation. However, if the order increase reaches and stays consistently at a point where the numbers of cross trained workers required are more equal than the total number of dedicated workers in the system, a manager must evaluate the need for hiring dedicated workers. In such scenarios, because of the less training and limited skillset, a dedicated worker is cheaper compared to a cross trained worker.

4.2.2.1 Competitor Out Of Business

In the competitor out of business influence effect, the number of orders entering the system increases through a decrease in the supplier interarrival time and the same two levels used for supplier control action (15% and 30% decrease in interarrival time) are applied. However, as discussed earlier, the 15% decrease in interarrival time of orders was able to be sustained with increase in component inventory from the suppliers and without the addition of floater resources. In addition, for the 30 % decrease in interarrival time in order influence effect to be completely mitigated two control actions are necessary: additional supplier and additional resource. The mitigation of the 30 % decrease in order IAT level by applying the two control actions will be discussed in a later section.

4.2.2.2 Product Customization

The product customization influence effect occurs when more than one type of product enters the system. When this influence effect occurs, the proportion of the custom products entering the system is increased and is considered as the controllable factor in this study. There are two types of products introduced in the system during this simulation. The first type is the standard product type with the base line scenario. The second product type is the defined as the custom product type where the average processing time at each station is increased by 25%. A set up time of 0.9 hour occurs every time a product type switches to another type at each processing station. Based on the preliminary investigation results and the response study analysis of individual influences on the system, two levels of customization influence are 30 % and 60 % of custom products entering the system.

30% Custom Products

In a 30% custom products level, the ratio of custom to standard products entering the system is 3:7. Since the additional resource control action has only one controllable factor (capacity of the floater resource) in this study, a single factor analysis was conducted where the capacity of the floater resource is increased from one to four. Recall in the previous discussion about limiting the number of floater resources to be equal or less than the dedicated number of resources in the system, hence the higher experiment level is limited to four. Figure 82 shows plots for a 30% custom product in the system with varying floater resource capacity (control action factor). The peak time-in system value seems to decrease by 50% for every increment (of one floater) to the number of floaters in the system. By plotting in a smaller Y axis scale the response for adding 3 and 4 floaters to the system under the influence of 30% custom products effect, the influence risk slopes and the peak time-in-system responses could be inferred. Although the influence risk slopes show a zero slope (sign of possible recovery) the peak time in system values are still above the base line scenario. A manger could infer that the additional resource control actions are not the only cost effective solutions to mitigating the effects of the customization influence. The NPV estimations are done for both the 3 floater resources and 4 floater resources additions in order to assist a manger to justify the selection of an appropriate level of control action.

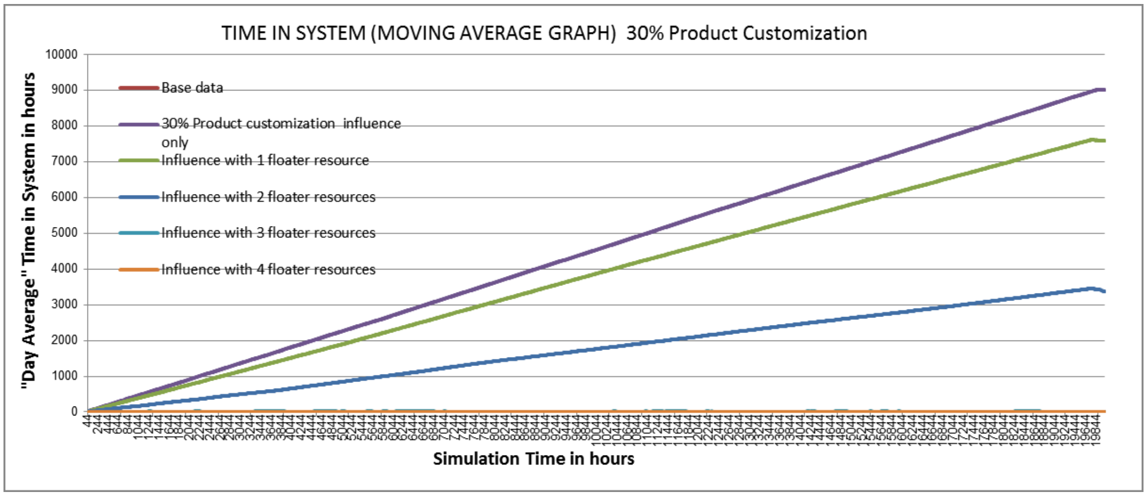


Figure 82 Resource Control Action Response Plot For 30% Product Customization

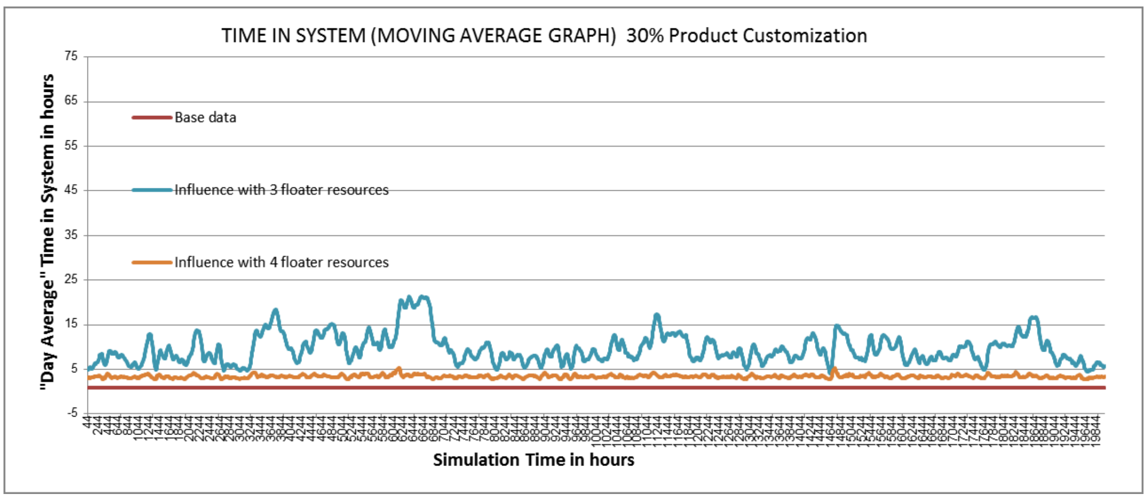


Figure 83 Floater 3 And 4 Addition Response Plot For 30% Product Customization

The two work sheets calculating the NPVs for 3 and 4 floater resources are attached in Appendix D. Recalling the earlier definition of control action investment metrics, these metrics assist in measuring the investment costs for a control action. In case of the additional resource control action, the number of floaters added to the system for each year control action investment metric. This metric is decided through graphical estimation as previously discussed or through. In the actual system, hiring a fulltime floater resource means the organization would have to pay a yearly salary. In a lot of manufacturing organizations even though a floor worker is paid on an hourly basis, union contracts and other employee contracts ensure a minimum number of pay hours required for the worker. This policy translates to idle capacity in cases of low demand. Hence this case study assumes the worst case scenario where a minimum number of pay hours is guaranteed. In the simulation it translates to an integer increment in capacity and in the NPV calculation the floater resource payroll cost is added in the cash out section (accounted as part of the investment). In addition, the one-time cost of adding resources such as advertisements, training is added in under the cash flow in section of the worksheet. For this case study the cost of initial resource set up and training for one floater addition is assumed to be $10,000 and $1500 respectively and the hourly wage is set at $18 per hour. The initial resource setup costs include cost of advertisements, medical fitness tests, and other miscellaneous one-time costs. The training costs involve approximately a two week pay dedicated for employee training and other miscellaneous expenses incurred during the training process. These values are derived from the case study organizations historical data.

The cash flow in section of the worksheet is similar to the additional supplier control action and it estimates the potential savings accrued due to the mitigation of the external influence. The two basic savings that mitigate the external influence effects are additional opportunity costs and lost sales recovery costs. Additional opportunity costs reflect the increased sales due to the mitigation effect on the external influence by the control action. The lost sales recovery is cost recovered from the on-time delivery of orders to the customer which would have otherwise been late due to the external influence effects. For this control action as previously discussed for additional supplier control action, the penalty for delayed delivery is cancellation of late orders from the customer and the product market price are set as $300. In real world scenarios, the penalties can range from order cancellation to a late premium for every ordered delivered late. The total net cash flow is the deduction of cash flow in from the cash flow out for each corresponding year. This cash flow analysis extends over a span of 10 years which is equivalent to 20,000 hours of simulation time.

Using 7.5% as the discount rate, NPV is calculated for the additional resource control action settings by increasing the number of floaters from 1 through and up to 6, when 30% product customization influence is affecting the system. The experiment summary is shown in Table 35.

Table 35 Experiment Summary For 30 % Product Customization

Experimental Factors	**Average of Response Variables**			
Number of Floater Resources	**Net Present Value ($)**	**Net Loss Not Recovered ($)**	**Influence Slope**	**Peak Time in System (Hours)**
0	($10,689,867)	($10,689,867)	0.4503	9031.67 *
1	($234,317)	($10,924,184)	0.3786	7602.16
2	($468,635)	($11,158,502)	0.173	3372.72
3	$6,180	($10,683,687)	0	21.39
4	$3,298,190	($7,391,677)	0	5.31
5	$4,511,756	($6,178,111)	0	2.77 **
6	$4,463,872	($6,225,995)	0	2.608

The NPVs for both levels (floater capacity of size 3 and 4) of the additional resource control actions are negative. However, despite the negative results, the negative NPV is less in case of 2 floaters compared to the other floater sizes. Based on the results, the additional resource control action is not the best method to mitigate the effect of product customization influence effect. It is possible that in combination of another control action such as setup time reduction control action this strategy might be viable from a managerial perspective. The set up time in this case study is set as the value as the average time-in-system value of the base line scenario. In some cases, the number of custom products in the system might justify the cost of setting up another manufacturing line where only one product variety flows through the system.

60% Custom Products

A negative NPV for additional resources control action in mitigating the effects of 30% custom products entering the system suggests that the application of additional resource control action individually will not be an ideal choice for managers. Hence further investment cost analysis of this control action in mitigating higher levels of custom products entering the system influence effects is differed to future scope of study.

4.2.3 Additional Resource and Additional Supplier Control Actions

As discussed in the previous section where the additional supplier control action is being used to mitigate the 15% decrease in order interarrival time influence effects, higher levels of order numbers increase in the system require additional capacity either in terms of sub-contracting, and/or hiring workers (dedicated or cross trained). Hence, the control actions additional resource and additional supplier can both be simultaneously applied on an external influence to maximize the mitigation of the influence effects. The competitor out of business influence effect is one such external influence whose effects could be mitigated by applying the two control actions simultaneously. Based on this discussion, the 30% decrease in order IAT level is considered for this analysis.

30% Decrease in Order Interarrival Time

There are three factors for the experiment design with two from additional supplier and one from additional resource control actions. The control action factors supplier lot size and average supply IAT from supplier control action and floater resource capacity from resource control action are selected. Based on the previous analysis of the external influence and the control actions, pre-determined levels based on previous experiments, are selected for the control action factors: supplier lot size level are 120 units and 15 units, average supplier interarrival times levels are 170 hours and 42.5 hours, and floater resource levels are one and two resources. Due to the increase in data size, computation issues in data transfer, plot and analysis was not possible at 20000 simulation hours. For this analysis the simulation time was changed to 12,000 hours after warm-up period. Two graphs shown in Figures 84 and 85 has the response curve for time in system obtained by keeping the supply lot size constant and varying the remaining control actions.

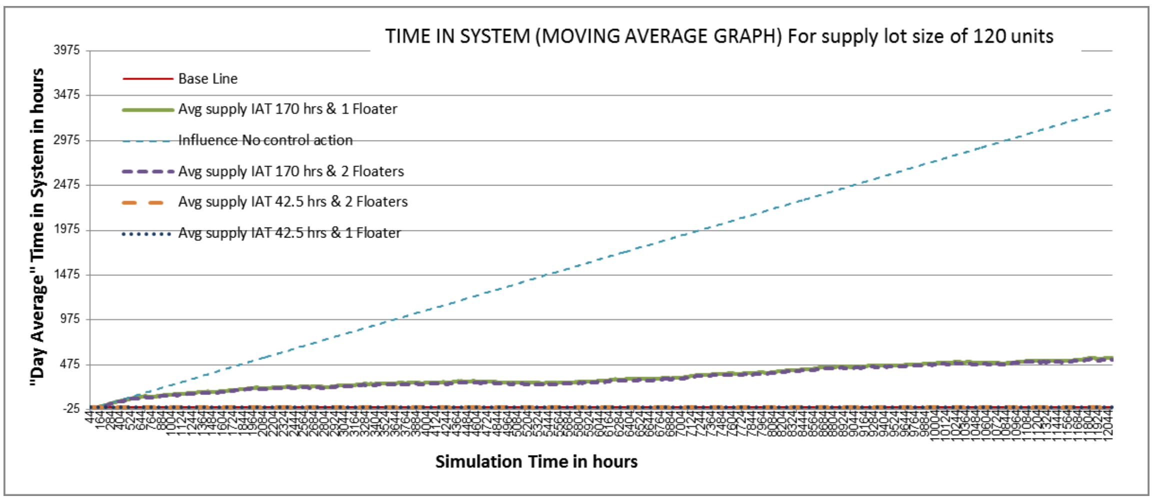


Figure 84 Dual Control Action With 30% Decrease In Order IAT At Supply Size Of 120 Units

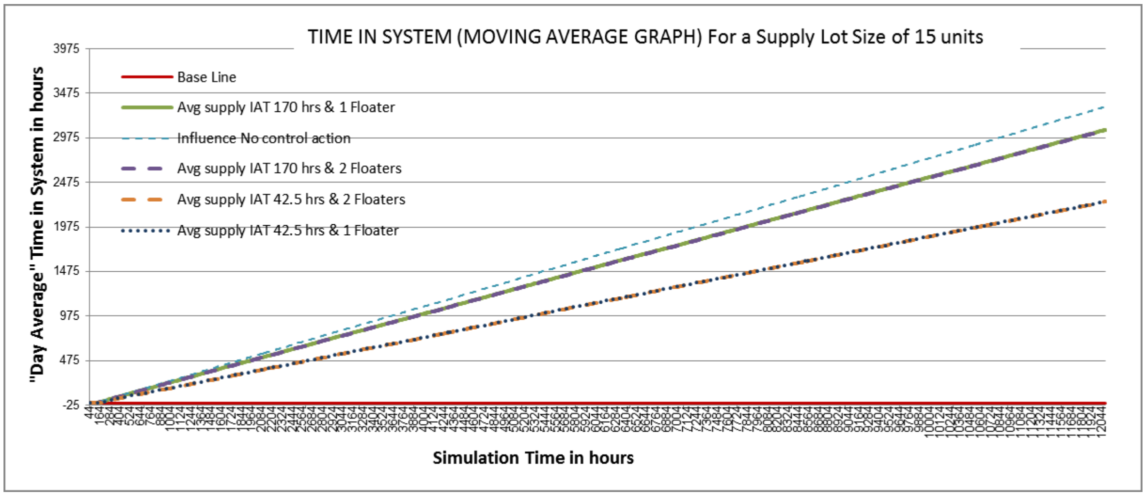


Figure 85 Dual Control Action With 30% Decrease In Order IAT At Supply Size Of 15 Units

This overlapping of the responses with the base line indicates that the control action has completely mitigated the effects of the external influence with an influence risk ratio of zero and the peak value of time in system coinciding with the average time in system of the base line system. Figure 85 shows that for control action factors average supply IAT of 42.5 hours, with 120 unit lots size the influence effect seems to be mitigated for both resource levels. The data for the design of experiments with the average response variables is shown in the Table 36. Since both the time in system response variables are correlated, the peak time in system value was selected.

Table 36 Experiment Summary For 30 % Decrease In Order IAT

Experimental Factors				Average of Response Variables		
Floater Size	Additional Supplier Lot Size	Additional Supplier Interarrival Time	Supply Rate (Units/ hour)	Net Present Value ($)	Influence Risk Slope	Peak Time in System (Hours)
0	0	0	0	($11,748,900)	0.2760	9031.66
1	15	170	0.08	$2,905,885	0.2556	3835.61
1	15	42.5	0.35	$2,705,289	0.1885	2829.63
1	120	170	0.71	$2,464,670	0.0435	654.03
1	120	42.5	2.82	$7,820,449	0.0003	1.57
2	15	170	0.08	$830,543	0.2556	3835.52
2	15	42.5	0.35	$3,304,748	0.1885	2829.71
2	120	170	0.71	$3,864,567	0.0427	642.97
2	120	42.5	2.82	$7,579,885	0.0001	1.29

Because of multiple suppliers, the excess inventory response variable is converted into excess inventory costs which is the total cost of the increase in inventory for each component is multiplied by their unit supplier cost. The estimated effects, coefficients for the prediction equation and analysis of variance results are in Appendix C. Based on the results, the factors are able to predict the response variables (both peak value of time in system and total excess inventory costs) within 100% confidence interval. The floater resource factor in the prediction equation is defined by the variable (x_{FR}). The prediction equations for both the response variables are as follows.

$\hat{y}_{PTIS} = 667.156 + 14.5997 * x_{LS} - 5.02243 * x_{SIAT} - 15.6057 * x_{FR} - 0.01195 * x_{LS} * x_{SIAT} + 0.090 * x_{FR} * x_{SIAT} + 0.06443 * x_{FR} * x_{LS}$ -0.000369 $* x_{FR} * x_{LS} * x_{SIAT}$

$\hat{y}_{NPV} = 25301.98 + 33244.1 * x_{LS} + 16782.4 * x_{SIAT} 1580116 * x_{FR} - 344.009 * x_{LS} * x_{SIAT} - 23850.1 * x_{FR} * x_{SIAT} - 18107.5 * x_{FR} * x_{LS}$ +267.822$* x_{FR} * x_{LS} * x_{SIAT}$

Based on the plots and the data analysis for the factors x_{FR}, x_{LS} and x_{SIAT} the settings that provide the best results are 2 resources, 120 units and 42.5 hours respectively. The predicted $\hat{y}_{PTIS}$ and $\hat{y}_{NPV}$ using this solution are 1.29 hours and \$ 2,130,408, which is below the customer-required time in system.

The cash flow calculations use the two sub sections: one for additional supplier control action and the other for additional resource control action. The methodology and parameters for this control action is the same as described in sections 4.2.1 and sections 4.2.2 for additional supplier control action and additional resource control action respectively. Table 37 provides the NPV for the investment and the net loss not recovered. The competitor out of business influence provides a positive effect on a manufacturing system where more orders enter the system. In order to exploit this positive effect the additional supplier and resource control actions are applied simultaneously. However, the net loss recovered is negative for all levels of the control actions even though the net present value is positive. Despite the revenue from shipping more orders, the net loss remains on the negative side although 66% of the loss is recovered. The higher number of late orders exiting in the system than the base line scenario due to large queue lengths contribute to a higher loss in revenue (effect of the external influence). With 100 % rejection of late orders by the customers, the NPV without control action application and due to the influence is higher.

Table 37 Net Cash Flow for 30% Decrease in Order IAT, Competitor Going Out of Business with Additional Supplier and Resource Control Actions

Experimental Factors				Average of Response Variables	
Floater Size	Additional Supplier Lot Size	Additional Supplier Interarrival Time	Supply Rate (Units/ hour)	Net Present Value ($)	Net loss not recovered
0	0	0	0	($11,748,900)	($11,748,900)
1	15	170	0.08	$2,905,885	($8,843,015)
1	15	42.5	0.35	$2,705,289	($9,043,611)
1	120	170	0.71	$2,464,670	($9,284,230)
1	120	42.5	2.82	$7,820,449	($3,928,451)
2	15	170	0.08	$830,543	($10,918,357)
2	15	42.5	0.35	$3,304,748	($8,444,152)
2	120	170	0.71	$3,864,567	($7,884,333)
2	120	42.5	2.82	$7,579,885	($4,169,015)

A positive NPV might be an incentive to convince a manager that the settings for this control action will return a positive return on investment as well as mitigate the effects of the control action. A manager must be cautious to use the NPV as a measure to gauge the success in application of a control action. As stated earlier, the loss not recovered in Table 37 will be a measure that determines if the loss has been completely recovered by applying the control action.

4.3 Analysis and Results with Respect to Research Objectives

As we recall, the first objective of this study is to design and conduct a series of single factor experiments where external influence defined levels of change are applied to the manufacturing systems with and without embedded control actions. Part of this objective involved identification of relationships that exists between an external influence, and the manufacturing system through the system performance metrics. The transient response characteristics of a performance metric over simulation time were able to provide better understanding of the effects of the external influences. During the course of the study, based on the analysis of the results of the four external influences, the time in system performance metric was identified as the main performance metric, which could be used to compare the effects of different external influences on the system. In order to simplify the description of the response plot characteristics of the time in system metric, two "meta" performance metrics were introduced in this study: Influence risk slope and peak time in system value. The influence risk slope (β) will be able to describe the direction of the slope as well as the rate of recovery with or without the application of control actions. The Table 38 shows if there is a natural recovery of the system of the time-in-system performance metric based on values of β. A positive or zero β value will require a control action to mitigate their effects whereas a negative β indicates a recovery of the performance metric over time occurs without control action.

Table 38 Results Summary of External Influences with Control Actions

External Influence	Level Descriptions	Influence Experiment Levels	β	Optimum Control Action Levels			NPV	Net loss
				Supplier lot size	Supplier Interarrival Time	Floater resource number		
Supplier out of Business	No supply for a certain period	500 hours no supply	Negative	120 units	42.5 hours	0	Positive	Negative
		1000 hours no supply		120 units	42.5 hours	0	Positive	
Diminished Supplies over time	Supply lot size reduced twice consecutively in one year intervals	4% cumulative decrease	Positive	15 units	42.5 hours	0	Positive	Negative
		8% cumulative decrease		120 units	42.5 hours	0	Positive	
Competitor out of business	Increased order numbers through decrease in order Interarrival	15% decrease in order interarrival time	Positive	120 units	42.5 hours	0	Positive	Negative
		30% decrease in order interarrival time		120 units	42.5 hours	2	Positive	
Product Customization	Higher proportion of custom orders	30%	Positive	0	0	2	Negative	Negative
		60%		0	0	Not estimated	Projected Negative	

**Comparison between NPV(s) at 7 year level

As discussed in earlier sections, the net present value in all the cases (system affected by the external influence) reflect the amount that could be recovered from the loss incurred due to the influence effect. The control action is an investment to recover (mitigate/exploit) the loss due to the influence effect.   The second objective is to study the effects of a control action in mitigating or exploiting the external influence effects. The understanding of the results from a managerial aspect will help a manger to decide the application and level of possible control actions. With the two meta performance metrics β and peak time in system value, a manager could estimate the performance of the system under the different intensity levels of the external influences. To mitigate or exploit the effects of external influences on a system, a manager applies control action. The study selected net present value as the decision metric to capture the amount of "effort" put in to implementing a control action thereby a justifiable mitigated/exploited effect on the external influence occurs. Through a series of experiments applying the control actions on the two levels of the external influences in this study, the estimation of net present value is able to provide the manager an insight of the benefits obtained due to mitigation of external influences by the control action. One example is the product customization influence where the production time and setup time between product type switch at each station increases the time-in-system metric causing WIP and delayed orders. Additional resources (cross trained) were added to clear the WIP in the stations. The NPV for the application of additional resource control action to mitigate the effects of this influence was estimated to be negative for all practical increases in the number of cross trained resources. Based on these results, a manager has two options to consider: setup time reduction control action or a separate line for the custom products. The first option is to introduce quick change setup of fixtures for each type of product entering the system. The second option though not discussed in this study before would be to set up a separate line for the custom products. In cases where two external influences such as the product customization as well as the competitor going out of business, the second option becomes more viable because of the increased demand.

A scenario analysis could help a manager to evaluate the expected value of investment in a control strategy. By creating various scenarios having the external influences affecting the system and combining them with the probability that they will occur, a manager could determine if the investment in the control action is a viable option. The scenario analysis for supplier out of business external influence is shown in Figure 86.

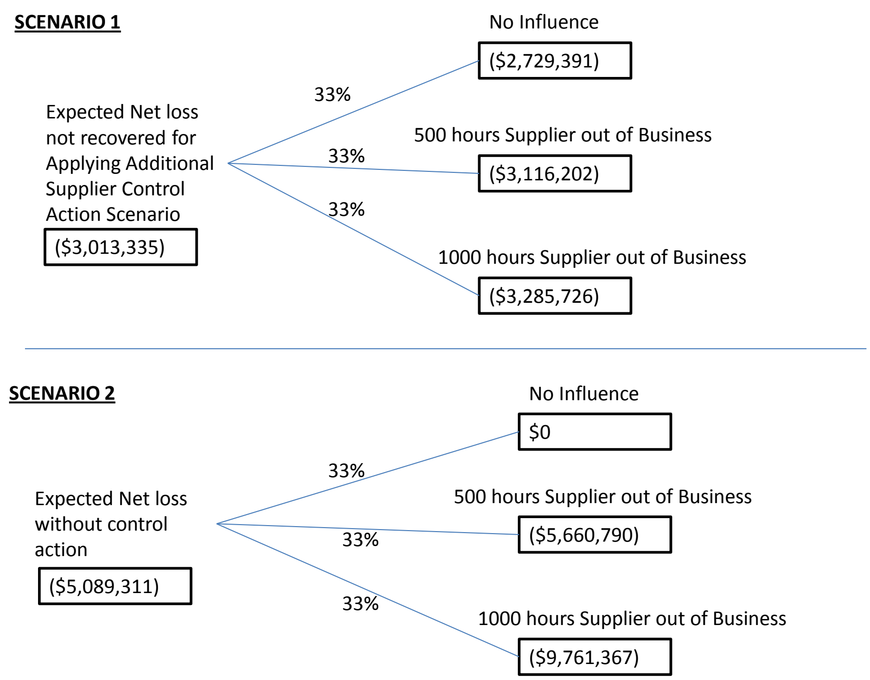


Figure 86 Scenario Analysis for Supplier Out of Business Influence

The figure shows a comparison between applying and not applying the additional supplier control action when the risk for different levels of supplier out of business exists. A risk probability of 33% is assumed for each of influence levels and the expected value is derived for both scenarios (with and without control action). The net loss value is used in this analysis because a manager must not be misled by the positive NPV value in applying the control action but rather take into account the loss due to the influence. In the supplier out of business influence scenario analysis, the net loss due to not applying a control action (scenario 2) is greater than the net loss due to applying a control action (scenario 1). The net present value can be extended to include the application of one or more control actions on a single influence.

The scenario analysis for diminished supplies external influence is shown in Figure 87. The risk probability is assumed to be 33% spread across three external influence levels. In scenario 1, application of additional supplier control action is considered and in scenario 2 the effect of the diminished supplies influence is considered without application of control action. Based on the analysis, a 60% reduction in net loss occurs if the manager choses to apply the control action instead of not applying it.

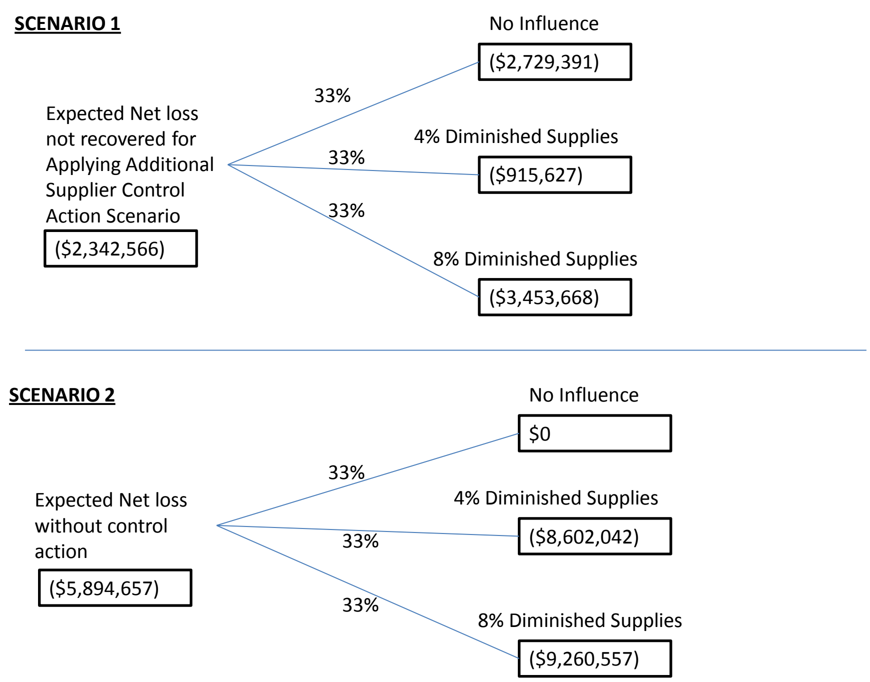


Figure 87 Scenario Analysis for Diminished Supplies Influence

A manager could compare the effect of two different external influences using the scenario analysis. For example by varying the probability of occurrence for each scenario in the diminished supplies external influence, the expected net loss is comparable to the expected net loss from the supplier out of business. This analysis provides the manager to relate in terms of a financial metric, the different external influences and their effects on the manufacturing system. Figure 88 illustrates the example discussed above.

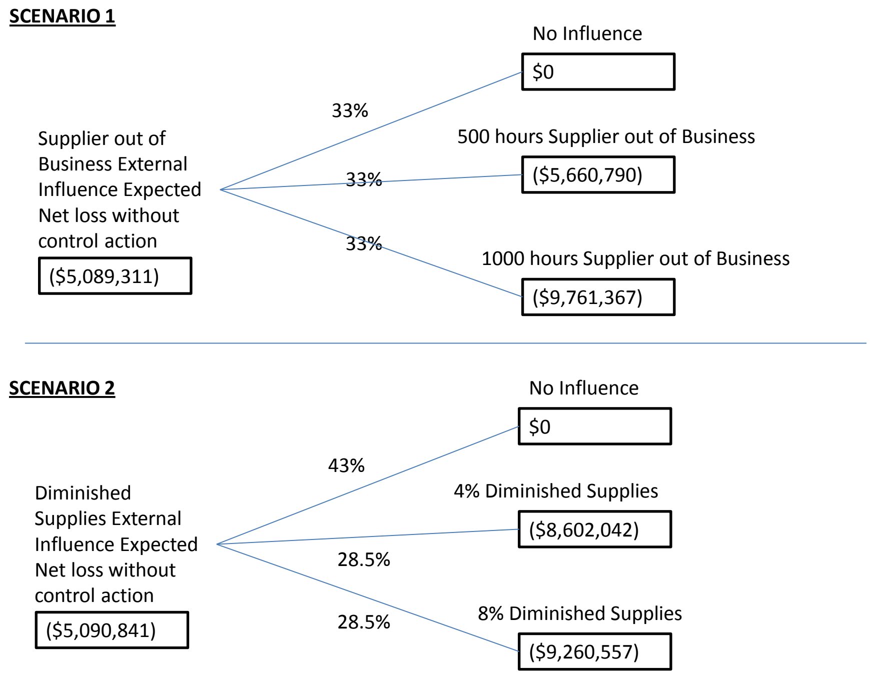


Figure 88 Scenario Analysis Comparing Supplier out of Business and Diminished Supplies Influences

The third objective is to study the special case scenarios where the more than one control action is required to mitigate/exploit the effect of one external influence. The higher level of the competitor out of business requires both the additional supplier as well as the additional resource control action applied together. In such cases, it is difficult to conduct scenario analysis without the assumption that both control actions are applied at all levels of the external influence. In the case study organization, the investment cost for application of the additional resource (-$240,564) is about 8% of the investment cost to apply additional suppliers for each component (-$6,848,062). But in cases where the investment cost of securing an additional supplier is significant less than the investment cost of adding resources, a different approach might be necessary to get a fair comparison. In the scenario analysis for the diminished supplies external influence shown in Figure 89, the expected loss from applying both the control actions is about 63% less than the expected loss from not applying the control actions.

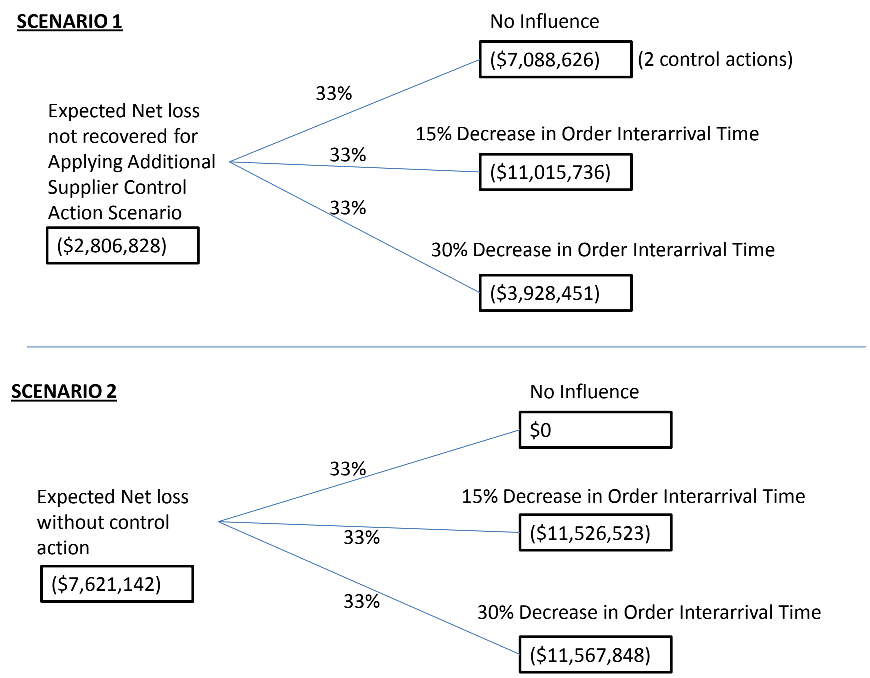


Figure 89 Scenario Analysis for Competitor Out of Business Influence

The final objective of this study is to identify and structure a preliminary process for the manager to effectively select the control action(s) based on the metrics of interest and the anticipated external influences affecting the system. The preliminary selection processes detailed Sections 3.4 and 3.5 of this study for the selection of performance metrics and control actions respectively, could guide a manager in selection of additional control actions for the appropriate external influences.

CHAPTER V

CONCLUSIONS AND FUTURE SCOPE OF STUDY

Conclusions

The primary objective of this study is to determine the effects of external influences with or without the application of one or more control actions that helps in mitigating the influence effects. The study began by identifying the key factors in the external influences as well as the control actions that could be varied in an experimental setup in order to better understand their relationship. Ultimately, two levels were selected for each of the factors. In order to ensure a fair comparison of the system performance under different external influences, only one factor was varied at a time while the other factors were kept constant. However, when a control action has more than one factor, the important factors were selected based on their applicability in the simulation model and their statistical significance in mitigating the external influence effects through the selected performance metrics.

The following part addresses the first research question which questions the effect of environmental influence on a system performance metrics. Several performance measures were considered during the course of the study in order to relate the effects of all the external influences on the manufacturing system. The peak time-in-system value is applied as the response variable (performance metric) in the experimental setup and response variable is the standard performance metric for understanding the effects of influences. The direction of recovery is defined by the influence risk slope while the degree of recovery is defined by the peak time-in-system. In order to assist a manager with the justification of selection and implementing control actions, managerial finance performance metric, net present value of the implementation is selected. With the control action factors, response variables in place the simulation model(s) were developed, verified and experimental runs were conducted. Upon completion of the experimental runs the results were analyzed, and interpreted as discussed in Chapter 4.

The general conclusions drawn from this study is that the transient behavior of key performance metric(s) such as the time in system over an extended period is essential to study the effects of external influences as well as the mitigating effects of the control action. This study is an event-based study where the response of a particular metric over time is studied. From a list of key performance metrics selected in this study (bottleneck workstation WIP, percentage of orders delayed, critical component inventory size) the response of Time in system performance metric along with NPV could be used as a fair comparison in order to study the effects of external influences. The graphical response output of the time in system performance metric can be describe through two “meta” performance metrics (peak value time-in-system and influence risk slope). The study uses influence risk slope to understand the long term effect of the influences and also the mitigating effect of the control actions. The experimental results of the response curves for all the external influence effects and the application of control action for the time in system show a linear response or a smoothed linear trend. The implementation of a control action must be justified by a managerial performance metric such as the net present value. The net present value for a control action is used as a mutually exclusive investment in this study where a product delayed and returned to the customer is deducted from an organization’s balance sheet as scrap and the control action cash flow in would be the recovery of the scrap from future delayed orders. Manufacturing literature does not connect this cost missing link between risk due to external influence and the control to mitigate the influence effects. Recall from the literature review that Keene & Gharbi (1999) uses the “incurred costs” as a dependent variable. The cost function does reflect a net cash flow to the system with the implementation of a control action. The study uses two basic components for estimating the cash flow in to the system: Additional Opportunity Revenue (AOR) and Lost Recovery sales (LSR). Lost sales recovery as discussed earlier is the cash flow gained by mitigating the external influence effects. Additional Opportunity Revenue introduced in this study captures the mitigation effect of a control action also improves the existing baseline scenario.

One of the findings of this study is that the estimation of cash flow out (investment) to apply a control action differs from one control action to another. The investment cost estimation differed from additional supplier between additional resource control action. This variation changes method to evaluate the control action investment costs. For example with an inventory strategy to mitigate any case of supply related external influences (such as supplier out of business, diminished supplies over time), the cost of inventory, obsolescence costs, holding costs, procurement costs etc. are used to estimate the costs of the mitigating strategy employed. In case of the resource related control strategies, pay rate, shift hours etc. are used to estimate investment costs. The net present value through the estimation of additional net cash flows (or avoidance of losses) provides the investment cost metric that is generated for all scenarios involving the application of one or more control actions to mitigate the effects of the external influences. The net present value also takes into account the discount rate (required rate of return) over time.

Certain levels of external influences do require application of more than one control action simultaneously in order to eliminate the effects of a single external influence and bring the performance measure back to base line scenario. The high level for competitor out of business external influence included both additional suppliers as well as additional resources to mitigate the effects and bring system performance back to base line. It is also highly imperative to understand the effects of an external influence before applying a control action. The application of a control action could be “local” or “global” in application and it depends on the type of external influence. In the study scenario, the supplier out of business and diminished supplies over time targets one critical component to create a disturbance and to mitigate the effect of the influence, only one additional supplier is added to the system with less investment costs. When the additional supplier control action was extended to mitigate the influences of competitor out of business, additional suppliers were added to all seven critical components. This addition increases the investment costs thereby reducing the net present value unless a sales increase along with the corresponding capacity increase occurs. In cases where the external influences recover completely with a negative influence risk slope (when the influence recedes after some time or the effect of influence is mitigated by the control actions already present in the system), the multiple occurrences of the external influence after each recovery will increase the net present value because multiple occurrences means more dynamic environment in which one must manage. In other words, with the same control action investment cost, the recovery costs and possibly additional opportunity revenue might increase.

The overall study was a systematic investigation in to the effects of the external influences and the control action factors that help mitigate the influence effects on the system performance metrics. The study provides the foundations for the development of a comprehensive initial methodology for the selection of the control actions based on the effects of the external influences on the manufacturing system. Upon reviewing the accomplishments of this research effort, it has made five major contributions to the area of the effect of external disturbances on a manufacturing system and their mitigation through control actions.

1. The study proposes a methodology that could help a manager to select from several overlapping tools and methodologies across different manufacturing philosophies and to define and propose an initial control action selection procedure.

2. A controlled study that proposes the concept of external influences on the manufacturing system, and providing a linkage between the external influences to the elements in the external environment.
3. This study proposes an initial selection process of the performance metrics that could help measure the impact of external influence effects on the manufacturing system.
4. This study connects the effects of external influences to control action(s) investment costs and the expectations of the customer through the use of a financial project management metric which helps to reflect the managerial aspects of the system recovery from influence effects through control actions. By conducting scenario analysis, a manager could compare the financial effects of different influences and also the application of control actions. The evaluation of different scenarios helps a manager to relate the mitigation/ exploitation effect of the control actions(s) to system input parameters through performance metrics with respect to customer expectations.
5. The contribution of this study is to recommend the application of response analysis approach in measuring the system performance under the influence effects and the recovery of the system from these effects through the application of the control actions. This study analyzes, and the interprets the effects of the stabilization of the system from transient state to the steady state exhibited by the response curves of the system performance metric during the mitigation of the external influences when a control action is applied. This is a significant contribution since it points out the need for further research in the analysis of the response plots during the time of the influence effects instead of analyzing and interpretation of the performance metrics at completion of the experiment time.

In addition to these contributions, this research effort brought to light several areas where future research scope may be promising. This document will conclude with a review and discussion of those areas.

Areas for Further Research

This research effort has opened a number of possibilities for further research in the study of control actions in mitigating the external influences created by the elements outside the boundary of a manufacturing system. This section will discuss in a brief review of the possibilities for future study and is broken into two basic areas: 1) replications of the study with parameter changes, and 2) possible extensions of the study.

In order to limit the scope of the study, the customer penalty rate is kept at a constant of 100% where a late order is being returned to the customer and the organization scraps the order completely. Future studies could be done by varying the customer penalty where the customer discounts the product price for late delivery by imposing a penalty percentage less than 100%. This study replication could also provide insight into managerial decisions where the manager decides to choose the option of not making the product instead of late delivery due to an influence effect on the system. In such a scenario, the inventory accumulation costs as well as the cost of idle resources must be weighed against the penalty rate for making a decision.

Another replication of this study could be conducted by changing the critical components bin size. The model used in the study limits the quantity of components available for production from the storage bins. This limited bin space is a reflection of the case study organization where limited space was available for manufacturing and material storage. The excess components supplied by the vendor are shipped back due to this space constraint. The additional storage space created might provide a temporary buffer that could mitigate or exploit low levels of external influence and would constitute as a temporary control action. From a managerial perspective the additional cost involved investment for additional space might or might not outweigh the benefits accrued from mitigating/exploiting an external influence effect.

The study uses a triangular distribution for the order interarrival time based on the data from the case study corporation. Different market scenarios could be simulated by changing the distribution parameters or the distribution. The results could help a manager to understand the influence effects on the system for different market scenarios. Another parameter where a stochastic process could be introduced is the setup time. In the current study, the setup time for each station between product changes is assumed as a constant due to lack of data. By collecting additional data for the setup time, fitting the data to a distribution, changing the corresponding parameters in the model, and analyzing the results, a manager could understand the varying effects of setup time on the system. The cost parameters that impact the net present value of a control action investment are product cost, discount rate at which the organization could borrow component costs, and customer late order penalty. By varying these parameters between the best and worst case scenarios either deterministically or through Monte Carlo simulation models, a manger could understand the effects of the parameters on the system during the influence and with a control action.

There are several possible extensions of this study. Some of these extensions are listed in this section. The first extension is to assess the combinatorial effects of the external influences. This study addresses the effect of each external influence acting individually on the system and also the control action(s) required to mitigate/exploit the effects. As a possible extension, a research objective could be added as follows.

- For a group of relevant external influences acting on the system, which performance metric of the system is affected the most and by what degree?
- For a group of relevant control actions, with a group of external influences acting on the system, which performance metric is affected the most and by what degree?

The second extension of the study could be the inclusion of multiple occurrences of the same external influences over time. This study extension is applicable for external influences that occur for a relatively short period of time compared to the simulation time such as the supplier out of business influence considered in this study. By assigning a probability to the multiple occurrences of this external influence over time, a manger could make a decision with regards to the level of investment in a control action.

In this study an external influence starts at the beginning of the simulation and ends with simulation time (except for supplier out of business influence). The control action is also applied throughout the simulation time. In both cases (control action and external influence) the parameters remain constant throughout the simulation time. In the proposed study extension, a dynamic feedback loop could be created where a control action is applied when an external influence occurs and removed when the influence ends. By comparing the results from this study extension to the current study, a manger could understand the impacts on a system when a proactive (current) and reactive (proposed study extension) control actions are applied.

In this study, an initial framework was proposed to capture the relationship between external influences, control actions and relevant performance metrics. Additional research effort could help the map more external influences and the relevant control actions. Also the initial performance metric and control action selection processes could be refined through the extension of this research. The lack of clear relationship linkage between the external elements, influences caused by them, the possible control actions that could mitigate them and the performance measures used to measure the recovery as well as investment costs is a fertile area for research. A great deal of research is done on parts of this linkage and connecting the links would help a manufacturing system to better prepare for uncertainties. This study lays the first step by building a foundation by connecting the different “actors” along with their interactions with the system.

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APPPENDICES

APPENDIX A

Selection of Performance Metrics

Metrics list adapted from White (1996), Law and Kelton (2000)

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
1	7	Cost relative to competitors	Not Applicable	$	Comparision among competitors- non uniform measurement methods and not applicable in all cases		Not selected	N/A
2	2	Perceived relative cost performance	Not Applicable	$	Comparision among competitors- non uniform measurement methods and not applicable in all cases	Redundant as above metric	Not selected	N/A
3	20	Manufacturing cost	Output	$	Defined also as Production cost/unit and could be correlated through lead time	Selected as Production cost/unit, Not applicable for simulation because constant costs for material and labor	Not selected	N/A
4	20	Capital Productivity	Output	Numbers/$	Ratio of output per unit to capital cost invested	Correlated to Throughput rate	Not selected	N/A
5	20	Labor Productivity	Output	Numbers/time	Ratio of output per unit to labor hours invested	Could be broken down as labor time (both direct as well as indirect) and throughput rate	Not selected	N/A
6	20	Machine Productivity	Output	Numbers/time	Ratio of output per unit to Machine hours invested	Could be broken down as station time and throughput rate	Not selected	N/A
7	20	Total factor Productivity	Output	Numbers/$	Includes all the above productivities	includes all the above productivities and their sub factors	Not selected	N/A
8	10	Total product cost as a function of lead time	Output	$/time	Has two basic units Production cost and lead time	Redundant as Production cost/unit & lead time	Not selected	N/A
9	20	Direct labor	Input	time	Not Defined interms of time or cost	Input for Simulation model	Not selected	N/A
10	20	Indirect labor	Input	time	Not Defined interms of time or cost	Input for Simulation model	Not selected	N/A
11	10	Percentage improvement in labor/desired labor	Output	%	Vague definition - desired labor	Apart from vague definition it is a Relative measure	Not selected	N/A
12	6	Relative labor cost	Output	$	Labor cost relative to before and after applying a control action?	Relative measure	Not selected	N/A
13	20	Labor Productivity	Output	Numbers/time	Redundant - already listed	Redundant	Not selected	N/A
14	20	Labor efficiency	Output	%	Defined as number of direct labor hours worked to number of hours budgeted	Could be correlated to lead time	Not selected	N/A
15	10	Percentage average set up time improvement per product line	Input	%	Uses setup time as a basic unit	Input for Simulation model	Not selected	N/A
16	10	Percentage reduction in employee turnover	Not Applicable	%	Use % change in employee turnover	Will impact lead time as well as indirect labor hrs with respect to training, learning curve for new employees	Not selected	N/A
17	20	Materials	Input	units and $	Same as inventory	Same as inventory, Used production cost /unit	Not selected	N/A
18	20	Inventory	Input	units and $	Used cost as basic unit	Selected for critical component inventory	Selected	Yes

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
19	10	Percentage Inventory turnover increase	Output	%	Can also be measured through inventory turnover	Can also be measured through inventory turnover and is correlated to Production cost/unit	Not selected	N/A
20	20	Scrap	Input	%	measured through % Production Yield	measured through % Production Yield	Not selected	N/A
21	20	Repair or rework	Input	$	Used cost as a basic unit	Used cost unit	Not selected	N/A
22	20	Cost of quality	Output	$	Measured through % Production Yield	Measured through % Production Yield	Not selected	N/A
23	20	Design cost	Input	$	Defined as basic unit - costs related to time and materials in designing a product	Basic unit	Not selected	N/A
24	6	Relative R& D expenditure	Input	$	relative measure	Redundant, captured under Product design cost	Not selected	N/A
25	20	Distribution cost	Output	$	Defined as Costs associatied with handling of finished goods	Could also be captured under distance travelled	Not selected	N/A
26	10	Percentage reduction in total number of data transactions per product	Output	%	Relative measure - Is correlated to lead time	Redundant, captured under Manufacturing lead time	Not selected	N/A
27	20	overhead	Input	$	Redundant, captured under Indirect labor time	Input for Simulation model	Not selected	N/A
28	2	Perceived relative quality performance	Output	N/a	Subjective measure - no standard measurment methods	Subjective measure	Not selected	N/A
29	7	Quality relative to competitors	Output	N/a	Subjective measure - no standard measurment methods	Subjective measure	Not selected	N/A
30	3	Product reliability relative to competitors	Output	N/a	Subjective measure - no standard measurment methods	Subjective measure	Not selected	N/A
31	3	Product durability relative to competitors	Output	N/a	Subjective measure - no standard measurment methods	Subjective measure	Not selected	N/A
32	4	Percentage of surveyed customers satisfied	Output	%	Subjective measure - no standard measurment methods	Subjective measure	Not selected	N/A
33	20	Customer satisfaction	Output	N/a	No units or scale defined and very subjective to rate	Measured on a scale - no uniformity in measurement methods	Not selected	N/A
34	11	Reputation	Output	N/a	No units or scale defined and very subjective to rate	Measured on a scale - no uniformity in measurement methods	Not selected	N/A
35	11	Expected product life	Not Applicable	Time	Product life cycle - length of time a product is introduced into the market	Could be redefined as Average Product life cycle; Not applicable in simulation model	Not selected	N/A
36	20	Number of complaints	Not Applicable	N/a	Complaints relate to product failures at some degree of failure (very subjective when used over different product types with different end use requirements)	Captured under rework and yield	Not selected	N/A
37	11	Service call rate	Input	Time/unit	Not defined in article - Assumed as Order interarrival time	Not defined in article - Assumed as Order interarrival time	Not selected	N/A

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
38	20	Lapse rate, renewal rate, retention rate	Not Applicable	Numbers/time	Repeat customers rate - No uniform method for measurement. For example it could be a 12 month period over which customers are retained or a 3 month period!	Will not work for a variety of industry and product categories; Not applicable for simulation	Not selected	N/A
39	5	Defect level as perceived and measured by customers	Not Applicable	N/a	Very hard to have an objective measurement	Serious functional defects will be back into the mfg system as rework or replacement; Not applicable for simulation	Not selected	N/A
40	12	value of returned merchandise	Not Applicable	$	Returned merchandise is usually categorized as a scrap or refurbishable product	Redundant - Captured under rework cost; Not applicable for simulation	Not selected	N/A
41	10	Percentage product returns or warranty claims reduction	Output	%	Redundant - Captured under rework cost	Redundant - Captured under rework cost; Not applicable for simulation	Not selected	N/A
42	13	Field failure per cent	Not Applicable	%	Failure at the customer location -Could eb captured as part of rework cost	Failure at the customer location -Could eb captured as part of rework cost	Not selected	N/A
43	20	Mean time between failures	Input	Time	Could be defined as MTBF for products or for work centers- Selected as MTBF for work centers	Selected as MTBF for work centers; Input for simulation model	Not selected	N/A
44	20	Up time percentage	Input	%	Redundant - Captured under MTBF	Redundant - Captured under MTBF; Input for simulation model	Not selected	N/A
45	10	Percentage unscheduled downtime reduction	Input	%	Redundant - Captured under MTBF	Redundant - Captured under MTBF	Not selected	N/A
46	20	Pass rate	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
47	4	Percentage conform to targets	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
48	20	Assembly line defects per 100 units	Input	Numbers	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
49	4	Percentage with no repair work	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
50	10	Percentage defect reduction	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
51	10	Percentage reduction in time between defect detection and correction	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
52	10	Percentage scrap	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
53	20	Percentage scrap value reduction	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
54	11	Repairmen per assembly line direct laborer	Input	Numbers	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
55	10	Percentage of inspection operations eliminated	Input	%	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
56	20	Cost of quality	Output	$	Captured under rework and yield	Captured under rework and yield; Input for simulation model	Not selected	N/A
57	1	Vendor quality	Input	%	Supplier quality - Defined as % vendor quality defects/lot	Supplier quality - Defined as % vendor quality defects/lot - Can be correlated to Lot size reduction	Not selected	N/A
58	10	Percentage supplier reduction	Input	%	Number of suppliers reduction - Quality metric under JIT	Selected as part of supplychain metric	Not selected	N/A
59	8	Perceived flexibility	Input	N/a	weighted scale of basic units that has setup time, economy of scope, technology and Systems like JIT	Captured under basic units such as setup time	Not selected	N/A
60	7	Flexibility relative to competitors	Not Applicable	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix; Not applicable in simulation	Not selected	N/A
61	3	Process flexibility relative to competitors	Not Applicable	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix; Not applicable in simulation	Not selected	N/A
62	14	Extent to which quality is unaffected by mix volume changes	Not Applicable	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix; Not applicable in simulation	Not selected	N/A
63	14	Extent to which cost is unaffected by mix/volume changes	Output	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix; Captured under Production cost/unit	Not selected	N/A
64	14	Extent to which delivery is unaffected by mix/volume changes	Input	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix; Captured under lead time	Not selected	N/A
65	2	Perceived relative product flexibility	Input	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix; Input for simulation	Not selected	N/A
66	14	How quickly a plant responds to product mix/volume changes	Output	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix; Subjective measurement	Not selected	N/A
67	15	Number of part types process simultaneously	Input	Units	Depends on layout	can be correlated with the lead time and cycle time of different products through a system; Input ofr simulation	Not selected	N/A
68	14	Production cycle time	Output	Time	The longest processing time at the bottleneck stations. In case of multiple operators at the station then Cycle time = Processing time/number of operators	Redefined as cycle time; Correlated to lead time	Not selected	N/A

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
69	14	Cycle time (make time/total time)	Output	Time	Redefined as above	redundant as above metric	Not selected	N/A
70	20	Setup time	Input	Time	Time taken to switch between product types	Input for Simulation model	Not selected	N/A
71	15	Time to replace tools, change tools, assemble or move fixtures	Input	Time	This could be defined as the tasks (time taken) to set up a product type	Redundant as part of setup time metric; Input for simulation	Not selected	N/A
72	10	Percentage increase in average number of setups per day	Input	%	Any change in number of setups will have an impact on the average Production lead time and throughput rate of the system	Use production lead time ; Input for simulation	Not selected	N/A
73	2	Percieved relative volume flexibility	Input	N/a	Redundant	Redundant; Input for simulation	Not selected	N/A
74	14	How well plant adapts to volumer changes	Output	N/a	No units or scale defined and very subjective to rate	Captured under basic units such as setup time, processing times, product volume mix	Not selected	N/A
75	14	Percentage change of order without lead time change	Input	N/a	Defined as % change in order types without change in manufacturing lead time	Use production lead time ; Input for simulation	Not selected	N/A
76	15	Smallest economical volume	Input	Numbers	Defined as Economic order quantity for inventory	This is more of an independent variable ; Input for simulation.	Not selected	N/A
77	14	Lot size	Input	Numbers	Defined as batch size flowing through the system	This is more of an independent variable ; Input for simulation	Not selected	N/A
78	16	Ability to perform multiple tasks efficiently	Not Applicable	N/a	Need to have a baseline effieciency defined in order to benchmark the ability to perform multiple tasks	Very subjective type of measurement	Not selected	N/A
79	14	Job classification	Not Applicable	N/a	Different industries use different variations of job classifications	Very subjective type of measurement	Not selected	N/A
80	14	Percentage workforce cross trained	Not Applicable	%	Cross training varies in several degrees - a person could be cross trained in running two of the ten machines in a system and still be called cross trained	Very subjective type of measurement	Not selected	N/A
81	14	Percentage workforce doing more than one job per month	Input	%	Similar to above definition	Very subjective type of measurement	Not selected	N/A
82	10	Percentage increase in average number of direct labor skills	Input	%	Related to direct labor	Can be correlated with the direct labor	Not selected	N/A
83	14	Percentage programmable equipment	Input	%	Related more to automation - Could also be defined as or part of % automation	Can be correlated with the lead time change	Not selected	N/A
84	14	Percentage multipurpose equipment	Input	%	Related to number of common equipments used	Input for Simulation model	Not selected	N/A

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
85	10	Percentage increase in multipurpose equipment	Input	%	Same as above	Input for Simulation model	Not selected	N/A
86	10	Percentage decrease in number of bottlenect work centers	Input	%	Related to cycle time	Input for Simulation model	Not selected	N/A
87	14	Percentage slack time for equipment, labor, etc	Input	%	Slack time represents time required to wait, queue	Part of indirect labor time	Not selected	N/A
88	10	Percentage increase in portion of product made for which a specified level of slack time exists	Input	%	Slack time represents time required to wait, queue	Input for Simulation model	Not selected	N/A
89	9	Percentage products using pull system	Input	%	Very hard to have an objective measurement	Assumption that the system is always a hybrid between push and pull within a system; Input for Simulation model	Not selected	N/A
90	14	WIP (work on station/total)	Output	%	Can be correlated to lead time, using Little's law	Selected to verify the model	Selected	Yes
91	15	Disruption caused by breakdowns	Input	N/a	Defined as machine failure	Redundant - part of MTBF	Not selected	N/A
92	14	Vendor lead time	Input	Time	Defined as time taken to supply a lot size	Usually an independent variable especially in case of a manufacturing facility - applicable in case of supply chain systems	Not selected	N/A
93	10	Percentage increase in vendor inputs obtainable in X days or less	Input	%	Relates to percentage increase in vendor supply time	Redundant; Input for simulation	Not selected	N/A
94	2	Perceived relative reliability	Not Applicable	N/a	Product reliability measure	Occurs outside the system. Also captured as part of rework, Scrap and yield; not applicable for simulation	Not selected	N/A
95	7	Reliability relative to competitors	Not Applicable	N/a	Product reliability measure	Occurs outside the system. Also captured as part of rework, Scrap and yield; not applicable for simulation	Not selected	N/A
96	20	Percentage on time delivery	Output	%	Relates to Products deliveried to customer on time	Captured as a metric for products delivered to customer ontime	Selected	yes
97	20	Due date adherence	Not Applicable	N/a	Relates to Products deliveried to customer on time	Captured as part of lead time; not applicable for simulation	Not selected	N/A
98	10	Percentage increase in portion of delivery promises met	Not Applicable	N/a	Relates to Products deliveried to customer on time	Captured as part of lead time; not applicable for simulation	Not selected	N/A
99	20	Percentage of orders with incorrect amount	Input	N/a	Relates to Products deliveried to customer on time	Captured as part of lead time; input for simulation	Not selected	N/A
100	17	Schedule attainment	Not Applicable	N/a	Relates to Products deliveried to customer on time	Captured as part of lead time	Not selected	N/A
101	18	Average delay	Output	N/a	Relates to Products deliveried to customer on time	Captured as part of lead time	Not selected	N/A

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
102	10	Percentage reduction in leadtime per product line	Output	%	Relates to Products deliveried to customer on time	Captured as part of lead time	Not selected	N/A
103	10	Percentage improvement in output/desired output	Output	%	Defines as ratio between Through put rate and capacity	Selected as throughput rate	Not selected	N/A
104	10	Percentage reduction in purchasing lead time	Input	%	Relates to suppliers lead time	Captured as part of lead time	Not selected	N/A
105	10	Percentage reduction in average service turnaround per warranty claim	Not Applicable	%	Relates to Quality and rework	Captured under rework and yield	Not selected	N/A
106	20	Lead time	Output	Time	Average Manufacturing Lead time is the average of total production time taken to manufacture or assemble products in a facility from the time it enters the first workstation until it exits the last workstation		Selected	yes
107	20	Cycle time	Output	Time	The longest processing time at the bottleneck stations. In case of multiple operators at the station then Cycle time = Processing time/number of operators	Inversely correlated to Throughput rate	Not selected	N/A
108	19	Time from customer's recognition of need to delivery	Not Applicable	Time	Relates to suppliers lead time	Captured as part of lead time	Not selected	N/A
109	20	Order processing time	Input	Time	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
110	20	Response time	Output	Time	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
111	4	Percentage on time for rush jobs	Not Applicable	%	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
112	20	Paperwork throughput time	Not Applicable	Time	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
113	20	Material throughput time	Output	Time	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
114	19	Value added as per cent of total elapsed time	Output	$	Related to production cost	Redundant as Production cost/unit & lead time	Not selected	N/A
115	17	Distance travelled	Input	Distance	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
116	19	Decision cycle time	Not Applicable	Time	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
117	19	Time lost waiting for decisions	Not Applicable	Time	Relates to Production lead time	Captured as part of lead time	Not selected	N/A
118	19	Percentage first competitor to market	Not Applicable	%	Relates to market share	More of an independent variable effect than being a dependant variable (lead time reduction could lead to more market share)	Not selected	N/A
119	5	New product introduction versus competition	Not Applicable	N/a	Relates to innovation and design	Added as part of design time	Not selected	N/A
120	17	Development time for new products	Not Applicable	Time	Relates to innovation and design	Added as part of design time	Not selected	N/A
121	5	Break even time	Not Applicable	Time	Relates to innovation and design	Added as part of design time	Not selected	N/A

Metrics #	Reference #	Performance metrics	Classify as Input and/or output for a model	Units	Analysis- (identify relationships)	Reason for selection/non selection	Selection Outcome	Applicable to Simulation model
122	19	Time from idea to market	Not Applicable	Time	Relates to innovation and design	Added as part of design time	Not selected	N/A
123	17	Average time between innovations	Not Applicable	Time	Relates to innovation and design	Added as part of design time	Not selected	N/A
124	17	Number of changes in projects	Not Applicable	Time	Relates to innovation and design	Added as part of design time	Not selected	N/A
125	17	Engineering time	Not Applicable	Time	Relates to innovation and design	Added as part of design time	Not selected	N/A
126		Utilization	Output	%	Mathematically it is calculated as Utilization = [Number of parts completed by the resource] *[Average Time taken to serve each part]/ Total simulation time.	This measure is useful to identify bottleneck resources only	Not selected	N/A
127		Throughputrate	Output	Numbers/ unit time	Throughput rate is defined rate at which the products are being manufactured and exits the system.	Correlated with WIP and Lead time (Little's law)	Not selected	N/A

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APPENDIX B

DATA FIT SUMMARY FORM

USING ARENA INPUT ANALYZER

Order Inter Arrival Time Distribution

Distribution Summary

Distribution: Triangular
Expression: TRIA(0.22, 0.385, 0.55)
Square Error: 0.011822

Chi Square Test
Number of intervals = 3
Degrees of freedom = 1
Test Statistic = 0.408
Corresponding p-value = 0.533

Kolmogorov-Smirnov Test
Test Statistic = 0.0636
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 30
Min Data Value = 0.253
Max Data Value = 0.519
Sample Mean = 0.384
Sample Std Dev = 0.0699

Fit All Summary

Function	Sq Error
Triangular	0.0118
Normal	0.0138
Beta	0.0194
Weibull	0.0198
Gamma	0.0361
Erlang	0.037
Uniform	0.0556
Lognormal	0.0564
Exponential	0.117

Enclosure Prep Processing Time Distribution

Distribution Summary

Distribution: Triangular
Expression: TRIA(0.12, 0.13, 0.14)
Square Error: 0.0047

Chi Square Test
Number of intervals = 3
Degrees of freedom = 1
Test Statistic = 0.617
Corresponding p-value = 0.453

Kolmogorov-Smirnov Test
Test Statistic = 0.121
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 30
Min Data Value = 0.120
Max Data Value = 0.139
Sample Mean = 0.131
Sample Std Dev = 0.00408

Fit All Summary

Function	Sq Error
Triangular	0.0047
Erlang	0.00516
Lognormal	0.00779
Weibull	0.00801
Gamma	0.00827
Normal	0.0101
Beta	0.0148
Uniform	0.0733
Exponential	0.156

Assembly Station Processing Time Distribution

Distribution Summary

Distribution: Triangular
Expression: TRIA(0.16, 0.284, 0.330)
Square Error: 0.00411

Chi Square Test
Number of intervals = 3
Degrees of freedom = 1
Test Statistic = 3.56
Corresponding p-value = 0.626

Kolmogorov-Smirnov Test
Test Statistic = 0.186
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 30
Min Data Value = 0.181
Max Data Value = 0.315
Sample Mean = 0.266
Sample Std Dev = 0.0309

Fit All Summary

Function	Sq Error
Triangular	0.00411
Beta	0.00414
Weibull	0.00585
Normal	0.0194
Gamma	0.0289
Erlang	0.0291
Lognormal	0.0476
Uniform	0.111
Exponential	0.216

<u>Testing Station Processing Time Distribution</u>

Distribution Summary

Distribution: Triangular
Expression: TRIA(0.15, 0.293, 0.37)
Square Error: 0.046395

Chi Square Test
Number of intervals = 3
Degrees of freedom = 1
Test Statistic = 5.13
Corresponding p-value = 0.24

Kolmogorov-Smirnov Test
Test Statistic = 0.14
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 30
Min Data Value = 0.17
Max Data Value = 0.354
Sample Mean = 0.272
Sample Std Dev = 0.056

Fit All Summary

Function	Sq Error
Triangular	0.0464
Beta	0.0696
Normal	0.0824
Weibull	0.0918
Uniform	0.104
Gamma	0.108
Erlang	0.108
Lognormal	0.125
Exponential	0.179

Labeling Station Processing Time Distribution

Distribution Summary

Distribution: Triangular
Expression: TRIA(0.19, 0.242, 0.27)
Square Error: 0.001944

Chi Square Test
Number of intervals = 3
Degrees of freedom = 1
Test Statistic = 0.185
Corresponding p-value = 0.691

Kolmogorov-Smirnov Test
Test Statistic = 0.0931
Corresponding p-value > 0.15

Data Summary

Number of Data Points = 30
Min Data Value = 0.201
Max Data Value = 0.261
Sample Mean = 0.234
Sample Std Dev = 0.0154

Fit All Summary

Function	Sq Error
Triangular	0.00194
Beta	0.00659
Normal	0.0141
Weibull	0.0149
Gamma	0.0316
Erlang	0.0321
Lognormal	0.0459
Uniform	0.0667
Exponential	0.153

APPENDIX C

MINITAB RESULTS FOR CONTROL ACTION vs. EXTERNAL ELEMENTS

500 Hours No Supply with Additional Supplier Control Action.

Factorial Fit: NPV versus Supplier Lot Size, Supplier Average IAT

Estimated Effects and Coefficients for NPV (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		982139	37521	26.18	0.000
Supplier Lot Size	1363613	681806	37521	18.17	0.000
Supplier Average IAT	-2165410	-1082705	37521	-28.86	0.000
Supplier Lot Size* Supplier Average IAT	-1833261	-916630	37521	-24.43	0.000

S = 150082 PRESS = 480527249425
R-Sq = 99.32% R-Sq(pred) = 98.80% R-Sq(adj) = 99.15%

Analysis of Variance for NPV (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	2.61938E+13	2.61938E+13	1.30969E+13	581.44	0.000
2-Way Interactions	1	1.34434E+13	1.34434E+13	1.34434E+13	596.83	0.000
Residual Error	12	2.70297E+11	2.70297E+11	22524714817		
Pure Error	12	2.70297E+11	2.70297E+11	22524714817		
Total	15	3.99074E+13				

Unusual Observations for NPV

Obs	StdOrder	NPV	Fit	SE Fit	Residual	St Resid
13	13	739829	466408	75041	273421	2.10R

R denotes an observation with a large standardized residual.

Estimated Coefficients for NPV using data in uncoded units

Term	Coef
Constant	-54168
Supplier Lot Size	42086.2
Supplier Average IAT	1503.05
Supplier Lot Size* Supplier Average IAT	-273.876

Factorial Fit: Peak Lead time versus Supplier Lot Size, Supplier Average

Estimated Effects and Coefficients for Peak Lead time (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		320.2	0.9147	350.02	0.000
Supplier Lot Size	-274.4	-137.2	0.9147	-149.97	0.000
Supplier Average IAT	210.2	105.1	0.9147	114.88	0.000
Supplier Lot Size* Supplier Average IAT	152.9	76.5	0.9147	83.59	0.000

S = 3.65893 PRESS = 285.605
R-Sq = 99.97% R-Sq(pred) = 99.95% R-Sq(adj) = 99.96%

Analysis of Variance for Peak Lead time (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	477759	477759	238879	17843.13	0.000
2-Way Interactions	1	93549	93549	93549	6987.64	0.000
Residual Error	12	161	161	13		
Pure Error	12	161	161	13		
Total	15	571468				

Unusual Observations for Peak Lead time

Obs	StdOrder	Peak Lead time	Fit	SE Fit	Residual	St Resid
4	4	370.987	364.543	1.829	6.444	2.03R

R denotes an observation with a large standardized residual.

Estimated Coefficients for Peak Lead time using data in uncoded units

Term	Coef
Constant	485.271
Supplier Lot Size	-5.04038
Supplier Average IAT	0.106174
Supplier Lot Size* Supplier Average IAT	0.0228465

Alias Structure
I
Supplier Lot Size
Supplier Average IAT
Supplier Lot Size*Supplier Average IAT

1000 Hours No Supply with Additional Supplier Control Action.

Factorial Fit: NPV 10yr versus Supplier Lot Size, Supplier Average IAT

Estimated Effects and Coefficients for NPV 10yr (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		1737774	28034	61.99	0.000
Supplier Lot Size	2438967	1219483	28034	43.50	0.000
Supplier Average IAT	-3820026	-1910013	28034	-68.13	0.000
Supplier Lot Size* Supplier Average IAT	-3216741	-1608371	28034	-57.37	0.000

S = 112135 PRESS = 268250039547
R-Sq = 99.88% R-Sq(pred) = 99.78% R-Sq(adj) = 99.85%

Analysis of Variance for NPV 10yr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	8.21646E+13	8.21646E+13	4.10823E+13	3267.19	0.000
2-Way Interactions	1	4.13897E+13	4.13897E+13	4.13897E+13	3291.63	0.000
Residual Error	12	1.50891E+11	1.50891E+11	12574220604		
Pure Error	12	1.50891E+11	1.50891E+11	12574220604		
Total	15	1.23705E+14				

Unusual Observations for NPV 10yr

Obs	StdOrder	NPV 10yr	Fit	SE Fit	Residual	St Resid
3	3	494081	216648	56067	277433	2.86R

R denotes an observation with a large standardized residual.

Estimated Coefficients for NPV 10yr using data in uncoded units

Term	Coef
Constant	-93285.9
Supplier Lot Size	74287.6
Supplier Average IAT	2476.73
Supplier Lot Size* Supplier Average IAT	-480.559

Factorial Fit: Peak Lead time versus Supplier Lot Siz, Supplier Average

Estimated Effects and Coefficients for Peak Lead time (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		632.0	1.289	490.31	0.000
Supplier Lot Size	-519.1	-259.6	1.289	-201.36	0.000
Supplier Average IAT	461.0	230.5	1.289	178.83	0.000
Supplier Lot Size* Supplier Average IAT	281.0	140.5	1.289	108.99	0.000

S = 5.15613 PRESS = 567.162
R-Sq = 99.99% R-Sq(pred) = 99.97% R-Sq(adj) = 99.98%

Analysis of Variance for Peak Lead time (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	1928111	1928111	964056	36262.15	0.000
2-Way Interactions	1	315823	315823	315823	11879.42	0.000
Residual Error	12	319	319	27		
Pure Error	12	319	319	27		
Total	15	2244253				

Estimated Coefficients for Peak Lead time using data in uncoded units

Term	Coef
Constant	882.601
Supplier Lot Size	-9.40405
Supplier Average IAT	0.782460
Supplier Lot Size* Supplier Average IAT	0.0419781

Alias Structure
I
Supplier Lot Size
Supplier Average IAT
Supplier Lot Size*Supplier Average IAT

4 % Diminished Supplies with Additional Supplier Control Action.

Factorial Fit: NPV 10yr versus Supplier Lot Size, Supplier Average IAT

Estimated Effects and Coefficients for NPV 10yr (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		4502257	437365	10.29	0.000
Supplier Lot Size	-4404533	-2202267	437365	-5.04	0.000
Supplier Average IAT	-1788234	-894117	437365	-2.04	0.064
Supplier Lot Size* Supplier Average IAT	-3752019	-1876009	437365	-4.29	0.001

S = 1749459 PRESS = 6.529291E+13
R-Sq = 79.98% R-Sq(pred) = 64.40% R-Sq(adj) = 74.97%

Analysis of Variance for NPV 10yr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	9.03908E+13	9.03908E+13	4.51954E+13	14.77	0.001
2-Way Interactions	1	5.63106E+13	5.63106E+13	5.63106E+13	18.40	0.001
Residual Error	12	3.67273E+13	3.67273E+13	3.06061E+12		
Pure Error	12	3.67273E+13	3.67273E+13	3.06061E+12		
Total	15	1.83429E+14				

Unusual Observations for NPV 10yr

Obs	StdOrder	NPV 10yr	Fit	SE Fit	Residual	St Resid
13	13	475183	5722631	874729	-5247448	-3.46R

R denotes an observation with a large standardized residual.

Estimated Coefficients for NPV 10yr using data in uncoded units

Term	Coef
Constant	4803917
Supplier Lot Size	17607.9
Supplier Average IAT	23810.1
Supplier Lot Size* Supplier Average IAT	-560.526

Least Squares Means for NPV 10yr

	Mean	SE Mean
Supplier Lot Size		
15	6704523	618527
120	2299990	618527
Supplier Average IAT		
42.50	5396374	618527
170.00	3608139	618527
Supplier Lot Size*Supplier Average IAT		
15 42.50	5722631	874729
120 42.50	5070117	874729
15 170.00	7686415	874729
120 170.00	-470137	874729

Factorial Fit: Peak Lead time versus Supplier Lot Siz, Supplier Average

Estimated Effects and Coefficients for Peak Lead time (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		2.748	0.5599	4.91	0.000
Supplier Lot Size	-2.636	-1.318	0.5599	-2.35	0.036
Supplier Average IAT	2.581	1.290	0.5599	2.30	0.040
Supplier Lot Size* Supplier Average IAT	-2.636	-1.318	0.5599	-2.35	0.036

S = 2.23975 PRESS = 107.018
R-Sq = 57.73% R-Sq(pred) = 24.86% R-Sq(adj) = 47.17%

Analysis of Variance for Peak Lead time (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	54.432	54.4318	27.216	5.43	0.021
2-Way Interactions	1	27.790	27.7896	27.790	5.54	0.036
Residual Error	12	60.198	60.1975	5.016		
Pure Error	12	60.198	60.1975	5.016		
Total	15	142.419				

Unusual Observations for Peak Lead time

Obs	StdOrder	Peak Lead time	Fit	SE Fit	Residual	St Resid
15	15	13.2500	6.6746	1.1199	6.5754	3.39R

R denotes an observation with a large standardized residual.

Estimated Coefficients for Peak Lead time using data in uncoded units

Term	Coef
Constant	-0.53184
Supplier Lot Size	0.0167352
Supplier Average IAT	0.0468210
Supplier Lot Size* Supplier Average IAT	-3.93769E-04

Least Squares Means for Peak Lead time

	Mean	SE Mean
Supplier Lot Size		
15	4.066	0.7919
120	1.431	0.7919
Supplier Average IAT		
42.50	1.458	0.7919
170.00	4.039	0.7919
Supplier Lot Size*Supplier Average IAT		
15 42.50	1.458	1.1199
120 42.50	1.458	1.1199
15 170.00	6.675	1.1199
120 170.00	1.403	1.1199

Alias Structure
I
Supplier Lot Size
Supplier Average IAT
Supplier Lot Size*Supplier Average IAT

8 % Diminished Supplies with Additional Supplier Control Action.

Factorial Fit: NPV 10yr versus Supplier Lot Size, Supplier Average IAT

Estimated Effects and Coefficients for NPV 10yr (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		3004908	54661	54.97	0.000
Supplier Lot Size	-952155	-476077	54661	-8.71	0.000
Supplier Average IAT	-3390914	-1695457	54661	-31.02	0.000
Supplier Lot Size* Supplier Average IAT	-3165204	-1582602	54661	-28.95	0.000

S = 218644 PRESS = 1.019844E+12
R-Sq = 99.36% R-Sq(pred) = 98.87% R-Sq(adj) = 99.21%

Analysis of Variance for NPV 10yr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	4.96196E+13	4.96196E+13	2.48098E+13	518.98	0.000
2-Way Interactions	1	4.00741E+13	4.00741E+13	4.00741E+13	838.28	0.000
Residual Error	12	5.73662E+11	5.73662E+11	47805206529		
Pure Error	12	5.73662E+11	5.73662E+11	47805206529		
Total	15	9.02673E+13				

Unusual Observations for NPV 10yr

Obs	StdOrder	NPV 10yr	Fit	SE Fit	Residual	St Resid
4	4	-1230180	-749229	109322	-480951	-2.54R

R denotes an observation with a large standardized residual.

Estimated Coefficients for NPV 10yr using data in uncoded units

Term	Coef
Constant	3051478
Supplier Lot Size	41173.2
Supplier Average IAT	5322.62
Supplier Lot Size* Supplier Average IAT	-472.860

Factorial Fit: Peak Lead time versus Supplier Lot Siz, Supplier Average

Estimated Effects and Coefficients for Peak Lead time (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		303.6	1.207	251.40	0.000
Supplier Lot Size	-599.6	-299.8	1.207	-248.27	0.000
Supplier Average IAT	604.2	302.1	1.207	250.19	0.000
Supplier Lot Size* Supplier Average IAT	-599.6	-299.8	1.207	-248.27	0.000

S = 4.82997 PRESS = 497.678
R-Sq = 99.99% R-Sq(pred) = 99.99% R-Sq(adj) = 99.99%

Analysis of Variance for Peak Lead time (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	2898209	2898209	1449105	62116.95	0.000
2-Way Interactions	1	1437904	1437904	1437904	61636.83	0.000
Residual Error	12	280	280	23		
Pure Error	12	280	280	23		
Total	15	4336393				

Unusual Observations for Peak Lead time

Obs	StdOrder	Peak Lead time	Fit	SE Fit	Residual	St Resid

3	3	1195.25	1205.24	2.41	-9.98	-2.39R
7	7	1216.63	1205.24	2.41	11.39	2.72R

R denotes an observation with a large standardized residual.

Estimated Coefficients for Peak Lead time using data in uncoded units

Term	Coef
Constant	-456.903
Supplier Lot Size	3.80675
Supplier Average IAT	10.7850
Supplier Lot Size* Supplier Average IAT	-0.0895706

Alias Structure
I
Supplier Lot Size
Supplier Average IAT
Supplier Lot Size*Supplier Average IAT

15% Order IAT Decrease (Competitor Out of Business Influence) with Additional Supplier Control Action.

Factorial Fit: Peak lead time versus Supplier Lot Siz, Supplier Average

Estimated Effects and Coefficients for Peak lead time (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		430.5	3.070	140.22	0.000
Supplier Lot Size	-796.7	-398.3	3.070	-129.75	0.000
Supplier Average IAT	821.9	410.9	3.070	133.86	0.000
Supplier Lot Size* Supplier Average IAT	-761.0	-380.5	3.070	-123.94	0.000

S = 12.2799 PRESS = 3216.99
R-Sq = 99.98% R-Sq(pred) = 99.96% R-Sq(adj) = 99.97%

Analysis of Variance for Peak lead time (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	5240566	5240566	2620283	17376.30	0.000
2-Way Interactions	1	2316316	2316316	2316316	15360.55	0.000
Residual Error	12	1810	1810	151		
Pure Error	12	1810	1810	151		
Total	15	7558691				

Unusual Observations for Peak lead time

Obs	StdOrder	Peak lead time	Fit	SE Fit	Residual	St Resid
11	11	1597.10	1620.23	6.14	-23.13	-2.17R
15	15	1645.49	1620.23	6.14	25.26	2.38R

R denotes an observation with a large standardized residual.

Estimated Coefficients for Peak lead time using data in uncoded units

Term	Coef
Constant	-557.595
Supplier Lot Size	4.49162
Supplier Average IAT	14.1197
Supplier Lot Size* Supplier Average IAT	-0.113684

Factorial Fit: NPV 10 yr versus Supplier Lot Size, Supplier Average IAT

Estimated Effects and Coefficients for NPV 10 yr (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		-1842590	624095	-2.95	0.012
Supplier Lot Size	1640020	820010	624095	1.31	0.213
Supplier Average IAT	-3235318	-1617659	624095	-2.59	0.024
Supplier Lot Size* Supplier Average IAT	168584	84292	624095	0.14	0.895

S = 2496380   PRESS = 1.329475E+14
R-Sq = 41.36%   R-Sq(pred) = 0.00%   R-Sq(adj) = 26.70%

Analysis of Variance for NPV 10 yr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	2	5.26278E+13	5.26278E+13	2.63139E+13	4.22	0.041
2-Way Interactions	1	1.13683E+11	1.13683E+11	1.13683E+11	0.02	0.895
Residual Error	12	7.47830E+13	7.47830E+13	6.23191E+12		
Pure Error	12	7.47830E+13	7.47830E+13	6.23191E+12		
Total	15	1.27524E+14				

Unusual Observations for NPV 10 yr

Obs	StdOrder	NPV 10 yr	Fit	SE Fit	Residual	St Resid
12	12	3679083	-2555947	1248190	6235029	2.88R

R denotes an observation with a large standardized residual.

Estimated Coefficients for NPV 10 yr using data in uncoded units

Term	Coef

Constant	-20163
Supplier Lot Size	12943.3
Supplier Average IAT	-27075.1
Supplier Lot Size* Supplier Average IAT	25.185

Alias Structure
I
Supplier Lot Size
Supplier Average IAT
Supplier Lot Size*Supplier Average IAT

30% Order IAT Decrease (Competitor Out of Business Influence) with Additional Supplier Control Action.

Factorial Fit: Peak Time in versus Supplier IAT, Supplier Lot, ...

Estimated Effects and Coefficients for Peak Time in System (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		1829	30.13	60.69	0.000
Supplier IAT	826	413	30.13	13.71	0.000
Supplier Lot Size	-3008	-1504	30.13	-49.91	0.000
Floater Size	-3	-1	30.13	-0.05	0.963
Supplier IAT*Supplier Lot Size	-179	-90	30.13	-2.98	0.007
Supplier IAT*Floater Size	-3	-1	30.13	-0.05	0.964
Supplier Lot Size*Floater Size	-3	-1	30.13	-0.05	0.963
Supplier IAT*Supplier Lot Size* Floater Size	-3	-1	30.13	-0.04	0.965

S = 170.460 PRESS = 1239749
R-Sq = 99.11% R-Sq(pred) = 98.43% R-Sq(adj) = 98.86%

Analysis of Variance for Peak Time in System (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	77832267	77832267	25944089	892.88	0.000
2-Way Interactions	3	257647	257647	85882	2.96	0.053
3-Way Interactions	1	56	56	56	0.00	0.965
Residual Error	24	697359	697359	29057		
Pure Error	24	697359	697359	29057		
Total	31	78787329				

Unusual Observations for Peak Time in System

Obs	StdOrder	Peak Time in System	Fit	SE Fit	Residual	St Resid
4	4	1060.21	654.03	85.23	406.18	2.75R

8	8	1043.67	642.98	85.23	400.69	2.71R
20	20	225.16	654.03	85.23	-428.87	-2.91R
24	24	217.56	642.98	85.23	-425.42	-2.88R

R denotes an observation with a large standardized residual.

Estimated Coefficients for Peak Time in System using data in uncoded units

Term	Coef
Constant	2881.79
Supplier IAT	8.27560
Supplier Lot Size	-25.8418
Floater Size	-0.317
Supplier IAT*Supplier Lot Size	-0.0256155
Supplier IAT*Floater Size	0.01057
Supplier Lot Size*Floater Size	0.03025
Supplier IAT*Supplier Lot Size* Floater Size	-0.0007921

Factorial Fit: NPV 5yr versus Supplier IAT, Supplier Lot, Floater Size

Estimated Effects and Coefficients for NPV 5yr (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		1016693	179972	5.65	0.000
Supplier IAT	-3080494	-1540247	179972	-8.56	0.000
Supplier Lot Size	377467	188734	179972	1.05	0.305
Floater Size	943363	471681	179972	2.62	0.015
Supplier IAT*Supplier Lot Size	1085275	542638	179972	3.02	0.006
Supplier IAT*Floater Size	-193594	-96797	179972	-0.54	0.596
Supplier Lot Size*Floater Size	-286917	-143458	179972	-0.80	0.433
Supplier IAT*Supplier Lot Size* Floater Size	995295	497648	179972	2.77	0.011

S = 1018075 PRESS = 4.422304E+13
R-Sq = 80.47% R-Sq(pred) = 65.28% R-Sq(adj) = 74.77%

Analysis of Variance for NPV 5yr (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	8.41748E+13	8.41748E+13	2.80583E+13	27.07	0.000
2-Way Interactions	3	1.03810E+13	1.03810E+13	3.46033E+12	3.34	0.036
3-Way Interactions	1	7.92490E+12	7.92490E+12	7.92490E+12	7.65	0.011
Residual Error	24	2.48755E+13	2.48755E+13	1.03648E+12		
Pure Error	24	2.48755E+13	2.48755E+13	1.03648E+12		
Total	31	1.27356E+14				

Unusual Observations for NPV 5yr

Obs	StdOrder	NPV 5yr	Fit	SE Fit	Residual	St Resid
5	5	2350604	4120428	509038	-1769823	-2.01R
30	30	2457389	-1234231	509038	3691620	4.19R

R denotes an observation with a large standardized residual.

Estimated Coefficients for NPV 5yr using data in uncoded units

Term	Coef
Constant	-1147623
Supplier IAT	-439.8
Supplier Lot Size	41961.0
Floater Size	3767687
Supplier IAT*Supplier Lot Size	-283.938
Supplier IAT*Floater Size	-23109.9
Supplier Lot Size*Floater Size	-37061.7
Supplier IAT*Supplier Lot Size* Floater Size	297.380

Alias Structure
I
Supplier IAT
Supplier Lot Size
Floater Size
Supplier IAT*Supplier Lot Size
Supplier IAT*Floater Size
Supplier Lot Size*Floater Size
Supplier IAT*Supplier Lot Size*Floater Size

APPENDIX D

SAMPLE NPV CALCULATION WORKSHEETS

FOR EACH CONTROL ACTION

NPV Calculation for Additional Supplier control action

r 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Y
	$ 243,960.00	$ 454,632.00	$ 454,024.00	$ 460,332.00	$ 450,072.00	$ 457,672.00	$ 455,924.00	$
	$ 26,904.00	$ 26,144.00	$ 26,296.00	$ 26,828.00	$ 24,928.00	$ 24,700.00	$ 26,600.00	$
	$ 217,056.00	$ 428,488.00	$ 427,728.00	$ 433,504.00	$ 425,144.00	$ 432,972.00	$ 429,324.00	$
	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$
1,000.00	$ 1,000.00	$ 1,000.00	$ 1,000.00	$ 1,000.00	$ 1,000.00	$ 1,000.00	$ 1,000.00	$
600.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00	$ 600.00	$
1,600.00	$ 1,600.00	$ 1,600.00	$ 1,600.00	$ 1,600.00	$ 1,600.00	$ 1,600.00	$ 1,600.00	$
1,600.00	**$ 218,656.00**	**$ 430,088.00**	**$ 429,328.00**	**$ 435,104.00**	**$ 426,744.00**	**$ 434,572.00**	**$ 430,924.00**	**$**
	$ 1,593,300.00	$ 1,591,200.00	$ 1,593,300.00	$ 1,593,900.00	$ 1,592,400.00	$ 1,595,100.00	$ 1,592,400.00	$
	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$
	$ 1,593,300.00	$ 1,591,200.00	$ 1,593,300.00	$ 1,593,900.00	$ 1,592,400.00	$ 1,595,100.00	$ 1,592,400.00	$
	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$
	$ 834,900.00	$ 1,686,300.00	$ 1,691,100.00	$ 1,690,500.00	$ 1,690,800.00	$ 1,687,200.00	$ 1,692,600.00	$
	$ 834,900.00	**$ 1,686,300.00**	**$ 1,691,100.00**	**$ 1,690,500.00**	**$ 1,690,800.00**	**$ 1,687,200.00**	**$ 1,692,600.00**	**$**
1,600.00)	**$ 616,244.00**	**$ 1,256,212.00**	**$ 1,261,772.00**	**$ 1,255,396.00**	**$ 1,264,056.00**	**$ 1,252,628.00**	**$ 1,261,676.00**	**$**
7.50%								
	$6,454,822.85							
	$4,181,300.89							

n for Additional Resource control action

Number of Floaters = 2

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,00
$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,000.00	$ 72,00
$ 1,593,300.00	$ 1,591,200.00	$ 1,593,300.00	$ 1,593,900.00	$ 1,592,400.00	$ 1,595,100.00	$ 1,592,40
$ 1,448,100.00	$ 1,442,400.00	$ 1,452,000.00	$ 1,451,100.00	$ 1,442,700.00	$ 1,435,200.00	$ 1,456,20
$ (145,200.00)	$ (148,800.00)	$ (141,300.00)	$ (142,800.00)	$ (149,700.00)	$ (159,900.00)	$ (136,20
$ 120,600.00	$ 129,000.00	$ 120,600.00	$ 122,100.00	$ 128,100.00	$ 138,000.00	$ 116,40
$ (24,600.00)	$ (19,800.00)	$ (20,700.00)	$ (20,700.00)	$ (21,600.00)	$ (21,900.00)	$ (19,80
$ (96,600.00)	$ (91,800.00)	$ (92,700.00)	$ (92,700.00)	$ (93,600.00)	$ (93,900.00)	$ (91,80

APPENDIX E

PROCESS ANALYZER WORKSHEETS

FOR EACH INFLUENCE LEVEL AND CORRESPONDING CONTROL ACTION(S)

500 hours of No Supply External Influence and varying levels of Additional Supplier Control Action

Process Analyzer - [500 no supply.pan]

File Edit View Insert Tools Run Help

	Scenario Properties					Controls									Responses			
	S	Name	Program File	Reps	Rep Length	CompBusiness	Orderseperation	Percentdecrease	AltPCvendorqty	VendorMin	VendorMode	VendorMax	Vendortimeout	PCBoard_excessed	NumberOnTime	Numberdelayed	Production order.TotalTi
1		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	928	34	4579	298.991
2		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	2278	34	10200	248.130
3		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	3822	34	15808	192.180
4		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	5575	4050	17181	145.127
5		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	7257	9363	17181	116.261
6		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	9019	14679	17181	97.012
7		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	10811	19988	17181	83.284
8		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	12528	25307	17181	72.971
9		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	14214	30628	17181	64.949
10		Scenario 10	5 : NoEXCELSup	4	20080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	500.0000	15999	35931	17181	58.555
11		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	4657	5305	0	0.903
12		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	10589	10612	0	0.903
13		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	16621	15924	0	0.903
14		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	22643	21231	0	0.904
15		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	28584	26544	0	0.904
16		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	34609	31860	0	0.904
17		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	40580	37169	0	0.904
18		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	46541	42488	0	0.904
19		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	52493	47809	0	0.904
20		Scenario 10	5 : NoEXCELSupplierCA_TISm	4	20080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	500.0000	58456	53111	0	0.904
21		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	63	34	4260	423.727
22		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	182	34	9886	367.849
23		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	418	34	15494	310.360
24		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	670	132	21029	251.168
25		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	1166	4473	22071	201.376
26		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	1669	9788	22071	167.924
27		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	2201	15098	22071	144.068
28		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	2690	20417	22071	126.145
29		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	3158	25738	22071	112.204
30		Scenario 10	5 : NoEXCELSupplierCA_TISm	4	20080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	500.0000	3687	31040	22071	101.093
31		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	471	64	4374	361.920
32		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	1168	64	9996	310.514
33		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	1903	64	15619	253.546
34		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	2762	1560	19671	196.477
35		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	3799	6873	19671	157.330
36		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	4847	12189	19671	131.227
37		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	5897	17498	19671	112.611
38		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	6924	22817	19671	98.627
39		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	7943	28138	19671	87.751
40		Scenario 10	5 : NoEXCELSupplierCA_TISm	4	20080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	500.0000	8990	33441	19671	79.082

Double-click here to add a new scenario.

1000 hours of No Supply External Influence and varying levels of Additional Supplier Control Action

Process Analyzer - [1000 no supply.pan]

File Edit View Insert Tools Run Help

	Scenario Properties				Controls									Responses			
	S	Name	Program File	Reps	Rep Length	CompBusiness	Orderseperation	Percentdecrease	AltPCvendorqty	VendorMin	VendorMode	VendorMax	Vendortimeout	PCBoard_excessed	NumberOnTime	Numberdelayed	Production order.TotalTi
1		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	568	34	3496	631.686
2		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	1918	34	9122	620.554
3		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	3418	34	14729	573.383
4		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	4858	34	20364	518.743
5		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	6208	34	26027	460.323
6		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	7648	34	31638	401.068
7		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	9371	2810	34359	344.680
8		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	11088	8129	34359	301.642
9		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	12774	13450	34359	268.169
10		Scenario 10	5 : NoEXCELSup	4	20080.0000	1.0000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	1000.0000	14559	18753	34359	241.485
11		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	3217	5305	0	0.903
12		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	9149	10612	0	0.903
13		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	15181	15924	0	0.903
14		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	21203	21231	0	0.904
15		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	27144	26544	0	0.904
16		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	33169	31860	0	0.904
17		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	39140	37169	0	0.904
18		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	45101	42488	0	0.904
19		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	51053	47809	0	0.904
20		Scenario 10	5 : NoEXCELSupplierCA_TISm	4	20080.0000	1.0000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	1000.0000	57016	53111	0	0.904
21		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	40	34	2867	914.732
22		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	148	34	8491	872.584
23		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	373	34	14100	817.514
24		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	576	34	19733	759.363
25		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	744	34	25396	698.665
26		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	924	34	31009	637.868
27		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	1104	34	36672	576.233
28		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	1281	34	42295	515.291
29		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	1718	2901	44908	458.385
30		Scenario 10	5 : NoEXCELSupplierCA_TISm	4	20080.0000	1.0000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	1000.0000	2247	8204	44908	412.710
31		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	163	64	3161	766.015
32		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	860	64	8764	741.934
33		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	1595	64	14438	687.219
34		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	2240	64	20056	627.935
35		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	2986	64	25721	567.429
36		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	3748	64	31332	506.933
37		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	4507	64	37005	446.506
38		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	5484	3390	39098	390.859
39		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	6503	8712	39098	347.457
40		Scenario 10	5 : NoEXCELSupplierCA_TISm	4	20080.0000	1.0000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	1000.0000	7550	14014	39098	312.859

Double-click here to add a new scenario.

4% Diminished Supply External Influence and varying levels of Additional Supplier Control Action

Process Analyzer - [4 per dim supply]

File Edit View Insert Tools Run Help

	Scenario Properties					Controls									Responses			
	S	Name	Program File	Reps	Rep Length	CompBusiness	Orderseperation	Percentdecrease	AltPCvendorqty	VendorMin	VendorMode	VendorMax	Vendortimeout	PCBoard_excessed	NumberOnTime	Numberdelayed	Production order.TotalTi
1		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	1496	5305	0	0.903
2		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	2773	10612	0	0.903
3		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	4122	15924	0	0.904
4		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	5440	21231	0	0.904
5		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	6685	26544	0	0.904
6		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	7996	31860	0	0.904
7		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	9336	37169	0	0.903
8		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	10610	42488	0	0.903
9		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	11852	47809	0	0.904
10		Scenario 10	5 : NoEXCELSup	4	20080.0000	1.0000	100.0000	0.9600	120.0000	160.0000	170.0000	180.0000	0.0000	13183	53111	0	0.904
11		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	5857	5305	0	0.903
12		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	11356	10612	0	0.903
13		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	16937	15924	0	0.903
14		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	22508	21231	0	0.904
15		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	28007	26544	0	0.904
16		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	33581	31860	0	0.904
17		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	39105	37169	0	0.904
18		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	44620	42488	0	0.904
19		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	50125	47809	0	0.904
20		Scenario 10	5 : NoEXCELSup plierCA_TISm	4	20080.0000	1.0000	100.0000	0.9600	120.0000	40.0000	42.5000	45.0000	0.0000	55642	53111	0	0.904
21		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	272	5305	0	0.903
22		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	362	10609	3	0.904
23		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	447	15921	3	0.904
24		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	531	21228	3	0.904
25		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	595	26541	3	0.904
26		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	648	31835	24	0.906
27		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	726	37145	24	0.906
28		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	777	42454	34	0.906
29		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	812	47672	137	0.918
30		Scenario 10	5 : NoEXCELSup plierCA_TISm NoEXCELSup plierCA_TISm	4	20080.0000	1.0000	100.0000	0.9600	15.0000	160.0000	170.0000	180.0000	0.0000	876	52832	280	0.930
31		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	827	5305	0	0.903
32		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	1420	10612	0	0.903
33		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	2016	15924	0	0.903
34		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	2626	21231	0	0.904
35		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	3222	26544	0	0.904
36		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	3819	31860	0	0.904
37		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	4422	37169	0	0.904
38		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	5003	42488	0	0.904
39		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	5575	47809	0	0.904
40		Scenario 10	5 : NoEXCELSup plierCA_TISm	4	20080.0000	1.0000	100.0000	0.9600	15.0000	40.0000	42.5000	45.0000	0.0000	6176	53111	0	0.904

Double click here to add a new scenario

8% Diminished Supply External Influence and varying levels of Additional Supplier Control Action

Process Analyzer - [8 per dim supply]

File Edit View Insert Tools Run Help

	Scenario Properties				Controls									Responses			
	S	Name	Program File	Reps	Rep Length	CompBusiness	Orderseperation	Percentdecrease	AltPCvendor qty	VendorMin	VendorMode	VendorMax	Vendortimeout	PCBoard_excessed	NumberOnTime	Numberdelayed	Production order.TotalTi
1		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	1259	5304	0	0.904
2		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	2126	10597	15	0.909
3		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	3044	15909	15	0.907
4		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	3939	21216	15	0.906
5		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	4776	26529	15	0.906
6		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	5658	31845	15	0.905
7		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	6562	37147	22	0.906
8		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	7417	42455	33	0.906
9		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	8249	47755	54	0.908
10		Scenario 10	5 : NoEXCELSup	4	20080.0000	1.0000	100.0000	0.9200	120.0000	160.0000	170.0000	180.0000	0.0000	9143	53032	80	0.909
11		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	5617	5305	0	0.903
12		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	10706	10612	0	0.903
13		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	15859	15924	0	0.903
14		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	21003	21231	0	0.904
15		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	26083	26544	0	0.904
16		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	31229	31860	0	0.904
17		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	36331	37169	0	0.904
18		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	41423	42488	0	0.904
19		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	46505	47809	0	0.904
20		Scenario 10	5 : NoEXCELSup plierCA_TISm	4	20080.0000	1.0000	100.0000	0.9200	120.0000	40.0000	42.5000	45.0000	0.0000	51599	53111	0	0.904
21		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	45	5304	0	0.904
22		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	3903	21.010
23		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	8899	69.034
24		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	13848	124.371
25		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	18812	184.345
26		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	23732	246.629
27		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	28719	311.495
28		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	33661	376.265
29		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	38594	442.494
30		Scenario 10	5 : NoEXCELSup plierCA_TISm	4	20080.0000	1.0000	100.0000	0.9200	15.0000	160.0000	170.0000	180.0000	0.0000	46	6420	43524	509.695
31		Scenario 1	5 : NoEXCEL	4	2080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	587	5305	0	0.903
32		Scenario 2	5 : NoEXCEL	4	4080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	771	10612	0	0.903
33		Scenario 3	5 : NoEXCEL	4	6080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	939	15924	0	0.903
34		Scenario 4	5 : NoEXCEL	4	8080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	1122	21231	0	0.904
35		Scenario 5	5 : NoEXCEL	4	10080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	1298	26544	0	0.904
36		Scenario 6	5 : NoEXCEL	4	12080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	1468	31860	0	0.904
37		Scenario 7	5 : NoEXCEL	4	14080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	1647	37169	0	0.904
38		Scenario 8	5 : NoEXCEL	4	16080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	1805	42488	0	0.904
39		Scenario 9	5 : NoEXCEL	4	18080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	1958	47809	0	0.904
40		Scenario 10	5 : NoEXCELSup plierCA_TISm	4	20080.0000	1.0000	100.0000	0.9200	15.0000	40.0000	42.5000	45.0000	0.0000	2133	53111	0	0.904

15% Decrease in IAT due to Competitor Out of Business External Influence and varying levels of Additional Supplier Control Action

Process Analyzer - [15% comp business]

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	Scenario Properties				Controls									Responses									
	S	Name	Program	Reps	Rep Length	CompBusiness	Orderseperation	Percent decrea	AltPCvendor qty	VendorMin	VendorMode	VendorMax	Vendortimeout	PCBoard_excessed	Battery_excesse	Bracket_excesse	Enclosure_excessed	Label_excessed	Radio_excessed	Wiring_excessed	NumberOnTime	Number delayed	Production
1		Scenario 1	2 : N	4	2080.0000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	801	848	856	818	854	813	810	1410	4878	18.379
2		Scenario 2	2 : N	4	4080.0000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1505	1530	1569	1560	1557	1516	1579	2827	9729	18.736
3		Scenario 3	2 : N	4	6080.0000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2225	2252	2287	2238	2251	2247	2286	4798	14122	16.040
4		Scenario 4	2 : N	4	8080.0000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2997	2983	3013	3006	3006	3042	3057	7249	17971	13.890
5		Scenario 5	2 : N	4	10080.000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	3699	3718	3744	3736	3744	3766	3778	9347	22233	12.913
6		Scenario 6	2 : N	4	12080.000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	4431	4414	4489	4472	4445	4443	4505	11429	26432	12.124
7		Scenario 7	2 : N	4	14080.000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	5179	5152	5198	5194	5178	5171	5214	13432	30774	11.599
8		Scenario 8	2 : N	4	16080.000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	5928	5902	5943	5952	5933	5908	5964	14836	35681	11.404
9		Scenario 9	2 : N	4	18080.000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	6679	6675	6713	6707	6704	6624	6705	16226	40617	11.266
10		Scenario 10	2 : NoE	4	20080.0000	0.8500	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	7427	7433	7486	7427	7477	7387	7489	17328	45798	11.175
11		Scenario 1	2 : N	4	2080.0000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	5115	5117	5110	5114	5109	5102	5121	6308	0	0.897
12		Scenario 2	2 : N	4	4080.0000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	10029	10088	10035	10154	10076	10108	10133	12620	0	0.897
13		Scenario 3	2 : N	4	6080.0000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	15080	15042	15061	15049	15028	14993	15081	18941	0	0.897
14		Scenario 4	2 : N	4	8080.0000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	20030	19936	20073	20079	20063	20000	20046	25253	0	0.897
15		Scenario 5	2 : N	4	10080.000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	25004	24953	25041	24949	24951	24967	25070	31580	0	0.897
16		Scenario 6	2 : N	4	12080.000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	29934	29950	29957	30008	29985	29931	30083	37900	0	0.897
17		Scenario 7	2 : N	4	14080.000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	34938	34907	34963	35025	34901	34906	35006	44223	0	0.897
18		Scenario 8	2 : N	4	16080.000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	39834	39928	39956	39933	39908	39908	40002	50552	0	0.897
19		Scenario 9	2 : N	4	18080.000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	44890	44918	44969	44867	44904	44861	44926	56852	0	0.897
20		Scenario 10	2 : NoE XCE	4	20080.0000	0.8500	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	49888	49939	49962	49864	49873	49944	49951	63164	0	0.897
21		Scenario 1	2 : N	4	2080.0000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	56	60	62	16	53	56	49	591	5216	76.769
22		Scenario 2	2 : N	4	4080.0000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	79	92	95	16	88	88	96	591	10983	160.596
23		Scenario 3	2 : N	4	6080.0000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	79	99	113	16	104	99	103	591	16770	244.716
24		Scenario 4	2 : N	4	8080.0000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	98	106	127	16	112	102	109	591	22592	328.714
25		Scenario 5	2 : N	4	10080.000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	118	112	152	16	119	130	140	591	28385	410.916
26		Scenario 6	2 : N	4	12080.000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	122	115	208	16	164	141	153	591	34177	493.503
27		Scenario 7	2 : N	4	14080.000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	129	129	227	16	185	141	161	591	39977	576.373
28		Scenario 8	2 : N	4	16080.000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	167	164	237	16	202	154	174	591	45784	659.276
29		Scenario 9	2 : N	4	18080.000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	180	181	252	16	210	164	187	591	51600	742.205
30		Scenario 10	2 : NoE XCE	4	20080.0000	0.8500	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	197	197	288	16	251	170	201	591	57413	823.916
31		Scenario 1	2 : N	4	2080.0000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	102	90	105	104	105	87	116	4762	1546	2.376
32		Scenario 2	2 : N	4	4080.0000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	157	149	151	166	164	131	156	8718	3876	2.987
33		Scenario 3	2 : N	4	6080.0000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	185	175	192	215	193	146	191	11248	7667	4.217
34		Scenario 4	2 : N	4	8080.0000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	220	196	248	240	253	179	234	13615	11613	5.069
35		Scenario 5	2 : N	4	10080.000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	252	230	320	269	299	236	268	15962	15592	5.956
36		Scenario 6	2 : N	4	12080.000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	265	250	339	295	320	264	314	18061	19796	6.396
37		Scenario 7	2 : N	4	14080.000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	289	295	350	324	341	303	369	20190	24019	6.735
38		Scenario 8	2 : N	4	16080.000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	299	327	369	340	379	324	395	21715	28785	7.464
39		Scenario 9	2 : N	4	18080.000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	331	383	393	373	408	378	415	24560	32292	7.584
40		Scenario 10	2 : NoE XCE	4	20080.0000	0.8500	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	377	441	434	406	437	418	477	27658	35487	7.437

30% Decrease in IAT due to Competitor Out of Business External Influence and varying levels of Additional Supplier and Resource Control Actions

Process Analyzer - [30% comp business.pan]

	Controls										Responses									
	Rep Length	CompBusiness	Orderseperation	Percentdecrease	AltPCvendorqty	VendorMin	VendorMode	VendorMax	Vendortimeout	Floater 1	PCBoard_excessed	Battery_excessed	Bracket_excessed	Enclosure_excesse	Label_excessed	Radio_excessed	Wiring_excessed	NumberOnTime	Numberdelayed	Production order.Total
1	2080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1.0000	405	375	558	46	527	464	376	249	6305	183.552
2	4080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1.0000	491	553	696	46	684	582	522	249	13160	310.566
3	6080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1.0000	670	700	755	46	744	730	640	249	20191	426.915
4	8080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1.0000	848	847	932	46	954	877	787	249	27068	539.698
5	10080.000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1.0000	995	995	1058	46	1093	995	934	249	34011	655.016
6	12080.000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1.0000	1053	1053	1126	46	1194	1112	1052	249	40953	766.984
7	14080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	1.0000	1171	1200	1245	46	1303	1201	1170	249	47904	878.760
8	2080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	1.0000	3652	3665	3655	3659	3662	3643	3661	7783	0	0.929
9	4080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	1.0000	7171	7156	7086	7148	7153	7138	7153	15575	0	0.929
10	6080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	1.0000	10639	10611	10638	10637	10668	10638	10645	23362	0	0.929
11	8080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	1.0000	14180	14088	14056	14173	14218	14112	14198	31167	0	0.929
12	10080.000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	1.0000	17611	17574	17602	17638	17682	17605	17655	38968	0	0.929
13	12080.000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	1.0000	21098	21032	21028	21090	21222	21077	21119	46780	0	0.929
14	14080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	1.0000	24588	24565	24569	24586	24740	24604	24608	54566	0	0.929
15	2080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	1.0000	54	48	52	11	58	61	51	249	5536	253.383
16	4080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	1.0000	57	71	71	11	74	74	64	249	11343	511.339
17	6080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	1.0000	77	87	77	11	86	91	77	249	17115	766.796
18	8080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	1.0000	94	100	95	11	144	104	90	249	22949	1024.265
19	10080.000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	1.0000	107	113	101	11	175	110	97	249	28735	1279.382
20	12080.000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	1.0000	107	113	106	11	181	121	107	249	34575	1536.098
21	14080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	1.0000	107	160	136	11	228	130	154	249	40349	1790.110
22	2080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	1.0000	73	70	66	39	83	73	81	274	6039	184.902
23	4080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	1.0000	104	100	87	39	116	104	107	274	12362	374.725
24	6080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	1.0000	140	120	122	39	156	127	124	274	18672	564.164
25	8080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	1.0000	157	137	133	39	197	141	137	274	25009	753.777
26	10080.000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	1.0000	164	150	146	39	240	174	158	274	31337	942.598
27	12080.000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	1.0000	174	153	158	39	263	180	161	274	37674	1131.436
28	14080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	1.0000	181	160	165	39	315	183	168	274	43963	1319.160
29	2080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2.0000	395	366	532	46	507	455	366	277	6321	176.968
30	4080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2.0000	482	543	682	46	668	573	513	277	13162	302.013
31	6080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2.0000	661	691	730	46	730	721	631	277	20207	418.144
32	8080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2.0000	838	838	909	46	922	868	778	277	27073	530.729
33	10080.000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2.0000	986	986	1030	46	1074	985	925	277	34032	646.055
34	12080.000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2.0000	1044	1044	1078	46	1173	1103	1043	277	40970	757.810
35	14080.0000	0.7000	100.0000	1.0000	120.0000	160.0000	170.0000	180.0000	0.0000	2.0000	1161	1191	1205	46	1271	1191	1161	277	47911	868.927
36	2080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	2.0000	3652	3665	3655	3659	3662	3643	3661	7783	0	0.895
37	4080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	2.0000	7171	7156	7086	7148	7153	7138	7153	15575	0	0.895
38	6080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	2.0000	10639	10611	10638	10637	10668	10638	10645	23362	0	0.895
39	8080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	2.0000	14180	14088	14056	14173	14218	14112	14198	31167	0	0.895
40	10080.000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	2.0000	17611	17574	17602	17638	17681	17605	17655	38968	0	0.895
41	12080.000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	2.0000	21098	21032	21028	21090	21221	21077	21119	46780	0	0.895
42	14080.0000	0.7000	100.0000	1.0000	120.0000	40.0000	42.5000	45.0000	0.0000	2.0000	24588	24565	24569	24586	24740	24604	24608	54566	0	0.895
43	2080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	2.0000	54	48	51	11	58	61	51	273	5518	250.625
44	4080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	2.0000	57	71	71	11	73	74	64	273	11320	508.357
45	6080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	2.0000	77	87	77	11	78	91	77	273	17096	763.994
46	8080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	2.0000	94	100	94	11	112	104	90	273	22925	1021.019
47	10080.000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	2.0000	107	113	100	11	147	110	97	273	28726	1276.620
48	12080.000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	2.0000	107	113	100	11	162	121	107	273	34563	1533.047
49	14080.0000	0.7000	100.0000	1.0000	15.0000	160.0000	170.0000	180.0000	0.0000	2.0000	107	160	120	11	213	130	154	273	40329	1786.645
50	2080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	2.0000	73	70	66	39	83	73	81	354	5975	182.117
51	4080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	2.0000	104	100	86	39	116	104	107	354	12284	371.279
52	6080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	2.0000	140	120	122	39	136	127	124	354	18611	561.224
53	8080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	2.0000	157	137	132	39	194	141	137	354	24939	750.556
54	10080.000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	2.0000	164	150	141	39	240	174	158	354	31292	940.140
55	12080.000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	2.0000	174	153	152	39	254	180	161	354	37599	1128.037
56	14080.0000	0.7000	100.0000	1.0000	15.0000	40.0000	42.5000	45.0000	0.0000	2.0000	181	160	156	39	315	183	168	354	43910	1316.387
57	14080.0000	0.7000	100.0000	1.0000	0.0000	40.0000	42.5000	45.0000	0.0000	1.0000	21	16	23	10	165	17	22	249	39163	1930.442

new scenario

30% Increase in Custom Orders due to Product Customization External Influence and varying levels of Additional Resource Control Action

Process Analyzer - [Product customization2.pan]

File Edit View Insert Tools Run Help

	Scenario Properties				Controls										Responses			
	S	Name	Program File	Reps	Rep Length	Floater 1	AltPCvendorqty	VendorMax	VendorMin	VendorMode	Vendortimeout	CompBusiness	Percentdecrease	Orderseperation	Production order.TotalTime	Numberdelayed	NumberOnTime	Production order.NumberOut
1		Scenario 1	2 : NOEXCEL_	4	2080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	486.488	2930	0	2929.500
2		Scenario 2	2 : NOEXCEL_	4	4080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	933.066	5833	0	5833.250
3		Scenario 3	2 : NOEXCEL_	4	6080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1385.377	8781	0	8780.750
4		Scenario 4	2 : NOEXCEL_	4	8080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1829.376	11646	0	11646.000
5		Scenario 5	2 : NOEXCEL_	4	10080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2281.626	14527	0	14526.500
6		Scenario 6	2 : NOEXCEL_	4	12080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2729.990	17360	0	17360.250
7		Scenario 7	2 : NOEXCEL_	4	14080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3191.280	20264	0	20264.000
8		Scenario 8	2 : NOEXCEL_	4	16080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3651.184	23173	0	23172.500
9		Scenario 9	2 : NOEXCEL_	4	18080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	4108.867	26075	0	26075.000
10		Scenario 10	2 : NOEXCEL_AIIC	4	20080.0000	0.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	4566.081	28982	0	28981.500
11		Scenario 1	2 : NOEXCEL_	4	2080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	405.114	3312	0	3312.000
12		Scenario 2	2 : NOEXCEL_	4	4080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	781.585	6638	0	6638.000
13		Scenario 3	2 : NOEXCEL_	4	6080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1153.656	9886	0	9886.250
14		Scenario 4	2 : NOEXCEL_	4	8080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1532.444	13080	0	13079.750
15		Scenario 5	2 : NOEXCEL_	4	10080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1919.863	16292	0	16291.750
16		Scenario 6	2 : NOEXCEL_	4	12080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2313.325	19545	0	19545.250
17		Scenario 7	2 : NOEXCEL_	4	14080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2705.724	22807	0	22807.250
18		Scenario 8	2 : NOEXCEL_	4	16080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3097.173	26078	0	26077.750
19		Scenario 9	2 : NOEXCEL_	4	18080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3486.894	29351	0	29351.250
20		Scenario 10	2 : NOEXCEL_AIICA_TISmetric_111210.p	4	20080.0000	1.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3875.533	32621	0	32620.750
21		Scenario 1	2 : NOEXCEL_	4	2080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	176.929	4458	0	4457.750
22		Scenario 2	2 : NOEXCEL_	4	4080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	337.285	8895	0	8895.250
23		Scenario 3	2 : NOEXCEL_	4	6080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	505.785	13206	0	13206.000
24		Scenario 4	2 : NOEXCEL_	4	8080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	684.078	17486	0	17486.000
25		Scenario 5	2 : NOEXCEL_	4	10080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	867.832	21880	0	21879.500
26		Scenario 6	2 : NOEXCEL_	4	12080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1047.628	26266	0	26266.000
27		Scenario 7	2 : NOEXCEL_	4	14080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1225.913	30647	0	30646.500
28		Scenario 8	2 : NOEXCEL_	4	16080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1404.275	35081	0	35081.000
29		Scenario 9	2 : NOEXCEL_	4	18080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1579.062	39471	0	39471.250
30		Scenario 10	2 : NOEXCEL_AIICA_TISmetric_111210.p	4	20080.0000	2.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	1753.297	43823	0	43823.250
31		Scenario 1	2 : NOEXCEL_	4	2080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	7.542	4782	517	5299.250
32		Scenario 2	2 : NOEXCEL_	4	4080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	8.735	9677	927	10603.500
33		Scenario 3	2 : NOEXCEL_	4	6080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	9.475	14709	1197	15905.750
34		Scenario 4	2 : NOEXCEL_	4	8080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	10.281	19770	1461	21230.750
35		Scenario 5	2 : NOEXCEL_	4	10080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	9.780	24699	1837	26536.250
36		Scenario 6	2 : NOEXCEL_	4	12080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	9.892	29686	2169	31854.750
37		Scenario 7	2 : NOEXCEL_	4	14080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	9.677	34461	2703	37164.500
38		Scenario 8	2 : NOEXCEL_	4	16080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	9.733	39523	2966	42488.000
39		Scenario 9	2 : NOEXCEL_	4	18080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	9.564	44508	3289	47796.500
40		Scenario 10	2 : NOEXCEL_AIIC	4	20080.0000	3.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	9.541	49313	3794	53107.250
41		Scenario 1	2 : NOEXCEL_	4	2080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.307	2928	2371	5299.250
42		Scenario 2	2 : NOEXCEL_	4	4080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.348	5912	4699	10610.000
43		Scenario 3	2 : NOEXCEL_	4	6080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.412	9067	6850	15916.250
44		Scenario 4	2 : NOEXCEL_	4	8080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.435	12169	9059	21227.750
45		Scenario 5	2 : NOEXCEL_	4	10080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.431	15217	11326	26542.750
46		Scenario 6	2 : NOEXCEL_	4	12080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.436	18286	13573	31858.500
47		Scenario 7	2 : NOEXCEL_	4	14080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.425	21260	15909	37168.500
48		Scenario 8	2 : NOEXCEL_	4	16080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.438	24398	18089	42486.750
49		Scenario 9	2 : NOEXCEL_	4	18080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.437	27470	20335	47805.000
50		Scenario 10	2 : NOEXCEL_AIIC	4	20080.0000	4.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	3.428	30395	22714	53108.500
51		Scenario 1	2 : NOEXCEL_	4	2080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.725	2275	3026	5301.250
52		Scenario 2	2 : NOEXCEL_	4	4080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.741	4589	6022	10610.750
53		Scenario 3	2 : NOEXCEL_	4	6080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.766	6962	8961	15922.750
54		Scenario 4	2 : NOEXCEL_	4	8080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.774	9307	11922	21228.750
55		Scenario 5	2 : NOEXCEL_	4	10080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.771	11628	14916	26543.750
56		Scenario 6	2 : NOEXCEL_	4	12080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.774	13981	17879	31859.750
57		Scenario 7	2 : NOEXCEL_	4	14080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.769	16258	20911	37168.500
58		Scenario 8	2 : NOEXCEL_	4	16080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.774	18646	23841	42487.250
59		Scenario 9	2 : NOEXCEL_	4	18080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.776	20996	26812	47807.750
60		Scenario 10	2 : NOEXCEL_AIIC	4	20080.0000	5.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.772	23285	29824	53109.000
61		Scenario 1	2 : NOEXCEL_	4	2080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.572	2186	3116	5302.500
62		Scenario 2	2 : NOEXCEL_	4	4080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.586	4411	6201	10611.500
63		Scenario 3	2 : NOEXCEL_	4	6080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.603	6677	9247	15923.500
64		Scenario 4	2 : NOEXCEL_	4	8080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.608	8926	12304	21229.250
65		Scenario 5	2 : NOEXCEL_	4	10080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.607	11154	15391	26544.000
66		Scenario 6	2 : NOEXCEL_	4	12080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.608	13389	18471	31859.750
67		Scenario 7	2 : NOEXCEL_	4	14080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.603	15576	21593	37168.500
68		Scenario 8	2 : NOEXCEL_	4	16080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.606	17834	24654	42487.250
69		Scenario 9	2 : NOEXCEL_	4	18080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.607	20076	27733	47808.250
70		Scenario 10	2 : NOEXCEL_AIICA_TISmetric_1	4	20080.0000	6.0000	0.0000	45.0000	40.0000	42.5000	0.0000	1.0000	1.0000	70.0000	2.604	22267	30842	53109.500

ACROSS REP DATA: Min 3.36 Max 3.49 HW 0.0848 Obs 4

NUM

APPENDIX F

ARENA SIMAN CODE

```
; PROJECT,    "Base Model","Rajesh Krishnamurthy",,,Yes,Yes,Yes,Yes,No,No,Yes,Yes,No,No;

ATTRIBUTES:   Labeling setuptime:
          Labeling Process time:
          Assembly Process time:
          Prep Setuptime:
          Assembly setuptime:
          timeIn:
          Testing setuptime:
          Prep process time:
          Testing Process time;

VARIABLES:    Order_time,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),1.0:
          AltPCBoard_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Testing.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
          Labeling_Packing.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
          Switch setuptime base.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
          Dispose 5.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Decide 10.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
          Dispose 8.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          level1,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),1.25:
          Prep process.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Dispose 12.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Assembly process.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
          VendorMax,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),180:
          Decide 7.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
          Order Creation.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Labeling_Packing.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"),DATATYPE(Real):
          Vendortimeout,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0:
          Assembly process.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
          Decide 7.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
          AltBracket_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Labeling_Packing.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
          TestTimeIncrement,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0:
          CompBusiness,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0.7:
          VendorMode,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),170:
          Decide 11.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
          Assembly process.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Dispose 4.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Dispose 7.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Battery_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          CompetitorsOutOfBusiness.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Dispose 11.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          PrepTimeIncrement,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0:
          Ship to customer.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          AltWiring_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Assembly process.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
          Decide 1.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
          SMEDoutcome,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),1:
          Wiring_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Decide 10.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
          Labeling_Packing.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
          Decide 8.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
```

Labeling_Packing.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
Testing.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
Decide 8.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
Label_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
CustomTimeshift,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0:
Diminished supply over time.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
PCBoard_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Prep process.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"),DATATYPE(Real):
PCvendorqty,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),240:
Switch setuptime custom.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
Customer satisfaction decision.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
Decide 12.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
AltPCvendorqty,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),15:
Prep process.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
Prep process.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
Switch setuptime custom.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
Testing.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
Dispose 9.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Decide 9.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
AltLabel_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Enclosure_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Labeling_Packing.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
Testing.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
Dispose 13.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
VendorMin,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),160:
Switch setuptime base.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
Testing.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"),DATATYPE(Real):
Dispose 3.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Order seperator.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
Decide 11.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
CustomType,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real):
Prep process.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
Decide 9.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
Assembly process.NumberIn,CLEAR(Statistics),CATEGORY("Exclude"):
Order seperator.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
Customer satisfaction decision.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
Bracket_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Testing.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
Labeling_Packing.VATime,CLEAR(Statistics),CATEGORY("Exclude"):
Assembly process.WIP,CLEAR(System),CATEGORY("Exclude-Exclude"),DATATYPE(Real):
Dispose 10.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Radio_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Prep process.VACost,CLEAR(Statistics),CATEGORY("Exclude"):
LabelTimeIncrement,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0:
Orderseperation,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),100:
Percentdecrease,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),1.0:
Decide 1.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
AssemTimeIncrement,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0:
OrderIATMode,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),0.4:
var_warm_up,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),80:
Testing.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Assembly process.WaitTime,CLEAR(Statistics),CATEGORY("Exclude"):
Decide 12.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):
AltBattery_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
Decide 6.NumberOut True,CLEAR(Statistics),CATEGORY("Exclude"):
ProductCustomization.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
leadtime,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),2.25:
Decide 6.NumberOut False,CLEAR(Statistics),CATEGORY("Exclude"):

```
        MinInventory,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real),240:
        BaseType,CLEAR(System),CATEGORY("User Specified-User Specified"),DATATYPE(Real):
        Prep process.WaitCost,CLEAR(Statistics),CATEGORY("Exclude"):
        AltEnclosure_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude"):
        AltRadio_vendor.NumberOut,CLEAR(Statistics),CATEGORY("Exclude");

QUEUES:     Enclosure_bin,FIFO,,AUTOSTATS(Yes,,):
        Labeling_Packing.Queue,FIFO,,AUTOSTATS(Yes,,):
        Assembly process.Queue,FIFO,,AUTOSTATS(Yes,,):
        label_bin,FIFO,,AUTOSTATS(Yes,,):
        wiring_bin,FIFO,,AUTOSTATS(Yes,,):
        Battery_bin,FIFO,,AUTOSTATS(Yes,,):
        Testing.Queue,FIFO,,AUTOSTATS(Yes,,):
        PCBoard_bin,FIFO,,AUTOSTATS(Yes,,):
        PrepStation_hold.Queue,FIFO,,AUTOSTATS(Yes,,):
        AssemblyStation_hold.Queue,FIFO,,AUTOSTATS(Yes,,):
        bracket_bin,FIFO,,AUTOSTATS(Yes,,):
        LabelingStation_hold.Queue,FIFO,,AUTOSTATS(Yes,,):
        Prep process.Queue,FIFO,,AUTOSTATS(Yes,,):
        Radio_bin,FIFO,,AUTOSTATS(Yes,,);

PICTURES:   Picture.Airplane:
        Picture.Green Ball:
        Picture.Blue Page:
        Picture.Telephone:
        Picture.Blue Ball:
        Picture.Yellow Page:
        Picture.EMail:
        Picture.Yellow Ball:
        Picture.Bike:
        Picture.Report:
        Picture.Van:
        Picture.Widgets:
        Picture.Envelope:
        Picture.Fax:
        Picture.Truck:
        Picture.Person:
        Picture.Letter:
        Picture.Box:
        Picture.Woman:
        Picture.Package:
        Picture.Man:
        Picture.Diskette:
        Picture.Boat:
        Picture.Red Page:
        Picture.Ball:
        Picture.Green Page:
        Picture.Red Ball;

RESOURCES:  TestingResource 1,Capacity(1),,,COST(15.00,15.00,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
        Floater 1,Capacity(2),,,COST(0.0,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
        Floater 2,Capacity(1),,,COST(0.0,0.0,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
        LabelingResource 1,Capacity(1),,,COST(15.00,15.00,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,):
        PrepResource1,Capacity(1),,,COST(15.00,15.00,0.06),CATEGORY(Resources),,AUTOSTATS(Yes,,):
        AssemblyResource 1,Capacity(1),,,COST(15.00,15.00,0.0),CATEGORY(Resources),,AUTOSTATS(Yes,,);

COUNTERS:   NumberOnTime,,Replicate:
        Label_excessed,,Replicate:
```

```
          PCBoard_excessed,,Replicate:
          Bracket_excessed,,Replicate:
          Numberdelayed,,Replicate:
          Radio_excessed,,Replicate:
          Wiring_excessed,,Replicate:
          Enclosure_excessed,,Replicate:
          Battery_excessed,,Replicate;

TALLIES:  Assembly process.WaitTimePerEntity,,DATABASE(,"Wait Time Per Entity","Process","Assembly process"):
          Assembly process.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","Assembly process"):
          Testing.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","Testing"):
          Labeling_Packing.WaitTimePerEntity,,DATABASE(,"Wait Time Per Entity","Process","Labeling_Packing"):
          Prep process.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","Prep process"):
          Prep process.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","Prep process"):
          Assembly process.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","Assembly process"):
          Labeling_Packing.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","Labeling_Packing"):
          Labeling_Packing.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","Labeling_Packing"):
          Prep process.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","Prep process"):
          Testing.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","Testing"):
          Testing.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","Testing"):
          Assembly process.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","Assembly process"):
          Assembly process.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","Assembly process"):
          Testing.WaitTimePerEntity,,DATABASE(,"Wait Time Per Entity","Process","Testing"):
          Labeling_Packing.TotalTimePerEntity,,DATABASE(,"Total Time Per Entity","Process","Labeling_Packing"):
          Prep process.WaitTimePerEntity,,DATABASE(,"Wait Time Per Entity","Process","Prep process"):
          Labeling_Packing.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","Labeling_Packing"):
          Labeling_Packing.WaitCostPerEntity,,DATABASE(,"Wait Cost Per Entity","Process","Labeling_Packing"):
          Prep process.VACostPerEntity,,DATABASE(,"VA Cost Per Entity","Process","Prep process"):
          Testing.VATimePerEntity,,DATABASE(,"VA Time Per Entity","Process","Testing"):
          Prep process.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","Prep process"):
          Assembly process.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","Assembly process"):
          Testing.TotalCostPerEntity,,DATABASE(,"Total Cost Per Entity","Process","Testing");

OUTPUTS:  Testing.WaitCost,,Testing Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process","Testing"):
          Labeling_Packing.VACost,,Labeling_Packing Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","Labeling_Packing"):
          Labeling_Packing.WaitTime + Labeling_Packing.VATime,,Labeling_Packing Total Accum Time,DATABASE(,
          "Total Accum Time","Process","Labeling_Packing"):
          Prep process.NumberOut,,Prep process Number Out,DATABASE(,"Number Out","Process","Prep process"):
          Assembly process.WaitCost,,Assembly process Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process",
          "Assembly process"):
          Labeling_Packing.WaitCost + Labeling_Packing.VACost,,Labeling_Packing Total Accum Cost,DATABASE(,
          "Total Accum Cost","Process","Labeling_Packing"):
          Assembly process.VATime,,Assembly process Accum VA Time,DATABASE(,"Accum VA
Time","Process","Assembly process"):

NC(NumberOnTime)/(NC(NumberOnTime)+NC(Numberdelayed)),"",PercentOnTime,DATABASE(,"Output","User
Specified",
          "PercentOnTime"):
          Labeling_Packing.NumberIn,,Labeling_Packing Number In,DATABASE(,"Number
In","Process","Labeling_Packing"):
          Testing.WaitCost + Testing.VACost,,Testing Total Accum Cost,DATABASE(,"Total Accum
Cost","Process","Testing"):
          Assembly process.NumberOut,,Assembly process Number Out,DATABASE(,"Number
Out","Process","Assembly process"):
          TSTD(Production order.TotalTime),"",LeadTimeStdev,DATABASE(,"Output","User
Specified","LeadTimeStdev"):
```

```
        Assembly process.VACost,,Assembly process Accum VA Cost,DATABASE(,"Accum VA
Cost","Process","Assembly process"):
        Labeling_Packing.NumberOut,,Labeling_Packing Number Out,DATABASE(,"Number
Out","Process","Labeling_Packing"):
        Labeling_Packing.WaitTime,,Labeling_Packing Accum Wait Time,DATABASE(,"Accum Wait Time","Process",
        "Labeling_Packing"):
        Testing.VATime,,Testing Accum VA Time,DATABASE(,"Accum VA Time","Process","Testing"):
        Prep process.WaitCost + Prep process.VACost,,Prep process Total Accum Cost,DATABASE(,"Total Accum
Cost","Process",
        "Prep process"):
        Prep process.NumberIn,,Prep process Number In,DATABASE(,"Number In","Process","Prep process"):
        Prep process.VATime,,Prep process Accum VA Time,DATABASE(,"Accum VA Time","Process","Prep process"):
        Testing.NumberIn,,Testing Number In,DATABASE(,"Number In","Process","Testing"):
        Labeling_Packing.WaitCost,,Labeling_Packing Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process",
        "Labeling_Packing"):
        Testing.VACost,,Testing Accum VA Cost,DATABASE(,"Accum VA Cost","Process","Testing"):
        Testing.WaitTime + Testing.VATime,,Testing Total Accum Time,DATABASE(,"Total Accum
Time","Process","Testing"):
        Prep process.WaitTime,,Prep process Accum Wait Time,DATABASE(,"Accum Wait Time","Process","Prep
process"):
        Assembly process.NumberIn,,Assembly process Number In,DATABASE(,"Number In","Process","Assembly
process"):
        Prep process.WaitTime + Prep process.VATime,,Prep process Total Accum Time,DATABASE(,"Total Accum
Time","Process",
        "Prep process"):
        Testing.WaitTime,,Testing Accum Wait Time,DATABASE(,"Accum Wait Time","Process","Testing"):
        Labeling_Packing.VATime,,Labeling_Packing Accum VA Time,DATABASE(,"Accum VA
Time","Process","Labeling_Packing"):
        Assembly process.WaitTime + Assembly process.VATime,,Assembly process Total Accum Time,DATABASE(,
        "Total Accum Time","Process","Assembly process"):
        Prep process.VACost,,Prep process Accum VA Cost,DATABASE(,"Accum VA Cost","Process","Prep process"):
        Testing.NumberOut,,Testing Number Out,DATABASE(,"Number Out","Process","Testing"):
        Assembly process.WaitTime,,Assembly process Accum Wait Time,DATABASE(,"Accum Wait Time","Process",
        "Assembly process"):
        Prep process.WaitCost,,Prep process Accum Wait Cost,DATABASE(,"Accum Wait Cost","Process","Prep
process"):
        Assembly process.WaitCost + Assembly process.VACost,,Assembly process Total Accum Cost,DATABASE(,
        "Total Accum Cost","Process","Assembly process");

REPLICATE,    4,,HoursToBaseTime(20080),Yes,Yes,HoursToBaseTime(80),,,24,Hours,No,No,,,Yes;

ENTITIES:     Production order,Picture.Report,0.0,1.00,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        CustomProductFactor,Picture.Report,0.0,0.0,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        label,Picture.Report,0.0,0.60,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        enclosure,Picture.Box,0.0,15.45,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        battery,Picture.Yellow Ball,0.0,17.35,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        wiring,Picture.Green Ball,0.0,7.00,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        radio,Picture.Diskette,0.0,69.00,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        CompOutOfBusiness,Picture.Report,0.0,0.0,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        SupplyDecreaseInfluence,Picture.Report,0.0,0.0,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        pcboard,Picture.Report,0.0,96.00,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,):
        bracket,Picture.Widgets,0.0,5.21,0.0,0.0,0.0,0.0,AUTOSTATS(Yes,,);

SETS:         Prep,PrepResource1,Floater 1:
        Tester,TestingResource 1,Floater 1:
        Assembler,AssemblyResource 1,Floater 1:
        Packer,LabelingResource 1,Floater 1;
```

```
;
;    Model statements for module:  BasicProcess.Create 1 (Order Creation)
;

67$         CREATE,       1,HoursToBaseTime(1.0),Production order:
                    HoursToBaseTime(TRIA( OrderIATMode*Order_time-0.2, OrderIATMode*Order_time ,
0.13+OrderIATMode*Order_time,2 ))
                    :NEXT(68$);

68$         ASSIGN:       Order Creation.NumberOut=Order Creation.NumberOut + 1:NEXT(56$);


;
;
;    Model statements for module:  BasicProcess.Assign 13 (assign time attribute)
;
56$         ASSIGN:       timeIn=TNOW:NEXT(29$);


;
;
;    Model statements for module:  BasicProcess.Decide 2 (Order seperator)
;
29$         BRANCH,       1:
                    With,(Orderseperation)/100,71$,Yes:
                    Else,72$,Yes;
71$         ASSIGN:       Order seperator.NumberOut True=Order seperator.NumberOut True + 1:NEXT(30$);

72$         ASSIGN:       Order seperator.NumberOut False=Order seperator.NumberOut False + 1:NEXT(31$);


;
;
;    Model statements for module:  BasicProcess.Assign 6 (Assign Base type process times)
;
30$         ASSIGN:       BaseType=BaseType+1:
                    Labeling Process time=TRIA( 0.19, 0.24, 0.27,3):
                    Testing Process time=TRIA( 0.15, 0.293, 0.37,3):
                    Assembly Process time=TRIA( 0.16, 0.284, 0.33,3):
                    Prep process time=TRIA( 0.12, 0.13, 0.14,3):NEXT(34$);


;
;
;    Model statements for module:  BasicProcess.Decide 3 (Switch setuptime base)
;
34$         BRANCH,       1:
                    If,BaseType>1,73$,Yes:
                    Else,74$,Yes;
73$         ASSIGN:       Switch setuptime base.NumberOut True=Switch setuptime base.NumberOut True +
1:NEXT(36$);

74$         ASSIGN:       Switch setuptime base.NumberOut False=Switch setuptime base.NumberOut False +
1:NEXT(32$);
```

```
;
;
;    Model statements for module:  BasicProcess.Assign 11 (Reset Base values)
;
36$         ASSIGN:       BaseType=1:
                    CustomType=0:
                    Assembly setuptime=0:
                    Testing setuptime=0:
                    Labeling setuptime=0:
                    Prep Setuptime=0:NEXT(4$);


;
;
;    Model statements for module:  AdvancedProcess.Hold 1 (PrepStation_hold)
;
4$          QUEUE,        PrepStation_hold.Queue;
          SCAN:         NQ(Enclosure_bin)  >= 1:NEXT(3$);


;
;
;    Model statements for module:  AdvancedProcess.Pickup 1 (Pickup Enclosure)
;
3$          PICKUP:       Enclosure_bin,1,1:NEXT(12$);


;
;
;    Model statements for module:  BasicProcess.Process 5 (Prep process)
;
12$         ASSIGN:       Prep process.NumberIn=Prep process.NumberIn + 1:
                    Prep process.WIP=Prep process.WIP+1;
104$        STACK,        1:Save:NEXT(78$);

78$         QUEUE,        Prep process.Queue;
77$         SEIZE,        2,VA:
                    SELECT(Prep,POR, ),1:NEXT(76$);

76$         DELAY:        Prep Process time+Prep setuptime*SMEDoutcome,,VA:NEXT(119$);

119$        ASSIGN:       Prep process.WaitTime=Prep process.WaitTime + Diff.WaitTime;
83$         TALLY:        Prep process.WaitTimePerEntity,Diff.WaitTime,1;
120$        ASSIGN:       Prep process.WaitCost=Prep process.WaitCost + Diff.WaitCost;
81$         TALLY:        Prep process.WaitCostPerEntity,Diff.WaitCost,1;
85$         TALLY:        Prep process.TotalTimePerEntity,Diff.StartTime,1;
86$         TALLY:        Prep process.TotalCostPerEntity,
                    Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
109$        ASSIGN:       Prep process.VATime=Prep process.VATime + Diff.VATime;
110$        TALLY:        Prep process.VATimePerEntity,Diff.VATime,1;
114$        ASSIGN:       Prep process.VACost=Prep process.VACost + Diff.VACost;
111$        TALLY:        Prep process.VACostPerEntity,Diff.VACost,1;
75$         RELEASE:      SELECT(Prep,LAST),1;
124$        STACK,        1:Destroy:NEXT(123$);

123$        ASSIGN:       Prep process.NumberOut=Prep process.NumberOut + 1:
                    Prep process.WIP=Prep process.WIP-1:NEXT(7$);
```

```
;
;
;    Model statements for module:  AdvancedProcess.Hold 2 (AssemblyStation_hold)
;
7$          QUEUE,        AssemblyStation_hold.Queue;
          SCAN:        NQ(Battery_bin)  >= 1  &&  NQ(wiring_bin)>=1 && NQ(PCBoard_bin)>=1 &&
NQ(Radio_bin)>=1:NEXT(6$);


;
;
;    Model statements for module:  AdvancedProcess.Pickup 2 (Pickup Battery)
;
6$          PICKUP:       Battery_bin,1,1:NEXT(19$);


;
;
;    Model statements for module:  AdvancedProcess.Pickup 6 (Pickup Radio)
;
19$         PICKUP:       Radio_bin,1,1:NEXT(18$);


;
;
;    Model statements for module:  AdvancedProcess.Pickup 5 (Pickup wiring)
;
18$         PICKUP:       wiring_bin,1,1:NEXT(23$);


;
;
;    Model statements for module:  AdvancedProcess.Pickup 8 (Pickup PCBoard)
;
23$         PICKUP:       PCBoard_bin,1,1:NEXT(13$);


;
;
;    Model statements for module:  BasicProcess.Process 6 (Assembly process)
;
13$         ASSIGN:       Assembly process.NumberIn=Assembly process.NumberIn + 1:
                      Assembly process.WIP=Assembly process.WIP+1;
155$        STACK,        1:Save:NEXT(129$);

129$        QUEUE,        Assembly process.Queue;
128$        SEIZE,        2,VA:
                      SELECT(Assembler,POR, ),1:NEXT(127$);

127$        DELAY:        Assembly Process time +Assembly setuptime*SMEDoutcome,,VA:NEXT(170$);

170$        ASSIGN:       Assembly process.WaitTime=Assembly process.WaitTime + Diff.WaitTime;
134$        TALLY:        Assembly process.WaitTimePerEntity,Diff.WaitTime,1;
171$        ASSIGN:       Assembly process.WaitCost=Assembly process.WaitCost + Diff.WaitCost;
132$        TALLY:        Assembly process.WaitCostPerEntity,Diff.WaitCost,1;
136$        TALLY:        Assembly process.TotalTimePerEntity,Diff.StartTime,1;
137$        TALLY:        Assembly process.TotalCostPerEntity,
```

```
                Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
160$      ASSIGN:     Assembly process.VATime=Assembly process.VATime + Diff.VATime;
161$      TALLY:      Assembly process.VATimePerEntity,Diff.VATime,1;
165$      ASSIGN:     Assembly process.VACost=Assembly process.VACost + Diff.VACost;
162$      TALLY:      Assembly process.VACostPerEntity,Diff.VACost,1;
126$      RELEASE:    SELECT(Assembler,LAST),1;
175$      STACK,      1:Destroy:NEXT(174$);

174$      ASSIGN:     Assembly process.NumberOut=Assembly process.NumberOut + 1:
                Assembly process.WIP=Assembly process.WIP-1:NEXT(16$);


;
;
;   Model statements for module:  BasicProcess.Process 8 (Testing)
;
16$       ASSIGN:     Testing.NumberIn=Testing.NumberIn + 1:
                Testing.WIP=Testing.WIP+1;
206$      STACK,      1:Save:NEXT(180$);

180$      QUEUE,      Testing.Queue;
179$      SEIZE,      2,VA:
                SELECT(Tester,POR, ),1:NEXT(178$);

178$      DELAY:      Testing Process time+Testing setuptime*SMEDoutcome,,VA:NEXT(221$);

221$      ASSIGN:     Testing.WaitTime=Testing.WaitTime + Diff.WaitTime;
185$      TALLY:      Testing.WaitTimePerEntity,Diff.WaitTime,1;
222$      ASSIGN:     Testing.WaitCost=Testing.WaitCost + Diff.WaitCost;
183$      TALLY:      Testing.WaitCostPerEntity,Diff.WaitCost,1;
187$      TALLY:      Testing.TotalTimePerEntity,Diff.StartTime,1;
188$      TALLY:      Testing.TotalCostPerEntity,
                Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
211$      ASSIGN:     Testing.VATime=Testing.VATime + Diff.VATime;
212$      TALLY:      Testing.VATimePerEntity,Diff.VATime,1;
216$      ASSIGN:     Testing.VACost=Testing.VACost + Diff.VACost;
213$      TALLY:      Testing.VACostPerEntity,Diff.VACost,1;
177$      RELEASE:    SELECT(Tester,LAST),1;
226$      STACK,      1:Destroy:NEXT(225$);

225$      ASSIGN:     Testing.NumberOut=Testing.NumberOut + 1:
                Testing.WIP=Testing.WIP-1:NEXT(10$);


;
;
;   Model statements for module:  AdvancedProcess.Hold 3 (LabelingStation_hold)
;
10$       QUEUE,      LabelingStation_hold.Queue;
      SCAN:       NQ(label_bin)  >= 1 && NQ(bracket_bin)>=1:NEXT(9$);


;
;
;   Model statements for module:  AdvancedProcess.Pickup 3 (Pickup labels)
;
9$        PICKUP:     label_bin,1,1:NEXT(22$);
```

```
;
;
;    Model statements for module:  AdvancedProcess.Pickup 7 (Pickup bracket)
;
22$         PICKUP:      bracket_bin,1,1:NEXT(14$);


;
;
;    Model statements for module:  BasicProcess.Process 7 (Labeling_Packing)
;
14$         ASSIGN:      Labeling_Packing.NumberIn=Labeling_Packing.NumberIn + 1:
                    Labeling_Packing.WIP=Labeling_Packing.WIP+1;
257$        STACK,       1:Save:NEXT(231$);

231$        QUEUE,       Labeling_Packing.Queue;
230$        SEIZE,       2,VA:
                    SELECT(Packer,POR, ),1:NEXT(229$);

229$        DELAY:       Labeling Process time+Labeling setuptime*SMEDoutcome,,VA:NEXT(272$);

272$        ASSIGN:      Labeling_Packing.WaitTime=Labeling_Packing.WaitTime + Diff.WaitTime;
236$        TALLY:       Labeling_Packing.WaitTimePerEntity,Diff.WaitTime,1;
273$        ASSIGN:      Labeling_Packing.WaitCost=Labeling_Packing.WaitCost + Diff.WaitCost;
234$        TALLY:       Labeling_Packing.WaitCostPerEntity,Diff.WaitCost,1;
238$        TALLY:       Labeling_Packing.TotalTimePerEntity,Diff.StartTime,1;
239$        TALLY:       Labeling_Packing.TotalCostPerEntity,
                    Diff.WaitCost + Diff.VACost + Diff.NVACost + Diff.TranCost + Diff.OtherCost,1;
262$        ASSIGN:      Labeling_Packing.VATime=Labeling_Packing.VATime + Diff.VATime;
263$        TALLY:       Labeling_Packing.VATimePerEntity,Diff.VATime,1;
267$        ASSIGN:      Labeling_Packing.VACost=Labeling_Packing.VACost + Diff.VACost;
264$        TALLY:       Labeling_Packing.VACostPerEntity,Diff.VACost,1;
228$        RELEASE:     SELECT(Packer,LAST),1;
277$        STACK,       1:Destroy:NEXT(276$);

276$        ASSIGN:      Labeling_Packing.NumberOut=Labeling_Packing.NumberOut + 1:
                    Labeling_Packing.WIP=Labeling_Packing.WIP-1:NEXT(57$);


;
;
;    Model statements for module:  BasicProcess.Decide 13 (Customer satisfaction decision)
;
57$         BRANCH,      1:
                    If,leadtime>=(TNOW-timeIn),279$,Yes:
                    Else,280$,Yes;
279$        ASSIGN:      Customer satisfaction decision.NumberOut True=Customer satisfaction decision.NumberOut
True + 1
                    :NEXT(58$);

280$        ASSIGN:      Customer satisfaction decision.NumberOut False=Customer satisfaction decision.NumberOut
False + 1
                    :NEXT(59$);

58$         COUNT:       NumberOnTime,1:NEXT(60$);
```

```
;
;
;    Model statements for module:  AdvancedProcess.Dropoff 3 (Dropoff 3)
;
60$         DROPOFF,      1,(NG):15$:NEXT(15$);


;
;
;    Model statements for module:  BasicProcess.Dispose 2 (Ship to customer)
;
15$         ASSIGN:       Ship to customer.NumberOut=Ship to customer.NumberOut + 1;
281$         DISPOSE:      Yes;

59$         COUNT:        Numberdelayed,1:NEXT(60$);


;
;
;    Model statements for module:  BasicProcess.Assign 9 (Base setuptime assign)
;
32$         ASSIGN:       CustomType=0:
                    Assembly setuptime=1.0:
                    Testing setuptime=1.0:
                    Labeling setuptime=1.0:
                    Prep Setuptime=1.0:NEXT(4$);


;
;
;    Model statements for module:  BasicProcess.Assign 7 (Assign Custom type process times)
;
31$         ASSIGN:       CustomType=CustomType+1:
                    Labeling Process time=
                    TRIA( 0.19+LabelTimeIncrement, 0.24+LabelTimeIncrement, 0.27+LabelTimeIncrement,3):
                    Testing Process time=
                    TRIA( 0.15+TestTimeIncrement, 0.293+TestTimeIncrement, 0.37+TestTimeIncrement,4):
                    Assembly Process time=
                    TRIA( 0.16+AssemTimeIncrement, 0.284+AssemTimeIncrement, 0.33+AssemTimeIncrement,5):
                    Prep process time=TRIA( 0.12+PrepTimeIncrement, 0.13+PrepTimeIncrement,
0.14+PrepTimeIncrement,6)
                    :NEXT(35$);


;
;
;    Model statements for module:  BasicProcess.Decide 4 (Switch setuptime custom)
;
35$         BRANCH,       1:
                    If,CustomType>1,282$,Yes:
                    Else,283$,Yes;
282$        ASSIGN:       Switch setuptime custom.NumberOut True=Switch setuptime custom.NumberOut True +
1:NEXT(37$);

283$        ASSIGN:       Switch setuptime custom.NumberOut False=Switch setuptime custom.NumberOut False +
1:NEXT(33$);
```

```
;
;
;    Model statements for module:  BasicProcess.Assign 12 (Reset custom values)
;
37$         ASSIGN:       BaseType=0:
                   CustomType=1:
                   Assembly setuptime=0:
                   Testing setuptime=0:
                   Labeling setuptime=0:
                   Prep Setuptime=0:NEXT(4$);


;
;
;    Model statements for module:  BasicProcess.Assign 10 (Custom setuptime assign)
;
33$         ASSIGN:       BaseType=0:
                   Assembly setuptime=0.903:
                   Testing setuptime=0.903:
                   Labeling setuptime=0.903:
                   Prep Setuptime=0.903:NEXT(4$);


;
;
;    Model statements for module:  BasicProcess.Create 6 (Enclosure_vendor)
;

284$        CREATE,       240,HoursToBaseTime(0),enclosure:HoursToBaseTime(TRIA( 80, 85, 90,3)):NEXT(285$);

285$        ASSIGN:       Enclosure_vendor.NumberOut=Enclosure_vendor.NumberOut + 1:NEXT(39$);


;
;
;    Model statements for module:  BasicProcess.Decide 7 (Decide 7)
;
39$         BRANCH,       1:
                   If,NQ(Enclosure_bin) <= MinInventory,288$,Yes:
                   Else,289$,Yes;
288$        ASSIGN:       Decide 7.NumberOut True=Decide 7.NumberOut True + 1:NEXT(0$);

289$        ASSIGN:       Decide 7.NumberOut False=Decide 7.NumberOut False + 1:NEXT(49$);

0$          QUEUE,        Enclosure_bin:DETACH;
49$         COUNT:        Enclosure_excessed,1:NEXT(40$);


;
;
;    Model statements for module:  BasicProcess.Dispose 7 (Dispose 7)
;
40$         ASSIGN:       Dispose 7.NumberOut=Dispose 7.NumberOut + 1;
290$        DISPOSE:      Yes;


;
;
```

```
;    Model statements for module:  BasicProcess.Create 7 (Battery_vendor)
;

291$         CREATE,        240,HoursToBaseTime(0),battery:HoursToBaseTime(TRIA( 80, 85, 90,3)):NEXT(292$);

292$         ASSIGN:        Battery_vendor.NumberOut=Battery_vendor.NumberOut + 1:NEXT(41$);


;
;
;    Model statements for module:  BasicProcess.Decide 8 (Decide 8)
;
41$          BRANCH,        1:
                       If,NQ(Battery_bin) <= MinInventory,295$,Yes:
                       Else,296$,Yes;
295$         ASSIGN:        Decide 8.NumberOut True=Decide 8.NumberOut True + 1:NEXT(1$);

296$         ASSIGN:        Decide 8.NumberOut False=Decide 8.NumberOut False + 1:NEXT(50$);

1$           QUEUE,         Battery_bin:DETACH;
50$          COUNT:         Battery_excessed,1:NEXT(42$);


;
;
;    Model statements for module:  BasicProcess.Dispose 8 (Dispose 8)
;
42$          ASSIGN:        Dispose 8.NumberOut=Dispose 8.NumberOut + 1;
297$         DISPOSE:       Yes;


;
;
;    Model statements for module:  BasicProcess.Create 8 (Label_vendor)
;

298$         CREATE,        240,HoursToBaseTime(0),label:HoursToBaseTime(TRIA( 80, 85, 90,3)):NEXT(299$);

299$         ASSIGN:        Label_vendor.NumberOut=Label_vendor.NumberOut + 1:NEXT(63$);


;
;
;    Model statements for module:  BasicProcess.Decide 11 (Decide 11)
;
63$          BRANCH,        1:
                       If,NQ(label_bin)<= MinInventory,302$,Yes:
                       Else,303$,Yes;
302$         ASSIGN:        Decide 11.NumberOut True=Decide 11.NumberOut True + 1:NEXT(2$);

303$         ASSIGN:        Decide 11.NumberOut False=Decide 11.NumberOut False + 1:NEXT(54$);

2$           QUEUE,         label_bin:DETACH;
54$          COUNT:         Label_excessed,1:NEXT(64$);


;
;
```

```
;     Model statements for module:  BasicProcess.Dispose 11 (Dispose 11)
;
64$          ASSIGN:       Dispose 11.NumberOut=Dispose 11.NumberOut + 1;
304$         DISPOSE:      Yes;


;
;
;     Model statements for module:  BasicProcess.Create 10 (Wiring_vendor)
;

305$         CREATE,       240,HoursToBaseTime(0),wiring:HoursToBaseTime(TRIA( 80, 85, 90,3)):NEXT(306$);

306$         ASSIGN:       Wiring_vendor.NumberOut=Wiring_vendor.NumberOut + 1:NEXT(43$);


;
;
;     Model statements for module:  BasicProcess.Decide 9 (Decide 9)
;
43$          BRANCH,       1:
                     If,NQ(wiring_bin)<= MinInventory,309$,Yes:
                     Else,310$,Yes;
309$         ASSIGN:       Decide 9.NumberOut True=Decide 9.NumberOut True + 1:NEXT(17$);

310$         ASSIGN:       Decide 9.NumberOut False=Decide 9.NumberOut False + 1:NEXT(51$);

17$          QUEUE,        wiring_bin:DETACH;
51$          COUNT:        Wiring_excessed,1:NEXT(44$);


;
;
;     Model statements for module:  BasicProcess.Dispose 9 (Dispose 9)
;
44$          ASSIGN:       Dispose 9.NumberOut=Dispose 9.NumberOut + 1;
311$         DISPOSE:      Yes;


;
;
;     Model statements for module:  BasicProcess.Create 12 (Radio_vendor)
;

312$         CREATE,       240,HoursToBaseTime(0),radio:HoursToBaseTime(TRIA( 80, 85, 90,3)):NEXT(313$);

313$         ASSIGN:       Radio_vendor.NumberOut=Radio_vendor.NumberOut + 1:NEXT(45$);


;
;
;     Model statements for module:  BasicProcess.Decide 10 (Decide 10)
;
45$          BRANCH,       1:
                     If,NQ(Radio_bin)<= MinInventory,316$,Yes:
                     Else,317$,Yes;
316$         ASSIGN:       Decide 10.NumberOut True=Decide 10.NumberOut True + 1:NEXT(20$);
```

```
317$        ASSIGN:      Decide 10.NumberOut False=Decide 10.NumberOut False + 1:NEXT(53$);

20$        QUEUE,       Radio_bin:DETACH;
53$        COUNT:       Radio_excessed,1:NEXT(46$);


;
;
;    Model statements for module:  BasicProcess.Dispose 10 (Dispose 10)
;
46$        ASSIGN:      Dispose 10.NumberOut=Dispose 10.NumberOut + 1;
318$        DISPOSE:     Yes;


;
;
;    Model statements for module:  BasicProcess.Create 13 (Bracket_vendor)
;

319$        CREATE,       240,HoursToBaseTime(0),bracket:HoursToBaseTime(TRIA( 80, 85, 90,3)):NEXT(320$);

320$        ASSIGN:      Bracket_vendor.NumberOut=Bracket_vendor.NumberOut + 1:NEXT(47$);


;
;
;    Model statements for module:  BasicProcess.Decide 12 (Decide 12)
;
47$        BRANCH,       1:
                  If,NQ(bracket_bin) <= MinInventory,323$,Yes:
                  Else,324$,Yes;
323$        ASSIGN:      Decide 12.NumberOut True=Decide 12.NumberOut True + 1:NEXT(21$);

324$        ASSIGN:      Decide 12.NumberOut False=Decide 12.NumberOut False + 1:NEXT(55$);

21$        QUEUE,       bracket_bin:DETACH;
55$        COUNT:       Bracket_excessed,1:NEXT(48$);


;
;
;    Model statements for module:  BasicProcess.Dispose 12 (Dispose 12)
;
48$        ASSIGN:      Dispose 12.NumberOut=Dispose 12.NumberOut + 1;
325$        DISPOSE:     Yes;


;
;
;    Model statements for module:  BasicProcess.Create 17 (PCBoard_vendor)
;

326$        CREATE,       PCvendorqty,HoursToBaseTime(0),pcboard:HoursToBaseTime(TRIA( 80, 85,
90,3)):NEXT(327$);

327$        ASSIGN:      PCBoard_vendor.NumberOut=PCBoard_vendor.NumberOut + 1:NEXT(26$);
```

```
;
;
;    Model statements for module:  BasicProcess.Decide 1 (Decide 1)
;
26$         BRANCH,       1:
                   If,(TNOW  >= (80) ) && (TNOW  <= (Vendortimeout+80) ),330$,Yes:
                   Else,331$,Yes;
330$        ASSIGN:       Decide 1.NumberOut True=Decide 1.NumberOut True + 1:NEXT(25$);

331$        ASSIGN:       Decide 1.NumberOut False=Decide 1.NumberOut False + 1:NEXT(38$);


;
;
;    Model statements for module:  BasicProcess.Dispose 3 (Dispose 3)
;
25$         ASSIGN:       Dispose 3.NumberOut=Dispose 3.NumberOut + 1;
332$        DISPOSE:      Yes;


;
;
;    Model statements for module:  BasicProcess.Decide 6 (Decide 6)
;
38$         BRANCH,       1:
                   If,NQ(PCBoard_bin)  <= MinInventory,333$,Yes:
                   Else,334$,Yes;
333$        ASSIGN:       Decide 6.NumberOut True=Decide 6.NumberOut True + 1:NEXT(24$);

334$        ASSIGN:       Decide 6.NumberOut False=Decide 6.NumberOut False + 1:NEXT(52$);

24$         QUEUE,        PCBoard_bin:DETACH;
52$         COUNT:        PCBoard_excessed,1:NEXT(25$);


;
;
;    Model statements for module:  BasicProcess.Create 19 (Diminished supply over time)
;

335$        CREATE,       1,HoursToBaseTime(80),SupplyDecreaseInfluence:HoursToBaseTime(2080),2:NEXT(336$);

336$        ASSIGN:       Diminished supply over time.NumberOut=Diminished supply over time.NumberOut +
1:NEXT(28$);


;
;
;    Model statements for module:  BasicProcess.Assign 5 (ChangeSupplyDecreaseInfluence)
;
28$         ASSIGN:       PCvendorqty=PCvendorqty*Percentdecrease:NEXT(27$);


;
;
;    Model statements for module:  BasicProcess.Dispose 5 (Dispose 5)
;
27$         ASSIGN:       Dispose 5.NumberOut=Dispose 5.NumberOut + 1;
```

```
339$        DISPOSE:      Yes;


;
;
;    Model statements for module:  BasicProcess.Create 20 (AltPCBoard_vendor)
;

340$        CREATE,       AltPCvendorqty,HoursToBaseTime(0),pcboard:
                    HoursToBaseTime(TRIA( VendorMin, VendorMode, VendorMax,3)):NEXT(341$);

341$        ASSIGN:       AltPCBoard_vendor.NumberOut=AltPCBoard_vendor.NumberOut + 1:NEXT(38$);


;
;
;    Model statements for module:  BasicProcess.Create 21 (ProductCustomization)
;

344$        CREATE,
1,HoursToBaseTime(CustomTimeshift),CustomProductFactor:HoursToBaseTime(600),1:NEXT(345$);

345$        ASSIGN:       ProductCustomization.NumberOut=ProductCustomization.NumberOut + 1:NEXT(61$);


;
;
;    Model statements for module:  BasicProcess.Assign 14 (Product Customization)
;
61$         ASSIGN:       PrepTimeIncrement=0.0325:
                    LabelTimeIncrement=0.0583:
                    AssemTimeIncrement=0.0645:
                    TestTimeIncrement=0.0678:NEXT(62$);


;
;
;    Model statements for module:  BasicProcess.Dispose 13 (Dispose 13)
;
62$         ASSIGN:       Dispose 13.NumberOut=Dispose 13.NumberOut + 1;
348$        DISPOSE:      Yes;


;
;
;    Model statements for module:  BasicProcess.Create 22 (AltEnclosure_vendor)
;

349$        CREATE,       AltPCvendorqty,HoursToBaseTime(0),enclosure:
                    HoursToBaseTime(TRIA( VendorMin, VendorMode, VendorMax,3)):NEXT(350$);

350$        ASSIGN:       AltEnclosure_vendor.NumberOut=AltEnclosure_vendor.NumberOut + 1:NEXT(39$);


;
;
;    Model statements for module:  BasicProcess.Create 23 (AltBattery_vendor)
;
```

```
353$        CREATE,        AltPCvendorqty,HoursToBaseTime(0),battery:
                    HoursToBaseTime(TRIA( VendorMin, VendorMode, VendorMax,3)):NEXT(354$);

354$        ASSIGN:        AltBattery_vendor.NumberOut=AltBattery_vendor.NumberOut + 1:NEXT(41$);


;
;
;    Model statements for module:  BasicProcess.Create 24 (AltWiring_vendor)
;

357$        CREATE,        AltPCvendorqty,HoursToBaseTime(0),wiring:HoursToBaseTime(TRIA( VendorMin,
VendorMode, VendorMax,3))
                    :NEXT(358$);

358$        ASSIGN:        AltWiring_vendor.NumberOut=AltWiring_vendor.NumberOut + 1:NEXT(43$);


;
;
;    Model statements for module:  BasicProcess.Create 25 (AltRadio_vendor)
;

361$        CREATE,        AltPCvendorqty,HoursToBaseTime(0),radio:HoursToBaseTime(TRIA( VendorMin, VendorMode,
VendorMax,3))
                    :NEXT(362$);

362$        ASSIGN:        AltRadio_vendor.NumberOut=AltRadio_vendor.NumberOut + 1:NEXT(45$);


;
;
;    Model statements for module:  BasicProcess.Create 26 (AltLabel_vendor)
;

365$        CREATE,        AltPCvendorqty,HoursToBaseTime(0),label:HoursToBaseTime(TRIA( VendorMin, VendorMode,
VendorMax,3))
                    :NEXT(366$);

366$        ASSIGN:        AltLabel_vendor.NumberOut=AltLabel_vendor.NumberOut + 1:NEXT(63$);


;
;
;    Model statements for module:  BasicProcess.Create 27 (AltBracket_vendor)
;

369$        CREATE,        AltPCvendorqty,HoursToBaseTime(0),bracket:
                    HoursToBaseTime(TRIA( VendorMin, VendorMode, VendorMax,3)):NEXT(370$);

370$        ASSIGN:        AltBracket_vendor.NumberOut=AltBracket_vendor.NumberOut + 1:NEXT(47$);


;
;
;    Model statements for module:  BasicProcess.Create 18 (CompetitorsOutOfBusiness)
;
```

```
373$        CREATE,      1,HoursToBaseTime(80),CompOutOfBusiness:HoursToBaseTime(600),1:NEXT(374$);

374$        ASSIGN:      CompetitorsOutOfBusiness.NumberOut=CompetitorsOutOfBusiness.NumberOut +
1:NEXT(65$);


;
;
;    Model statements for module:  BasicProcess.Assign 4 (ChangeCompOutOfBusiness)
;
65$         ASSIGN:      Order_time=CompBusiness:NEXT(66$);


;
;
;    Model statements for module:  BasicProcess.Dispose 4 (Dispose 4)
;
66$         ASSIGN:      Dispose 4.NumberOut=Dispose 4.NumberOut + 1;
377$        DISPOSE:     Yes;
```

VITA

Rajesh Krishnamurthy

Candidate for the Degree of

Doctor of Philosophy

Thesis: STUDY OF CONTROL ACTIONS ON A MANUFACTURING SYSTEM SUBJECT TO A DYNAMIC ENVIRONMENT CREATED BY CUSTOMERS, SUPPLIERS AND COMPETITORS

Major Field: Industrial Engineering and Management

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Industrial Engineering and Management at Oklahoma State University, Stillwater, Oklahoma in December, 2011.

Completed the requirements for the Master of Science in Manufacturing Systems Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2000.

Completed the requirements for the Bachelor of Engineering in Mechanical Engineering at Coimbatore Institute of Technology, Coimbatore, Tamil Nadu, India in March 1998.

Experience:

Manufacturing Engineer, Black Sivalls & Bryson Safety Systems LLC,
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Operations Manager, Black Sivalls & Bryson Safety Systems LLC,
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Pages in Study: 266 Candidate for the Degree of Doctor of Philosophy/Education

Major Field: Industrial Engineering and Management

The existence of multiple, overlapping manufacturing philosophies creates confusion among manufacturing system managers who seek to better control the performance of the manufacturing system when responding to changes in the external elements such as suppliers, customers and competitors. Given the scenario where a set of random and difficult to predict external influences may change and impact the performance metrics of the system, a manager is often unable to pick most cost effective control actions to mitigate or exploit the effects of the influences. The control action is an investment to recover (mitigate/exploit) the effect of external influence(s) and to improve system performance.

This research study addresses the managerial actions needed to select the control actions in the face of individual and grouped external influences acting on a system's performance metrics. Based on preliminary findings, the transient response characteristics of selected performance metrics were able to provide better understanding of the value of the control actions. Using the performance metrics response and a methodology proposed in this study to select control actions, a manager could estimate the performance of the control action(s) at the different intensity levels of the external influences. This study connects the cost impact of the changes in external influences to the control action(s) investment cost using net present value.

ADVISER'S APPROVAL: ______________________________

(Dr. John W. Nazemetz)