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A comparative study of Just-In-Time (JIT) and Theory of Constraints (TOC) systems with varying constraint locations and operational characteristics

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A COMPARATIVE STUDY OF JUST-IN-TIME (JIT) AND THEORY OF CONSTRAINTS (TOC) SYSTEMS WITH VARYING CONSTRAINT LOCATIONS AND OPERATIONAL CHARACTERISTICS

BY

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ABSTRACT

Various researchers have extolled the benefits of Theory of Constraints (TOC), Just-in-Time (JIT), and other manufacturing strategies. Some supporters of JIT argue it is the least costly, while others point to the overall benefits of TOC. There are conflicting claims as to the best manufacturing philosophies which is compounded by the fact that no one system is best in every situation. The success of a production system truly depends on the manufacturing environment rather than the philosophy being used. This study uses computer simulations of differing manufacturing environments to compare Just-in-Time (JIT) and Theory of Constraints (TOC) philosophies over two response variables, make span and work-in-process (WIP).

Results showed significant differences favoring both TOC and JIT in different manufacturing environments with respect to both make span and work-in-process (WIP). The study showed evidence that both JIT and TOC are essentially the same when a production system has a bottleneck located at the last station. However, the performance of TOC could equal that of JIT with less inventory.

This supports the concept of strategic inventory use for the constrained resource in TOC over the JIT concept of having at least two Kanban cards at each workstation. Different process structures showed different performance for the two strategies used. The study suggested that higher setup and process variation did not have much effect on WIP level, but they did have a significant effect on the make span variable. In conclusion, the study proved that not one system is best in every condition. Each manufacturing environment will be best served by a unique manufacturing strategy.

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1. INTRODUCTION

1.1 BACKGROUND

The issue of production and inventory management has played a significant role in creating a competitive edge in most organizations, especially in today's highly competitive global markets. Most companies have been searching for a technique that provides higher throughput and at the same time results in inventory reduction. Throughput in this sense does not mean only the products that are produced, but that they also must be sold to generate money, since finished goods count for nothing but inventory. The past literature has been focused largely on the issue of inventory reduction since inventory has long been recognized for its large share of production cost. It was said that inventory accounts for about 50% of manufacturing production total cost (Kim and Lee, 1989). Therefore, there is a trend among many manufacturing companies to emphasize inventory reduction strategies.

Inventory was once viewed by most accountants based on a traditional account system as an asset of an organization, in that it can be converted into money at any time. Furthermore, based on traditional manufacturing approaches, having inventory means having a cushion against variability that might occur in the manufacturing system. However, this does not hold true anymore. Based on current practices worldwide, especially Japanese manufacturing techniques, inventory is now viewed more as an obstacle to an organization in improving productivity and product quality. Moreover, it also has an effect in reducing manufacturing flexibility in offering the customers a variety of products in a short lead-time. Buxey (1989) states, in his study, work-in-process (WIP) is not seen as a convenient means of avoiding production control crises, but as a waste of resources that serves to mask the real nature of production problems.

Large inventories normally result from the use of large production batches, the larger the production batch size, the larger the inventory level. Large inventories can result in many problems to an organization, such as obsolete products, damage during storage, and other losses. Therefore, in order to reduce an inventory level, small production lot size is becoming more common. There are many advantages of using a small lot technique. For instance, if the small lots are produced and there is any part defect detected, a supervisor or engineer can react quickly to the problem rather than having to wait and rework numerous parts when large lots were produced. Moreover, small lot sizes also provide flexibility to an organization in responding to various customers' demand.

Due to these problems, most emerging manufacturing techniques have been designed to lower the organizations' inventory level. There have been many emerging manufacturing technologies and philosophies that aim to reduce inventory in an organization and at the same time provide more flexibility to react to market demand more quickly. Among these are Material Requirements Planning (MRP), Manufacturing Resource Planning (MRP II), Just-in-Time (JIT), and Theory of Constraints (TOC). These systems have received much attention from researchers during the last three decades. Even though MRP and MRP II will not be included in this study, they will be discussed to provide the reader with a broader understanding of the various inventory management philosophies.

1.2 DEVELOPMENT OF MATERIAL REQUIREMENTS PLANNING (MRP), JUST-IN-TIME (JIT), AND THEORY OF CONSTRAINTS (TOC)

The three inventory management philosophies of MRP, JIT, and TOC have been the most widespread techniques utilized in a variety of industries during the past few decades. These three systems were developed in different parts of the world under different cultures. Therefore, to fully understand each concept, the development of each philosophy will first be discussed.

1.2.1 Material Requirements Planning (MRP). MRP (Material Requirements Planning) system was first developed in the U.S. during the early 1950s as a computer-based production planning and control system, which targets reducing work-in-process (WIP) level in an organization. MRP systems operate by forecasting the future demand of the company and then constructing a Master Production Schedule (MPS) based on the forecast for how many and when the products will be needed. The system then provides the latest date to start each production activity using time-phased technique in order to have the products available when customers want them. The definition of MRP was given in the 1998 edition of the *American Production and Inventory Control Society (APICS) Dictionary* as:

> A set of techniques that uses bill of material data, inventory data, and the master production schedule to calculate requirements for materials. It makes recommendations to release replenishment orders for material. Further, because it is time-phased, it makes recommendations to reschedule open orders when due dates and need dates are not in phase. Time-phased MRP begins with the items listed on the MPS and determines (1) the quantity of all components and materials required to fabricate those items and (2) the date that the components and material are required. Time-phased MRP is accomplished by exploding the bill of material, adjusting for inventory quantities on hand or on order, and offsetting the net requirements by the appropriate lead times.

Also in the *APICS Dictionary* (1998), the definition of a push system is given as:

> 1) In production, the production of items at times required by a given schedule planned in advance. 2) In material control, the issuing of material according to a given schedule or issuing material to a job at its start time. 3) In distribution, a system for replenishing field warehouse inventories where replenishment decision making is centralized, usually at the manufacturing site or central supply facility.

Thus, MRP is a push system in that it pushes the production from the preceding stage to the next stage in order to have the product finished on time without considering the status of the succeeding process.

During the early 1970s, MRP systems received much attention from both academicians and practitioners. It was the system that was implemented in many organizations, or at least planned to be implemented. During this period, a book was written titled *Material Requirements Planning* by Orlicky (1975). It was the first book ever published on the MRP system. It has been used by many researchers and practitioners as the primary reference for MRP systems. Hundreds of articles were also published in various journals about MRP. American Production and Inventory Control Society (APICS) also declared a decade long (1971-1979) effort to promote MRP called "The MRP Crusade" at the suggestion of Wight and Plossl (Gilbert and Schonberger, 1983). Since the very beginning of MRP crusade, it was estimated that over 1,000 companies have implemented the MRP system. However, by 1976 only 25 companies had come close to realizing the full potential of MRP (Latham, 1981). By 1979, majority reported MRP's failure to deliver the expected benefits.

Lambrecht and Decaluwe (1988) discussed a drawback of MRP: its inability to handle uncertainty due to the use of fixed parameters. They argued that MRP cannot cope with the dynamics of shop floor activities, and the use of predetermined factors in MRP such as lot sizes, fixed lead times, and others resulted in rigid implementation. Benton and Shin (1998) also argued other drawbacks of MRP for its negligence of capacity constraints in the system and stockpiling of work-in-process (WIP) inventory. Swann (1986) also spotted some shortcomings of MRP in his study including having rigid lot-sizing rules and average queue times, the lack of ability to split lots or send ahead partial lots.

Joe Orlicky stated that 90% of the companies failed to make MRP work because they ignore one or more of its fundamental prerequisites:

- Top management commitment
- Education of those who use the system
- Realistic master production schedule
- Accurate bills of material and inventory records

However, despite the failure of MRP implementation to achieve the expected results, there was an effort to develop MRP to the next step called closed-loop MRP or MRP II (Manufacturing Resource Planning). The major difference for MRP and MRP II given by Fogarty, Hoffmann, and Stonebraker (1989) is:

> MRP II is an explicit and formal manufacturing information system that integrates marketing, finance, and operations. It converts resource requirements (e.g., facilities, equipment, personnel, and material) into financial requirements and converts production outputs into monetary terms.

Comprehensive details of the MRP and MRP II systems can be found in the books written by Orlicky (1975) and Wight (1981, 1984). For ease of discussion the terms MRP and MRP II are used interchangeably in some contexts of this research.

1.2.2 Just-in-Time (JIT).

While U.S. manufacturers spent much of the 1970s developing and installing manufacturing resource planning systems (MRP and MRP II), the Japanese were working just as hard to make their manufacturing systems and processes simpler and more efficient (Loebel, 1986). In 1977, the Japanese authors Sugumari, Kusunoki, Cho, and Uchikawa (1977) published the first article in English that described the great triumph of the Kanban and Just-In-Time (JIT) system of the Toyota Motor Company while MRP implementation failures were becoming common. Benton and Shin (1998) also argued that the eminence of the JIT production system was partly enhanced by the operational failures of the existing MRP systems.

The 1998 edition of the *APICS Dictionary* defines Just-in-Time (JIT) as:

> A philosophy of manufacturing based on planned elimination of all waste and on continuous improvement of productivity. It encompasses the successful execution of all manufacturing activities required to produce a final product from design engineering to delivery, and includes all stages of conversion from raw material onward. The primary elements of Just-in-Time are to have only the required inventory when needed; to improve quality to zero defects; to reduce lead times by reducing setup times, queue lengths, and lot sizes; to incrementally revise the operations themselves; and to accomplish these activities at minimum cost. In the broad sense, it applies to all forms of manufacturing --- job shop, process, and repetitive --- and to many service industries as well. Syn: short-cycle manufacturing, stockless production, zero inventories.

The Just-in-time manufacturing system was first developed as a production technique at Toyota Motor Company in Japan in late 1950s by Mr. Taiichi Ohno, the former vice president of Toyota Motor Company. It is sometimes called Toyota Production System (TPS). This production system later became well known throughout the world, especially in the U.S. in late 1970s after Toyota had revealed its success. By then Toyota had disseminated its JIT production system to other carmakers in Japan and who adopted JIT (Nakamura et al., 1998). It was said to be a system that needed to be implemented if an organization wanted to survive in a very highly competitive business environment.

The JIT production system is also often called "Lean Production System" because it uses less of every resource compared with the conventional mass production system for the same output (Womack et al., 1990). In the book *The Machine that Changed the World: The Story of Lean Production* (Womack et al., 1990), this new manufacturing paradigm of Japanese car makers was discussed thoroughly including the efforts of U.S. car manufacturers trying to catch up with Japanese including IMVP (International MOTOR Vehicle Program) in a study conducted at MIT and with the involvement of GM in NUMMI (New United Motors Manufacturing, Inc.), its joint venture with Toyota.

The fundamental concept of JIT is that it is good practice to produce what the customer wants at the time it is needed, and nothing else, rather than tying up working capital and space in inventory. In essence, JIT means that we make "what we need, when we need it." The JIT philosophy aims to eliminate waste or any non-value added activity of a production process. Ohno (1988), the master of Toyota Production System, identifies seven wastes of manufacturing processes as follow:

- Waste of overproduction
- Waste of waiting
- Waste of transportation
- Waste of processing
- Waste of inventories
- Waste of movement
- Waste of making defective parts and products

JIT uses a Kanban card system as its shop floor control technique in order to accomplish eliminating of all seven wastes identified by Ohno (1988). The Kanban system works like a "pull" technique by working backward from customer orders to the very first stage of production process. Kanban will signal the preceding stage to produce parts only when they are needed by the succeeding stage. This conforms to the definition given by *APICS Dictionary* (1998) for the pull system as:

> 1) In production, the production of items only as demanded for use or to replace those taken for use. 2) In material control, the withdrawal of inventory as demanded by the using operations. Material is not issued until a signal comes from the user. 3) In distribution, a system for replenishing field warehouse inventories where replenishment decisions are made at the field warehouse itself, not at the central warehouse or plant.

However, it should be understood that JIT and Kanban are the same technique. Actually, Kanban, simply means "card" in Japanese, and is only a part of JIT system as a control mechanism being used to signal shop floor production, but Kanban itself cannot represent a JIT system. Kanban, in the JIT production system, is used to control or trigger workstations in manufacturing systems to start producing parts or products when they are needed. It simply works like a work order in a traditional system. There are two different types of Kanban, single-card and dual-card Kanban systems. Details of Kanban system can be read from Schonberger (1982a, p. 219-238).

Even though JIT was considered to be a fresh idea in manufacturing techniques to most manufacturers in the U.S. at the time it emerged. The rising productivity in Japan was convincing enough for the U.S. firms to study the system and implement it; as an excerpt from Schonberger (1982b), one of the pioneers of JIT in the U.S., states,

> For example, American Production and Inventory Control Society (APICS), together with Arthur Anderson and Company, had conducted

> seminar/workshops on Japanese material and shop-floor procedures in several U.S. cities during late 1970s and continued to 1980s. Also, in 1979 APICS established a Repetitive Manufacturing Group (with members from over 50 companies), which has sponsored studies of Japanese manufacturing management in a number of industries and involving Japanese subsidiary plants in the U.S. as well as companies in Japan.

Schonberger (1982a) published the book titled *Japanese Manufacturing Techniques: Nine Hidden Lessons in Simplicity*, perhaps the first comprehensive book on overall Japanese manufacturing techniques. This book continues to provide many American companies insight into JIT. He discusses in detail the Kawasaki plant in Lincoln, Nebraska, the very first plant in the U.S. to achieve JIT benefits. Another successful story of Kanban is by GE's Louisville, Kentucky, dishwasher assembly plant. Its WIP was greatly reduced. Hewlett-Packard and Harley-Davidson are two other successful stories of JIT journeys.

However, some shortcomings of JIT have also been reported. The major limitations of JIT that seem to concern most researchers are the cultural and demographic differences between Japan and the U.S. (Johnson, 1986). Another drawback is that JIT cannot tolerate constantly changing the master production schedules (Aggarwal and Aggarwal, 1985). It certainly starts breaking down if there are numerous changes in product volumes or models. Carlson and Yao (1992) also confirm in their study that JIT cannot cope with daily variations in demand on the shop floor unless it is supported by multifunction workers and flawless parts in the required quantities. Moreover, due to its very low level of WIP inventory, if anything wrong ever happens to the system, it will stop the entire system rapidly (Sohal and Howard, 1987).

1.2.3 Theory of Constraints (TOC). Beginning in the 1980s, while JIT had received a lot of attention from many researchers but its philosophy had yet to be well understood, there was another production planning and control system called Optimized Production Technology (OPT). It later became well known by the name Theory of Constraints (TOC). It has also been called Synchronous Manufacturing.

OPT was first developed by Eliyahu M. Goldratt, Israeli physicist, in 1979 as a computer-based production and planning control tool. Wheatley (1989) though argues that it is a combination of philosophy and software, rather than just software itself. OPT was first offered in the U.S. by Creative Output, Inc., of Milford, CT. It differs from MRP in the sense that OPT is specially designed to custom fit the organization, unlike MRP, that is more general to any organization. Moreover, the concept behind OPT was kept secret by Creative Output Inc.; some called it a "black box" system, while MRP is much more open.

Later in 1984, Goldratt published his first book, *The Goal,* explaining the essences of OPT. However, he did not use the term OPT in his book due to its inability to detail the actual functions of the production system (Spencer, 1991). Further in 1986, Goldratt and Fox (1986) went on to publish another book titled *The Race*, in which the concept called "drum-buffer-rope" (DBR), a shop floor control technique to overcome the problems in production systems, was first formally introduced. "Drum-buffer-rope" (DBR) technique is explained in *APICS Dictionary* (1998) as:

> The drum is the rate or pace of production set by the system's constraint. The buffers establish the protection against uncertainty so that the system can maximize throughput. The rope is a communication process from the constraint to the gating operation that checks or limits material released into the system to support the constraint. See: synchronized production.

Beginning in 1987, the overall concept became known as the Theory of Constraints (TOC). TOC, the replacement of OPT, is more of a production philosophy like JIT than a computer tool like MRP. As with MRP and JIT, TOC also has a Constraints Management Special Interest Group (CM SIG), established by APICS in the 1990s to support the growing concepts of TOC by presenting several courses and seminars on TOC concepts.

TOC can be generally defined as a management approach which emphasizes improving bottleneck resources to continually improve the performance of manufacturing operations (Verma, 1997).

The *APICS Dictionary* (1998) defines TOC as:

> A management philosophy developed by Dr. Eliyahu M. Goldratt that can be viewed as three separate but interrelated areas --- logistics, performance measurement, and logical thinking. Logistics include drum-buffer-rope scheduling, buffer management, and VAT analysis. Performance measurement includes throughput, inventory and operating expense, and the five focusing steps. Thinking process tools are important in identifying the root problem (current reality tree), identifying and expanding win-win solutions (evaporating cloud and future reality tree), and developing implementation plans (perquisite tree and transition tree). Syn: constraint theory.

Figure 1.1 taken in part from Spencer and Cox (1995a) is shown to clarify the definition of TOC given in the *APICS Dictionary.*

Most of the logistics side of the picture has been discussed in this study. The details on the problem solving and thinking process side can be found in Spencer and Cox's papers and books (1995a and 1998).

Regardless of the names, OPT and TOC were developed for the same purpose, to maximize throughput of the system. Goldratt (1984) defines throughput as money truly earned through sales, not just by producing the products. Goldratt believes that the goal of any company should be to make money both at present and in the future. However, the throughput of each system will be limited by the slowest process, which is identified as a constraint or bottleneck resources in OPT and TOC. Goldratt (1988) identifies a constraint as "anything that limits a system from achieving higher performance versus its goal." It can be either internal or external constraints. Internal constraints mean the constraint within the organizations, such as capacity constraint or managerial constraint, while external constraints refer to any uncontrollable factors outside the organizations, such as market constraint.

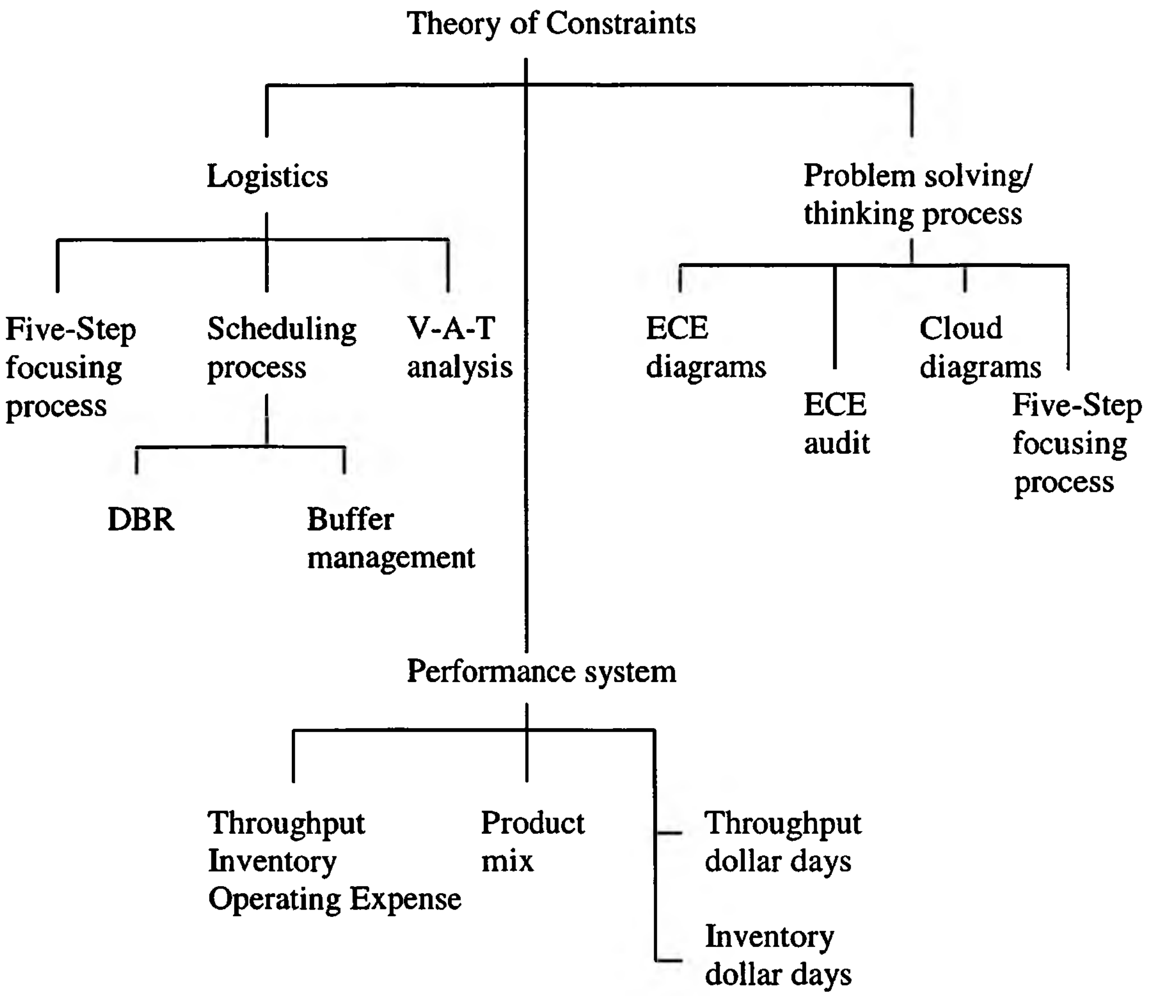


Figure 1.1 Schematic of the Theory of Constraints

Therefore, both OPT and TOC emphasize the planning of bottleneck resources by keeping it constantly busy in either setting up or processing, to maximize its throughput. The significant differences between OPT and TOC are that they operate under different sets of rules. OPT was designed to operate under its nine rules while TOC's emphasis is on its five focusing steps to implement the philosophy. However, some researchers may include another aspect of OPT as its tenth rule; that is "The sum of local optimums is not equal to the optimum of the whole." OPT's nine rules and the five steps of TOC are shown in Table 1.1.

Even though there are differences in Table 1.1, TOC and OPT both try to maximize utilization of the bottleneck. The real difference among these two is that OPT is used as a shop floor control technique, while TOC works toward a continuous improvement approach similar to the difference between JIT and Kanban.

Having been around for decades, there are published reports of OPT and TOC successes. There have been some impressive results reported from some big companies, including General Motors, Ford, Westinghouse, AVCO, Bendix, General Electric, and Caterpillar Tractors (Wheatley, 1989). There is increasing evidence of successful applications of OPT in different manufacturing companies (Booth, 1988; Fry et al., 1992). There has also been increasing discussions of successful implementations of TOC (Vollmann, 1986; Lambrecht and Decaluwe, 1988; Ptak, 1991).

Advantages and disadvantages are discussed in the literature (Plenert and Best, 1986; Taylor III, 1999; Everdell, 1984; Aggarwal and Aggarwal, 1985; and Grunwald et al., 1989). However, a concrete conclusion about the advantages and disadvantages of the system has not been reached. However, TOC has been said to combine the strengths from

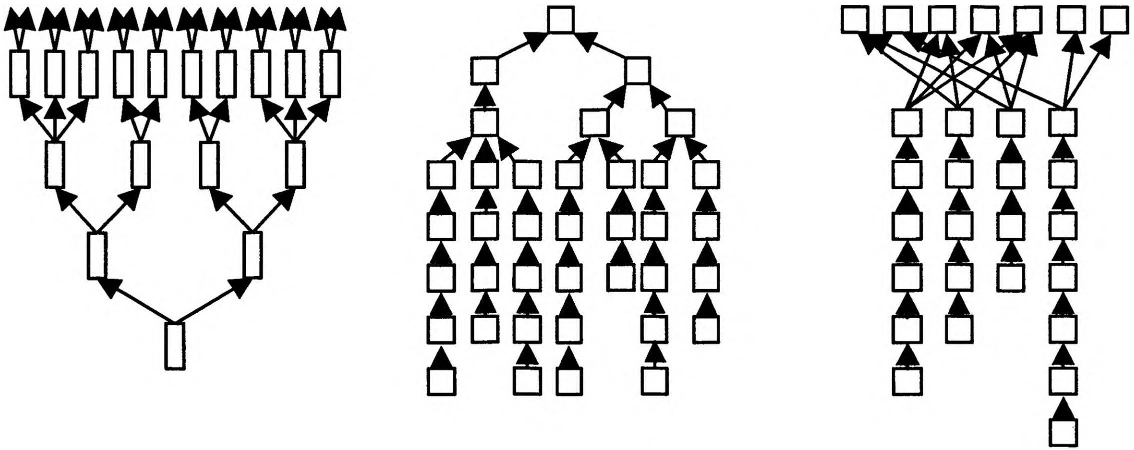
Table 1.1 OPT Nine Rules and TOC Five Steps

OPT nine rules.	TOC five steps.
1. Balance flow, not capacity.	1. Identify the system's constraint(s).
2. The level of utilization of a non-bottleneck is not determined by its own potential but by some other constraint in the system.	2. Decide how to exploit the system's constraint(s).
3. Utilization and activation of a resource are not synchronous.	3. Subordinate everything else to the above decision.
4. An hour lost at a bottleneck is an hour lost for the total system.	4. Elevate the system's constraint(s).
5. An hour saved at a non-bottleneck is just a mirage.	5. If in any of the previous steps a constraint is broken, go back to step 1. Do not let inertia become the next constraint.
6. Bottlenecks govern both throughput and inventories.	
7. The transfer batch may not, and many times should not, be equal to the process batch.	
8. The process batch should be variable not fixed.	
9. Schedules should be established by looking at all the constraints simultaneously. Lead times are the result of a schedule and cannot be determined.	

both MRP and JIT (Lundrigan, 1986; Wheatley, 1989) and can outperform any system in most environments. It is even said to be a substitute for both MRP and JIT (Reimer, 1991; Renn and Steven, 1991). TOC is considered to be a push system downstream from the CCR (Capacity Constraint Resource) and a pull system upstream from the CCR.

1.3 V-A-T ANALYSIS

The concept of V-A-T analysis was developed primarily by Eli Goldratt in the1980s. It is based on different product structures. Manufacturing processes can form V, A, and T shaped plants (Umble and Umble, 1999). However, there have been few articles that discuss the concept of V-A-T analysis (Fawcett and Pearson, 1991; Lockamy and Cox, 1991; Umble, 1992; Billatos and Wolffarth, 1999; Umble and Umble, 1999). The illustration of V, A, and T plants from Umble and Srikanth (1995) are also shown below in Figure 1.2.



V-plant A-plant T-plant

Figure 1.2 Illustration of V-A-T Plants

Basically, V-A-T plant characteristics are defined by the shape of the production system formed in that particular business. The V-plants is characterized by constantly diverging operations, with a small number of raw material being converted into a large number of end items, using highly specialized and expensive equipment. Many fabrication plants, which produce a variety of component parts from basic materials such as metal, plastic, and wood, are some example of a kind of V-Plant. For example, a tree is cut down and goes through different fabrication processes to make different kinds of wood products.

A-Plants are characterized by a large number of converging operations starting with a wide variety of raw material being assembled in succeeding levels to create a smaller number of end items. Components are usually unique to the end item and the technology used in assembly operations tends to be highly flexible, general-purpose equipment. A car manufacturer can be classified as an A-plant, where many of the component parts are assembled together to become one single car.

T-plants are characterized by a relatively low number of common raw material and component parts optioned into a large number of end items. T-plants in general occur in manufacturing environments where product families are highly optioned or have a large number of available packaging variations. The manufacture of computer products can be classified as a T-plant in which several options of end product are offered.

The analysis of V, A, and T plants and case studies were explained in details by Umble and Srikanth (1995) in their book *Synchronous Manufacturing: Principles for World-Class Excellence.* Umble and Srikanth (1995) discuss that many plants fall into one of these three categories. Plants that exhibit characteristics of more than one of the three categories are referred to as combination plants, which will not be included in this study.

The more comprehensive characteristics of each plant are defined by Lockamy and Cox (1986) as shown in Tables 1.2, 1.3, and 1.4, respectively. General characteristics of V, A, and T plants are shown in Table 1.5.

Table 1.2 V-Plant Characteristics, Business Issues, Action Items, and Primary Industries

Characteristics:	(1) Minimal or singular raw materials (2) Wide variety of unique end items (3) Product divergence and differentiation (4) Parallel routings with common matching activities (5) Specialized machinery (6) Process flow orientation
Business issues:	(1) Perceived as not being cost competitive (2) Very low profit margins (3) Has cut operating expenses as much as possible (4) Finished goods perceived as an advantage (5) Due date performance is normally considered acceptable
Action items:	(1) Prove validity of constraint 1.1 Overtime 1.2 Data accurate 1.3 Set-up 1.3.1 Efficiencies causing big batches 1.3.2 Finished goods (2) Concentrate IE/ME activities (3) Start to implement OPT philosophy
Industries:	(1) Textiles (2) Metals (3) Chemicals (4) Process/semi-process industries

Table 1.3 A-Plant Characteristics, Business Issues, Action Items, and Primary Industries

Characteristics:	(1) Numerous raw materials (2) Limited variety of unique end items (3) Product convergence with assembles (4) Parts follow different routings and do not necessarily use the same resources (5) General machining centers with departmentalization
Business issues:	(1) Run-away operating expenses (2) Overtime is the rule (3) Expediting reigns supreme, especially at month end (4) Due date performance is the driving force (5) Lead time/inventory is increasing (6) Synchronization of parts does not exist
Action items:	(1) With the list of suspected problem areas (a) Check inventory queues (b) Overtime common at this resource (c) Expediting common (d) Set-ups broken often (e) Data accurate (f) Is there a relationship among the suspect machines? (2) Assign IEs/MEs to improve activities at these resources (3) Schedule to improve flow to assembly area
Industries:	(1) Aircraft engines (2) Specialized equipment (3) Subfractional HP electric motors (4) Major assembly industries

Table 1.4 T-Plant Characteristics, Business Issues, Action Items, and Primary Industries

Characteristics:	(1) Numerous combination of end items from a limited number of component/sub-assembly parts
	(2) Final assembly scheduling based upon actual customer orders
	(3) Forecasting activities at the component stock level because the manufacturing lead time is longer than the quoted customer delivery lead time
	(4) Excessive inventory (40-50% of total assets) largely in 'component stores'
	(5) Labor intensive at the end of the process
	(6) Overtime exists everywhere
Business issues:	(1) Due date performance: approximately 40% behind, 20% on time and 40% early
	(2) Everything needs to be expedited
	(3) Lead time inventory is increasing
	(4) 'Stealing' parts to preserve shipping budget
Action items:	(1) Eliminate 'stealing' at assembly
	(2) Change procedures and measurements
	(3) At the capacity constraint resources, check inventory queues, overtime usage, expedite levels, frequency of broken set-ups, and data accuracy
	(4) Synchronization to assembly
Industries:	(1) Small appliances
	(2) Electronics
	(3) Electrical connectors
	(4) Door locks

Table 1.5 General Characteristics of V-A-T Plants

V-Plant	A-Plant	T-Plant
1. The number of end items is large compared to the number of raw materials.	1. The distinguishing trait is the assembly of a large number of manufactured parts into a relatively small number of end items.	1. Several common manufactured and/or purchased component parts are assembled together to produce the final product.
2. All end items sold by the plant are produced in essentially the same way	2. The component parts are unique to specific items	2. The component parts are common to many different end items.
3. The equipment is generally capital intensive and highly specialized.	3. The production routings for the component parts are highly dissimilar.	3. The production routings for the component parts do not include divergent or assembly processes.
	4. The machines and tolls used in the manufacturing process tend to be general purpose.	4. The production routings for any component parts that require processing are usually quite dissimilar.

1.4 PROBLEM STATEMENT

As previously mentioned, during the last three decades, the concepts of Material Requirements Planning (MRP), Just-in-Time (JIT), and Theory of Constraints (TOC) were developed in different parts of the world under different cultures but have been well recognized for their benefits to organizations all over the world. There have also been many efforts to try to adapt one of these systems to various organizations worldwide. Thus, it is a challenge for most mangers, nowadays, to determine the right inventory strategy for their manufacturing environments. Should they use MRP, JIT, or TOC? Can one outperform the other in specific environments? William Tallman of Emerson Consultants states, "All of these three systems can work to reduce inventory, improve labor and space utilization, and upgrade the factory if the corporation gains proper education, training, and implementation."

Even though, it may seem to be good for managers to have manufacturing strategies choices, choosing the right strategy for the organization seems to be a very difficult task. There have been many articles in various journals (Aggarwal and Aggarwal, 1985; Aggarwal, 1985; Gelders and Van Wassenhove, 1985; Plenert and Best, 1986; Sohal and Howard, 1987; Johnson, 1986; Lambrecht and Decaluwe, 1988; Buxey, 1989; Ptak, 1991; Cook, 1994; Taylor III, 1999) discussing these three systems during the past two or three decades, they have not yet; however, provided the framework to answer the above question of which system is really the best, especially under different process structures.

Furthermore, those studies that have been done during the last three decades comparing the three production systems; MRP, JIT, and TOC; are based upon a single or simple flow line. None of them, or only few studies, have ever been done on a more sophisticated system such as the three different logical structures of V, A, and T that was said to be able to represent almost any system in the real world, which this study intends to do.

Typically, different manufacturing environments will need different strategies to control their production systems: thus, it is hard to say which one is really the best. The study of Krajewski et al. (1987) has shown that the success of a production system depends on the manufacturing environment, not the system. Neely and Byrne (1992) also suggest that not one system is best in every environment, and in fact these three approaches complement each other. Thus, it can be expected that in specific environment each system will outperform the others.

However, instead of exploring all three manufacturing systems, this paper will emphasize the study of only JIT and TOC. The reasons for not including MRP in the study are: first, even though MRP seems to be alive and still works well in some specific conditions, many researchers have shown that MRP is the worst in managing shop floor levels compared to the other two strategies (Lambrecht and Decaluwe, 1988; Lee, 1989; Pyke and Cohen, 1990; Spearman and Zazanis, 1992). Second, the difficulties in comparing the MRP to JIT and TOC production systems originate from the fact that MRP was developed as a planning tool and JIT and TOC as controlling mechanisms. It has been said, nonetheless, that MRP is more suitable for use as a long range planning tool. Consequently, MRP will not be included in this study. Additionally, a pilot study determined that MRP was significantly worse with respect to WIP levels when compared to JIT and TOC.

The purpose of this study is to extend the research on production and inventory management issues. This study intends to establish a better understanding of JIT and TOC manufacturing systems by comparing the two systems under different process structures with different setup and process variations. This research also tries to develop a guideline for managers to be able to choose the right manufacturing technique that will provide their organizations the ability to respond to customer demand faster and with less inventory, based on their manufacturing conditions and process structures.

According to the study of Krajewski et al. (1987), they concluded that the success of a production system depends on the manufacturing environment, not the system. Also in the study of Bolander and Taylor (2000), they state, "The best system is the one that best fits the manufacturing environment in which the system is to be implemented." Thus, in order to justify this debate, this study will investigate different manufacturing environments to see if there would be any particular operating environment and process structure that will be most suitable for either Just-in-Time (JIT) or Theory of Constraints (TOC).

2. REVIEW OF LITERATURE

2.1 JUST-IN-TIME (JIT) LITERATURE

JIT was first developed during the late 1950s after World War II by Mr. Taiichi Ohno of Toyota Motor Company in Japan as an effort to catch up with the American auto industry (Ohno, 1988). In his book *Toyota Production System: Beyond Large-Scale Production* (Ohno, 1988), he explains in detail the fundamental concepts and development processes of Toyota Production System or JIT in Toyota Motor Company, Japan. However, the success of JIT was not revealed until the oil crisis hit the world in 1973. This resulted in the collapse of Japan's economy to a state of zero growth in 1974, except for Toyota Motor Company (Ohno, 1988). Since then, many auto companies in Japan adopted the JIT systems into their plants. Not only auto industries in Japan, but also many organizations in the U.S. tried to adopt the JIT production system. The U.S. auto industry found itself trying to catch up with the Japanese auto industry.

Since the first paper in English about just-in-time (JIT) production systems published in the late 1970s (Sugumari, Kusunoki, Cho and Uchikawa, 1977), the topic of Japanese manufacturing systems has received attention from both practitioners and academicians. Numerous articles and papers have been published in various journals and magazines since then topics include the various aspects of JIT and the Toyota production system (Monden, 1983), stockless production (Hall, 1983), and lean production (Womack et al., 1990). Schonberger (1982a), Monden (1983), and Hall (1983) are among the first authors who published books devoted to the Japanese manufacturing system.

Sohal et al. (1989), Goyal and Deshmukh (1992), and Keller and Kazazi (1993) reviewed the JIT literature in their studies and classified it into three major subjects:

1. Reviews of the JIT philosophy and definition
2. Reviews on the implementation aspects and benefits of JIT
3. Reviews of mathematical and simulation models of JIT

The review of JIT literature in this study will follow the same format.

2.1.1 Reviews of the JIT Philosophy and Definitions. After the success of JIT production system in Japan during the mid 1970s and the paper in English about just-in-time (JIT) production system first published in 1977 (Sugomori et. al, 1977), JIT has received attention from many academicians and practitioners throughout the world.

Besides the JIT production system definition by Ohno (1988) and Monden (1981,1983) from Japan, there are definitions by the pioneers of JIT in the U.S. such as Schonberger (1982) and Hall (1983). One observation of JIT is that there is a lack of consensus on its interpretation and meaning. One reason for this confusion is the broad nature of the definition of JIT in the literature.

Below are some of the definitions of JIT given by several authors:

Monden (1981, 1983) defines JIT as:

> The basis of Toyota Production System (TPS) on which the right parts are needed in assembly line at the time they are needed and only in the amount needed.

Schonberger (1982) describes a JIT system as to:

> Produce and deliver finished goods just in time to be sold, subassemblies just in time to be assembled into finished goods, fabricated parts just in time to go into subassemblies and purchased materials just in time to be transformed into fabricated parts.

Hall (1983) states that:

JIT is not confined to a set of techniques for improving production defined in the narrowest way as material conversion. It is a way to visualize the physical operations of the company from raw material to customer delivery.

According to Goddard (1986):

JIT is an approach to achieving excellence in a manufacturing company based on continuing elimination of waste can consistent improvement in productivity.

Sohal et al. (1989) believe that:

Just-in-Time is essentially more of a philosophy than a series of techniques, the basic tenet of which is to minimize cost by restricting the commitment to expenditure in any form, including manufacturing or ordering materials, components, etc, until the last possible moment.

In their book, Fogarty, Hoffmann and Stonebraker (1989), JIT is defined as:

JIT embodies a philosophy of excellence to establish demand-pulled inventory practices that produce to design specifications at a rapid but smoothed delivery rate with zero idle inventories, zero unnecessary lead times, and increased employee involvement in the process.

Bartezzaghi and Turco (1989) discuss that:

JIT aims at simultaneously reaching strategic objectives of quality, flexibility and productivity through coordinating interventions in the areas of product structure, production process, organization and personnel, production planning and control, supplier relationships.

Mehra and Inman (1992) purpose the following working definition of JIT:

JIT is a production strategy that strives to achieve excellence in manufacturing by reducing setup times and in-house lot sizes through the use of group technology, cross training of employees, and sound preventive maintenance. Additionally, JIT is a vendor strategy that yields higher levels of productivity and quality by minimizing vendor lot sizes and their lead-time through the use of sole sourcing and quality certification of supplies.

No matter how many definitions JIT may have, those definitions stand on the same philosophy, to maximize throughput and profit of an organization and to reduce WIP inventory level by having the right product at the right place in the right amount and at the right time using less time, money, and effort through the elimination of all waste or non-value added activities of manufacturing process.

2.1.2 Reviews on the Implementation Aspects and Benefits of JIT. There are numerous instances of successful application of JIT and related management techniques in the United States. Harley Davidson (Willis, 1986; Gelb, 1985), Hewlett Packard (Riopel, 1986), General Motors (Rohan, 1985), and John Deere (Quinlan, 1982) are only a few of the many companies that have successfully implemented these techniques.

Also, a study by Hall (1983) of four Japanese companies implementing the JIT system reported a reduction in inventory by 16-45%, a decrease in throughput time by 20-50%, an increase in productivity by as much as 50%, and a reduction in quality rejection rate by 90%.

Burnham (1987) concluded that JIT, when successfully implemented, did yield significant results in the United States. Im and Lee (1988) also recognized JIT benefits and reported on the extent of JIT implementation in the U.S. They concluded that JIT is most effective in repetitive manufacturing in various industries. They also discussed the sequence of JIT implementation practices as being different by industry.

Bartezzaghi and Turco (1989) did research concentrating on the analysis of JIT applicability (with particular reference for small and medium-sized companies in Italy). They defined in their study that "JIT applicability can be defined and measured by the potential benefits that can be achieved, compared with the expected costs to sustain the implementation of JIT techniques." The relationship between JIT techniques and potential benefits were also discussed. They identified the integration among a variety of elements of JIT as being particularly important in overall performance.

Crawford et al. (1988) surveyed companies that have implemented JIT and have identified benefits and problems associated with the implementation. This survey showed an average company-wide reduction of 41% in WIP inventory, with reductions in manufacturing cost of 71%, and reductions of lead-time by an average of 40%.

Gilbert (1990) randomly selected and surveyed a total of 250 U.S. manufacturing firms to determine the degree of JIT implementation. This study found there was a significant decrease in the investment of inventory associated with the implementation of JIT.

Safayeni et al. (1991), based on plant visits, discuss the meaning of JIT, the motivation for and expectation of JIT, and the problems associated with different degrees of JIT implementation. They classify the efforts toward JIT into four levels:

1. Education of "talking JIT"
2. Pilot project or "test-tube JIT"
3. Modified JIT or "push-JIT"
4. Total JIT or "smart organizations"

The major conclusion of their paper is that it is almost impossible for organizations to maintain the same structure, habits, and performance evaluation systems and simply add JIT to their existing practices and events and expect it to work.

Harber et al. (1990) focused on the implementation of JIT and concentrated on the issues affecting JIT programs and the primary factors, which need to be considered for implementation in western companies. They consider top management support, involvement of unions, education and training, JIT and quality and relationship with suppliers are the primary considerations for JIT implementation.

Mehra and Inman (1992) tested the four different hypotheses on the elements of JIT implementation as shown in Table 2.1.

Table 2.1. Elements of Just-in-Time

Four hypotheses implementation	Elements of JIT
JIT production strategy	Set-up time reduction In-house lot sizes Group technology Cross-training Preventive maintenance
JIT vendor strategy	Vendor lot sizes Sole sourcing Vendor lead-time Quality certification of suppliers
JIT education strategy	Pilot project JIT team Management education Outside consultant JIT champion
Management commitment	Formal means for listening Investigate suggestions Authority to stop line Quality circle

Based on 114 usable responses to questionnaires from the 550 sent out, Mehra and Inman (1992) conclude that a JIT production strategy is the most critical factor, with the JIT vendor strategy being somewhat less meaningful while JIT education strategy was not shown to be significant. One surprising result from their study is that management commitment is not a critical factor, which contradicts to most literature claiming that management's support is a very important element (Lee and Ebrahimpour, 1984; and Harber et al., 1990).

Huson and Nanda (1995) conducted a study to observe the impact of just-in-time manufacturing on firm performance in the U.S. using a sample of 55 manufacturing firms that implemented JIT between 1980 and 1990. The result from their study shows that JIT adoption did increase earnings to U.S. manufacturing firms. They found that the average increase in inventory turns after JIT adoption was 25% within a four-year period compared to a 9% industry average. Other measures indicating increased earnings were also reported in their study.

Markham and McCart (1995) provided a guideline to organizations that desire to incorporate JIT concepts into their systems by identifying the reasoning behind implementing JIT. They also examined the different degrees of success that can be anticipated from different first actions in implementing JIT.

Even though there are many benefits of JIT reported in several articles, Primrose (1992) indicates that:

> The introduction of JIT should not be regarded as an act of faith but must be evaluated in financial terms in the same way as any other investment project with all the costs and all the benefits being quantified and included in an investment appraisal.

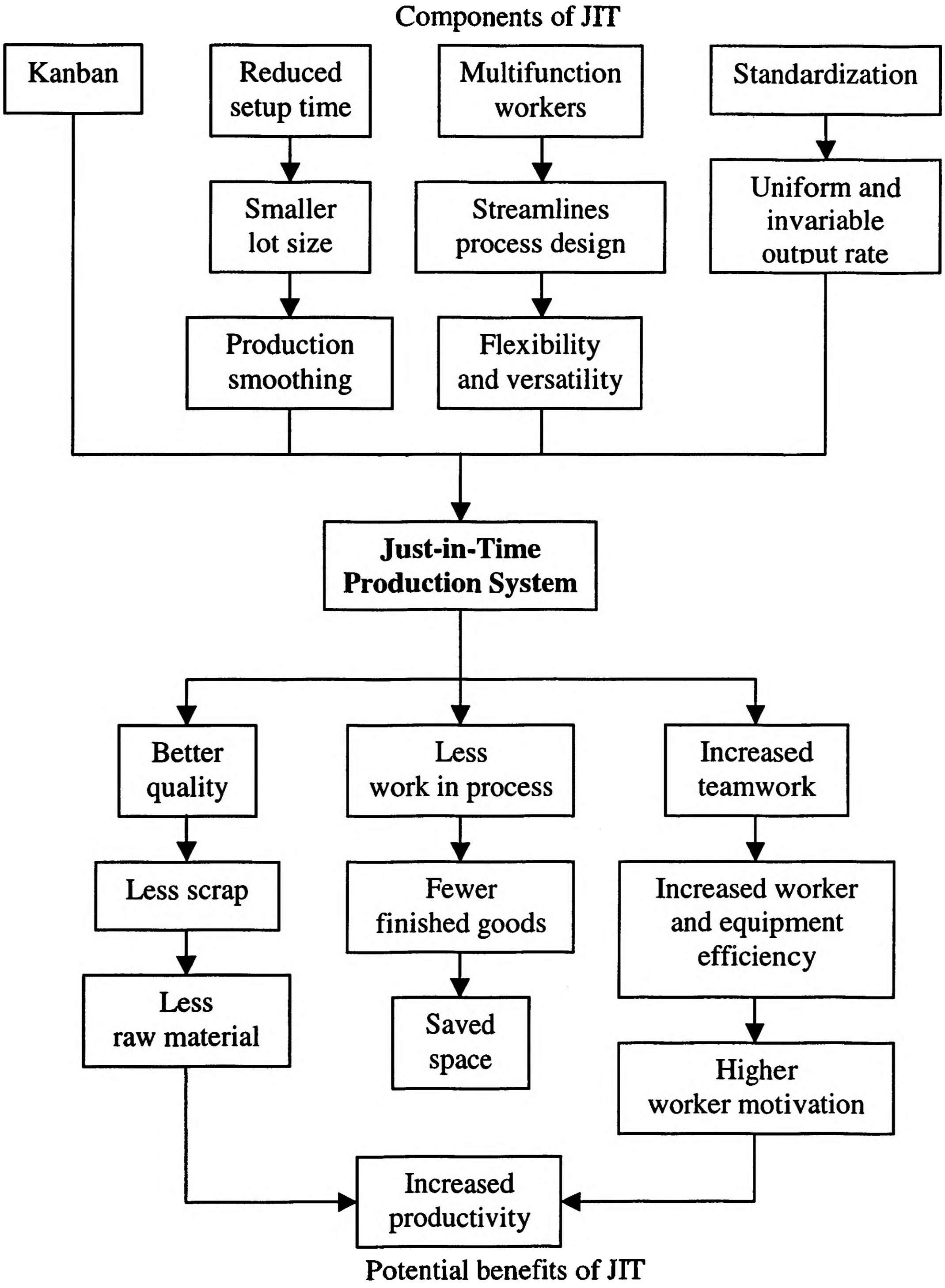


Figure 2.1 Components and Potential Benefits of JIT

Lee and Ebrahimpour (1987) argue that in order to implement JIT, some changes or requirements in an organization are necessary. Figure 2.1, modified from Lee and Ebrahimpour (1984, 1987), illustrates components and potential benefits of JIT system.

However, success of JIT implementation has not come easily in all cases either (Hutchins, 1986), since JIT requires management's support and understanding of the system; management and labor responsibilities; training; department function; supplier management; production layout and work flow; long-term planning; stockholders; labor organizations (unions); and government support as important requirements or modifications to make a JIT manufacturing system applicable in western firms (Lee and Ebrahimpour, 1984)

Wilson (1985) also argues that American management should be extremely cautious in adopting JIT techniques. The benefits resulting from inventory reduction are fairly small, but the potential cost of disrupting production could be very high since JIT operates under a low level of WIP inventory. As previously mentioned, due to its very low level of WIP inventory, the system will be very volatile for process disrupting if unexpected variation happens to the system.

Most recently, Fullerton and McWatters (2001) conducted a study to explore the production performance benefits from JIT implementation. Manufacturing executives at 447 carefully selected JIT firms that meet the set criterion received a detailed five-page survey. Of those 254 completed and returned the survey, for a response rate of 56.8%, their study indicates that managers adopting JIT practices have experienced benefits in all of the measured areas: quality improvements, time-based responses, employee flexibility, accounting simplification, firm profitability, and inventory reductions.

2.1.3 Reviews of Mathematical and Simulation Models of JIT. Uzsoy and Martin-Vega (1990) discuss the efforts to model Kanban-based pull systems. They grouped them into:

1. Simulation models, where digital simulation is used to explore the effects of different system parameters and configurations
2. Deterministic models, where a mathematical model of system behavior is developed that assumes only deterministic relations
3. Stochastic models, where demand and processing are characterized by stochastic process

Shen (1987) addresses some elements of manufacturing environments that can impact JIT performance and lot size, by simulating a two work-center Kanban production process using a SLAM computer model. The results indicate an adverse trade-off between reduced lot size and unfilled demand, although the level of inventories (and cycle stock) is lower. The interaction between lot size, setup time, and unfilled demand is also presented in his study.

Huang, Rees, and Taylor (1983) explore the effects of variable processing times, variable master production scheduling, variable input rates, and imbalances between production stages on a Japanese JIT system using a Q-Gert model. They conducted four simulation experiments, first exploring the impact of various processing time distributions; second, determining the impact of bottlenecks at different stages in the production process; third, analyzing the impact of variability in the demand rate; and fourth, combining the effect of variable processing time and demand rates. They conclude that variability in processing times has a definite impact on average overtime and production output and variability. They also found that if bottlenecks keep occurring repeatedly an additional number of Kanban cards are not going to improve the system performance. They further make an argument that the JIT system will perhaps never be cost effective for the company that experiences considerable unpredictability in its demand schedule or cannot expect to freeze its master production schedule.

Krajewski et al. (1987) argue that the operating conditions themselves are the key to major improvements in manufacturing performance. Based on their simulation studies, they found that even the old ROP (reorder point) technique can work as well as or even better than Kanban, under certain operating conditions. Thus, they argue that the key to improved performance is to shape the production environment through factors such as reduced setup times and lot sizes, improved product yield rates, and increased employee flexibility.

Voss (1987) lists the main benefits of JIT, in order of importance, as:

1. WIP reduction
2. Increased flexibility
3. Raw material/parts reduction
4. Increased quality
5. Increased productivity
6. Reduced space requirements
7. Lower overheads

Lee and Seah (1988) used a simulation model to investigate the effects of two important parameters associated with the JIT system, process time distribution and setup times and batch quantity. Two scheduling rules, fist-come-first-serve (FCFS) and short process time/lateness (SPT/LATE) were tested against four different processing times: negative exponential, constant process time, and normal distributions with coefficients of variation of 0.2 and 0.4. They concluded that if a suitable scheduling rule is used, it is not necessary for the process times of the various processes to be balanced. Smaller batch sizes also improved the overall performance of the system.

Gupta and Gupta (1989) used a single cell to analyze the fundamental building blocks of JIT-Kanban systems using systems dynamics (SD). The objective of this dynamic simulation is to determine the relationship of the number of Kanbans and the size of the containers to the production efficiency under various scenarios.

Meral and Erkip (1991) analyzed an ideal JIT line operating in an environment where the processing times at work stations are variable and demand arrivals are deterministic to evaluate whether the JIT system could perform well in such environments where the fundamentals of JIT are not completely satisfied. Four factors of coefficient variation (CV), daily demand rate, number of stations on the line and operating assignment strategy were employed in their simulation study.

Savsar and Al-Jawini (1995) developed a simulation model to investigate the effects of different operational factors on the performance of JIT systems and to compare JIT (pull) systems to push systems. They found that the throughput rate as well as the average station utilization is significantly affected by the variability in processing times and demand intervals. They also argued that push systems performed better than pull systems with respect to throughput rate as the processing time variability was increased, while pull systems are always better than push systems in reducing total WIP levels between stations. The line length also has significant effects on performance measures.

Lummus (1995), in his study, investigated the effect of sequencing alternative on productivity in a JIT process given various setup and processing times. Three sequencing rules were investigated in his study: Toyota's rule or alternating sequence, all A's then B's, and random pattern or customer driven. He concluded that the demand-driven sequence resulted in better performance than the other two. Also, those sequencing methods, which required more setups in a one-work center caused the poorest performance.

A six-station single-card Kanban-controlled line was used in the Hum and Lee (1998) simulation study to investigate an impact in relative performance of four scheduling rules under different JIT production scenarios. These four rules are first-come-first-served (FCFS), shortest processing time (SPT), number of Kanbans (NBK), and ratio of Kanbans (RKB). They identified NBK and RKB rules as follow:

> NKB gives priority to producing the type of parts that has the greatest number of kanbans waiting at the workstation while RKB rule gives priority to the part type that has the largest ratio since the risk of starving the downstream pulling station of this part type is apparently zero.

The important finding for the Hum and Lee study is that different scheduling rules will affect each JIT production environment in a different way; thus, it needs to match with the existing production condition of JIT. They also argued that the use of the FCFS rule does not appear to be justified and performs worse under tight production conditions.

Welgama and Mills (1995) did a simulation study evaluating the effectiveness of modeling JIT systems for an existing factory. Two basic simulation models were constructed for two different manufacturing cells to analyze the performance of each cell under the operating dynamics of a JIT environment. Various strategies were tested to obtain stability under the JIT system.

More extensive literature review for both JIT and Kanban can be found from the followings authors: Sohal et al., 1989; Golhar and Stamm, 1991; Berkley, 1992; Goyal and Deshmukh, 1992; Keller and Kazazi, 1993; Yavuz and Satir, 1995; Huang and Kusiak, 1996.

2.2 THEORY OF CONSTRAINTS (TOC) LITERATURE

According to the three areas of TOC as defined in the *APICS Dictionary* (1998), most of the studies during the last two decades have been devoted to the logistics and performance measurement standpoints. Only a few studies have been done on TOC logical thinking. Therefore, most of the literature reviewed here will have more emphasis on the area of Optimized Production Technology (OPT) and Drum-Buffer-Rope (DBR), while the literature of TOC thinking process will be reviewed as it is available. However, even though the concept of OPT's nine rules are no longer part of the current TOC approach (Rahman, 1998), it is still the closet source to study the effects of TOC on an organization.

Developed by Goldratt in the mid-1980s (Goldratt, 1988) TOC (Theory of Constraints) evolved from the OPT (Optimized Production Timetables) system (Goldratt, 1980) and was later known under the commercial name of Optimized Production Technology (OPT). By 1987, the overall concept became known as the Theory of Constraints (TOC), which Goldratt viewed as "an overall theory for running an organization" (Goldratt, 1988). To address the policy constraints and effectively implement the process of on-going improvement, Goldratt (1990, 1994) developed a generic approach called the "thinking process" as follows:

1. Decide what to change.
2. Decide what to change to.
3. Decide how to cause the change.

Goldratt (1990) also purposes three local measures that provide a connection from local actions to the global measures of profit and return on investment normally used by business organizations. These TOC measures are:

1. Throughput: the rate at which the system generates money through sales.
2. Inventory: all the money the system invests in purchasing things it intends to sell.
3. Operating expense: all the money the system spends in turning inventory into throughput.

Rahman (1998) in his study does an extensive review of TOC literature in both journal papers and books, including some of the comparison literature of MRP, JIT, and TOC.

Rahman (1998) summarizes the concepts of TOC as:

- Every system must have at least one constraint.
- The existence of constraints represents opportunities for improvement.

Jacobs (1983), Lundrigan (1986), Meleton (1986), Ronen and Starr (1990), and Fry et al. (1992) discussed how OPT works by presenting its network and model in the studies. Jacobs (1983) reported the first examination of OPT software and concluded it would work best in a high volume, large batch-size environment with few production operations. Lundrigan (1986) discussed OPT's nine rules and concluded that OPT integrates the best of MRP and JIT and uses the power of the computer to elevate production and inventory control to a new level. Meleton (1986), by the same token, discussed that if the OPT system does run as claimed, many benefits can be expected, such as WIP reduction and increased throughput, which would lead to decreased operating cost, improved cycle time and lower space requirement.

Vollmann (1986) explained the concepts of OPT as the next step to enhance the MRP performance. He argued that OPT made an important contribution to the field of manufacturing planning and control. Ptak (1991) also views OPT as embracing the precepts of JIT and builds upon the requirements of MRP.

Plenert and Best (1986) discuss some advantages and disadvantages of OPT as follows:

OPT advantages:
- A simplified technique for production scheduling
- User portion less complex
- Rapid projection of schedule
- Plant production analysis occurs

OPT disadvantages:
- Plant reorganization required
- Costing and accounting systems disrupted
- User disrupted

Ronen and Starr (1990) investigate the nine OPT rules in their study as well as its concepts and principles based on systems theory concepts, mathematical programming theory and techniques and queuing theory, the Pareto rule, and the Japanese production experience. They also discuss the drum-buffer-rope (DBR) technique and the classifications of V, A, and T processes. They distinguish the OPT strategic managerial principles (BIG OPT) from the OPT scheduling mechanism (SMALL OPT). They further conclude that BIG OPT is suitable for all types of manufacturing, while SMALL OPT is most suitable for the job shop environment or complex assembly lines.

Gardiner et al. (1993) also discuss the drum-buffer-rope (DBR) and buffer management concept in their study. They conclude that the DBR/buffer management approach:

- Provides a framework that distills the complexities of material flow into an understandable format
- Reduces drastically the number of resources that must be explicitly scheduled
- Warns of potential disruption to the production plan
- Controls lead time
- Guides continuous improvement efforts
- Offers a significantly improved alternative to the Kanban production system
- Aligns local resource performance measures with global organizational performance
- Makes traditional job shop capacity management techniques obsolete

Buxey (1989) also discusses about OPT as having the following advantages:

- Bottlenecks are identified and the production plan is a true schedule, aimed at 100% utilization of these key resources.
- Bottlenecks are scheduled using forward loading to finite capacity, so plans are feasible and precise.
- The possible use of overtime, substitute machine, etc. is integrated into the scheduling method.
- OPT considers the short-term balance of materials flow and relates lot size (per machine setup) and transfer batch size (progressive) to the needs of the schedule and the bottlenecks. Thus, lot size is varied, in a rational manner, and jobs are expedited in anticipation of schedule requirements.
- It is recognized that idle time and extra setups cost nothing at non-bottleneck resources. Accordingly, they are scheduled so that the idle time is evenly spread, by backward loading to infinite capacity, to minimize the risk of them becoming critical.
- Unlike MRP, OPT creates a detailed and realistic model of the production system.

Spencer and Cox (1995a) try to clear up the confusion between OPT and TOC in their study. In their study, the differences between TOC and OPT was presented by identifying the time frames, that is, the genealogy, of the methods. Then, the shop floor scheduling components discussed in *The Goal* was presented with their applicability within TOC or OPT or as a stand-alone.

Spencer (1991) and Spencer and Cox (1995a and b) discuss the evolution of synchronous manufacturing or TOC starting from the emergence of OPT software until it becomes well known as Theory of Constraints (TOC). Spencer (1991) further explains the implications of drum-buffer-rope (DBR) for both job shop and repetitive management. Spencer and Cox (1995b), on the other hand, explain the development of Master Production Schedule (MPS) for use in the TOC environment.

Fawcett and Pearson (1991) describe the principle objective of constraint management as a process of ongoing continuous improvement through synchronized manufacturing. They discuss its application of constraint management and also mention different types of constraints that may exist, such as managerial constraints, behavioral constraints, and logistical constraints. They also discuss synchronizing the manufacturing process by using drum-buffer-rope (DBR) technique.

Schragenheim and Ronen (1990) use a simulation model of a plant with stable market demand consisting of six different machines to illustrate the application of DBR technique. Neely and Byrne (1992) also did a simulation study on six different scheduling algorithms in a machine shop with a bottleneck. They found in their study that when the work was scheduled in such a way that the batch was going to tie up the bottleneck for the least time was loaded first, it should provide the best results.

Plenert (1993) uses an integer programming to solve a more complicate problem of TOC with multiple constrained resources. He concludes that TOC is not efficient at all when more than one constraint exists.

Some drawbacks in implementing TOC were also given by Taylor III (1999). First, TOC states there is no need for the applications of overhead and product cost.

Second, because of the excess capacity at all non-constraint workstations, efficiencies and equipment utilization will go down at all locations with the exception of the constraint location. If management is determined to measure system performance by insisting on high efficiencies and utilization rates at all locations, they will be disappointed.

Articles have been published under the TOC concepts. However, there have been many books about TOC published (Goldratt, 1990, 1991, 1994, and 1997; Noreen et al., 1995; Stein, 1996 and 1997; Cox and Spencer, 1998), which most readers can use as references.

2.3 COMPARISON LITERATURE

Most literature seemed to favor the results given by the implementation of TOC as always superior over JIT, especially under unstable condition (Jacobs, 1983; Lambrecht and Segaert, 1990; Cook, 1994; Gardiner et al., 1994; Taylor III, 1999). However, some researchers argue that JIT is the least costly manufacturing system (Sohal and Howard, 1987; Plenert, 1999) and can outperform any system in stable condition, lower process variation, and high volume with fewer product types (Rahman, 1991; Bolander and Taylor, 2000). Spencer (1991) also argues that if all of the variability in the system can be removed, JIT will outperform any other system. The study of Yenradee (1994) also shows better results for JIT than OPT and MRP.

Everdell (1984), Aggarwal and Aggarwal (1985), and Grunwald et al. (1989) concluded that all three systems, MRP, JIT, and TOC, have advantages and disadvantages, and their individual success would depend upon the specific environment.

Krajewski et al. (1987) and Bolander and Taylor (200) also argued that it was the manufacturing environment that made the performance differences, not the manufacturing strategy.

Aggarwal and Aggarwal (1985), in their study, state that typically each of these three systems would face personnel problems instead of problems with the techniques themselves. They further discuss that Kanban or JIT is a simple and straightforward system. It provides the authority and responsibility to employees, which is a challenge that they are willing to accept. Therefore, people problems are easily solved under JIT, which is probably why most successful stories have been reported by the users. In contrary, MRP requires a tremendous amount of discipline and commitment from employees, but provides much less challenge; thus, this might be why about 90 percent of its users are not satisfied with the results. OPT, right in the middle, tolerates minor disturbances and requires somewhat moderate discipline. Since the users will be asked to make some changes prior to introducing the OPT system in which, indirectly, people problems get taken care of, users seem to be delighted with the system.

Grunwald et al. (1989) provided a framework for quantitative comparison of production control concepts to support the choice of production control system in practice.

The following are some conjectures made based on their study:

- If uncertainty and complexity are small, certainly Kanban is favorable.

  Typically, Kanban assumes that final products will be produced on demand. However, in case that the production time for final products is greater than the desired customer delivery time, Kanban will not be able to deliver on its promise. Moreover, if a desired customer delivery time is reduced, resulting in more variations of the system, this will also result in lower performance of Kanban.

- For growing uncertainty, Statistical Inventory Control (SIC) or MRP with safety stocks is preferable.

  For higher uncertainty, production on order will become more difficult; thus, the anticipation of future demand would help. Thus, SIC and MRP with safety stocks are favorable.

- For relatively small non-stationary uncertainty, MRP with safety stocks can still be used.

  However, for growing non-stationary uncertainty, MRP with overplanning is preferred since MRP with safety stock has a disadvantage such that its safety stock should be adapted more frequently.

- If complexity increases, a concept like OPT is required.

  Since MRP neglects capacity constraints of the system, once complexities increase, it will fail to handle the system's capacities. Thus, OPT should be the right choice.

Gelders and Van Wassenhove (1985) analyze how MRP, JIT, and OPT react with respect to capacity constraints. They argued that even though MRP, JIT, and OPT would work best in specific conditions; however, the combination of three systems together will likely provide the best result. They made the conclusion in their study that, in such a hybrid system, OPT can act as a good MPS (Master Production Scheduling) by carefully planning for the bottleneck resources. Then, time-phased requirements can be generated using the MRP system. Finally, JIT should then be used to maximize throughput for the repetitive part in the system.

Johnson (1986) and Ptak (1991) also discuss the system of MRP, MRP II, JIT, and OPT for its benefits and drawbacks. Johnson (1986) concluded that in order to successfully implement a production system, the entire organization should be involved or else the failure of implementation is guaranteed. It is not only about how well the system is designed, but also how well it is used. Ptak (1991) also argue that these systems are the key to the planning and execution of long-term success. However, they have to be used where and how they make sense.

Plenert and Best (1986) discuss major differences between MRP, JIT, and OPT systems as follows:

- MRP assumes unlimited resources available in scheduling a production system, while JIT and OPT realize limited capacity in an organization.
- MRP uses the same fixed-size batch passed through all stages of production, in contrary to JIT and OPT, where small and variable batch sizes are used, respectively.
- JIT is the most flexible because of its minimal batch sizes and low inventory levels; however, OPT does not require a total reorganization of the factory as JIT does.

Plenert and Best (1986) also discuss differences between countries in which MRP, JIT, and TOC were developed. The working environments in the U.S., Japan, and Israel are extremely different. American factories are typically very large in space, which allows a large buildup of inventory to handle product variability requirements. On the other hand, because of space limitations for the other two countries, they need to come up with a system that is able to reduce their inventory to a great extent. This is how the pull and hybrid push/pull systems were invented.

Lambrecht and Segaert (1990) did a comparison study of Kanban system and long pull strategy, equivalent to the drum-buffer-rope technique in TOC, under various situations such as different layout, balanced and unbalanced line, several processing time distributions, buffer allocation. They concluded that long pull strategy outperforms Kanban technique with respect to achieved throughput in lower inventory investment.

Fogarty et al. (1991) used Monte Carlo simulation to compare MRP, JIT, and TOC. A simple two-station assembly was used in their study and the shop was set to operate for 200 days. They discussed three different approaches for each strategy in tackling the problem. The traditional approach or MRP added WIP in the system, JIT reduced variability in each workstation of a system, and TOC intentionally unbalanced the production line. From the simulation results of each approach, they conclude that TOC provides the best solution for the system.

Spencer (1991) describes the two different approaches of JIT and TOC: JIT deals with the production problem by trying to eliminate all causes of statistical variability that occur in the system and reducing inventory throughout the process, while in TOC (synchronous manufacturing), inventory is removed from all workstations except where it would strategically improve the system's performance.

Fawcett and Pearson (1991) summarize that both JIT and TOC advocate creating a continuous improvement process and reducing inventory so the problems in quality and in manufacturing systems will be easily revealed. They also argue that both systems rely to a great extent on synchronization to move material quickly and efficiently through the manufacturing system.

Cook (1994) did a simulation study to compare traditional, JIT, and TOC manufacturing systems in a flow shop with bottlenecks. From his simulation, he concluded that JIT and TOC are better than traditional systems and TOC outperforms JIT on a number of critical performance measures. He argued that JIT would have to virtually eliminate all variability across the whole system to make it equal to TOC. Gardiner et al. (1993 and 1994) also compare the TOC scheduling methods with Kanban and further conclude that TOC is more suitable for multi-product environments.

Yenradee (1994) compares three different production control policies; push, pull, and OPT, by conducting a case study of a battery factory in Thailand using a simulation model. From his study, the performance of OPT is in between those of push and pull policies. However, he concludes that OPT is a good trade-off between throughput and inventory, by producing a high throughput from only a limited amount of inventory. He also concludes that an application of OPT principles without the software to a relative simple flow shop is possible, but needs to be further investigated for more complex situations.

Chakravorty and Atwater (1995) compared the performances of lines designed using the line balancing techniques and JIT approaches. Two independent variables of system variability and total inventory in the system and one dependent variable, cycle time, were used in their study. They found that regardless of the amount of system variability, balanced lines achieved a lower cycle time than JIT lines when system inventory was low. However, a JIT line does attain a lower cycle time and comes closer to the optimal cycle time than a balanced line when system inventory is increased. These findings seemed a little bit confusing in the sense that JIT is said to operate well in a balanced condition; thus, it should not yield any difference between the two systems in this study. Processing times were modeled using the lognormal distribution because previous studies have cited it as representative of real world processing times.

Duclos and Spencer (1995) constructed three simulation models to replicate three manufacturing environments, MRP, DBR, and buffer-modified MRP, with fifteen different scenarios for five different levels of operational variability under a T-plant structure. Based on their simulation results, they concluded that the scheduling procedure under theory of constraints called drum-buffer-rope (DBR) produced significantly better results than the MRP methods used at the factory.

Zapfel and Missbauer (1993) reviewed different production planning and control concepts including MRP II, OPT, and JIT. They concluded that each concept is designed for a certain kind of planning situation, which can be described by characteristics like product structure, product variety, production volume, demand fluctuations, manufacturing technology, and others.

Taylor III (1999) compared the potential benefits of MRP, JIT, and TOC, with regard to the terms push, pull and hybrid push/pull strategies used in his study, and their effects on financial measurements, through the use of computer simulation. The results showed that hybrid push/pull strategy resulted in the highest net profit, return on investment (ROI), cash flow, and lowest inventory value, while the push system was the worst and pull was in the middle.

Bolander and Taylor (1999) use a simple model of a five-step manufacturing facility, which processes the materials at different rates to compare between MRP, JIT, and TOC. They conclude that JIT tends to work best in a stable flow manufacturing environment that assumes inexpensive setups, so that any production sequence and small lot size are allowed. On the other hand, they refer to MRP as the system that works best in a job shop manufacturing environment where product mix varies and the use of overtime and extra shifts can be used to accommodate temporary capacity bottlenecks, whereas TOC tends to work best in both environments with a single constraint process.

2.4 DISSERTATION STUDY

In addition to the above studies describing the different effects of MRP (Material Requirements Planning), JIT (Just-in-Time), and TOC (Theory of Constraints), there have also been many dissertation studies that try to study the performance difference of these three philosophies.

MRP (Materials Requirement Planning), JIT (Just-in-Time), and OPT (Optimized Production Technology) were studied to determine the conditions under which one technique performs superior to the other by Rahman (1991), of the University of Alabama in Huntsville. In his study, the various production conditions of setup times, process variability, lot size, and demand fluctuation were tested using simulation (SIMAN) and sensitivity analysis techniques. He finds setup time to be the most significant factor for JIT and processing time variability the second most important factor. For OPT, he finds all factors except demand fluctuation contribute to performance. In MRP, lot size and demand fluctuation are significant. In his study, he also finds Kanban to work best in low values of setup time and process time variability. MRP is best when the process has high value of setup and process variability. OPT is best for all intermediate ranges of the variability.

Rahman (1991) also finds JIT is most suitable in manufacturing conditions with low values of setup time and process time variability, while MRP, in contrast, is very suitable to a manufacturing condition with high values of setup time and process time variability. OPT is found to be the best for all intermediate ranges of variability.

Spencer (1992) explores three production planning and control systems; MRP, JIT, and TOC. The analysis is based on a comparison among three systems based on the process structure; V, A, and T. The research methodology was based on a case study of nine different manufacturing systems consisting of three different production systems (MRP, JIT, and TOC) versus three different logical structures (V, A, and T). The key characteristics of the three production systems on three different logical structures are given in his study, especially those in a repetitive manufacturing environment.

Wu (1992) developed simulation models to observe system behavior of a well-established plant, which alternately adopted both manufacturing management philosophies subject to different transition phases. He observed the role that work-in-process inventories play in manufacturing systems. In his study, the throughput time and average WIP (work-in-process) were used as performance measurements. There were four different transition phases with a total of eight simulations. The experimental results indicate that WIP inventories do play an important role in response to customer demand and WIP inventories are not bad, only "excess" working-in-process inventories are terrible. There also exists a close relationship between throughput time and WIP level in the system. The system performance of TOC model outperformed the pull model in every phase.

Taylor (1994) compares the potential benefits of three different management philosophies, MRP, JIT, and TOC, through the use of computer simulation (Simfactory 6.1). Three separate simulation models of a 20-station flow ship assembly line was developed in his study for a comparison purpose. In his study, ten performance measures are used:

- Net profit: TOC > JIT > MRP
- ROI (return on investment): TOC > JIT > MRP
- Cash flow: TOC > JIT > MRP
- Throughput: TOC > JIT > MRP
- Inventory: TOC > JIT > MRP
- Operating expenses: TOC > JIT > MRP
- Cost of goods sold: TOC > JIT > MRP
- Lead time: TOC > JIT = MRP
- Dollar days of inventory: TOC > JIT > MRP
- Utilization: TOC > JIT > MRP

Note: The > sign indicates a superior performance and = sign indicates no significant different results.

Putt (1995) makes a direct comparison of Kanban and Drum-Buffer-Rope control methods in terms of output, average inventory, and lead-time. A serial flow shop with setups is constructed as the study environment for his research. The factors included in his study are process batch size, transfer batch (Kanban) size, work center failure, work center protective capacity, protective inventory, and setup time. His study is done on three different simulation models of three, five, and seven work centers serial flow shops developed using Fortran. The followings are his simulation model parameters:

- Production rate of 1,000 units/day on 24 hours basis
- Setup time of 1, 5, and 25 minutes
- Setup time distribution is lognormal with CV (coefficient of variance) of 0.2
- Process batch size of 100 and 500
- Transfer batch size of 5 and 10
- Failure rate for work centers, 1%, 5%, and 10%
- Protective capacity is simulated at 5% and 10%

Putt (1995) concludes that DBR (Drum-Buffer-Rope) clearly outperformed Kanban in every facet. It shows higher output, shorter lead-time, and lower inventory level. Moreover, DBR is less sensitive to the parameters chosen for this study than Kanban is.

Fargher (1997) analyzed the impact of three manufacturing strategies, MRP II with shop floor control (SPC), MRP II with Kanban control, and MRP II with DBR control, in a remanufacturing cell environment using an average product unit cost calculated by process activity-based costing (ABC) methodology as performance measure. Capacity utilization and material availability delay are other factors in his study. All three implemented strategies are shown to be statistically significant in reducing the average product unit cost. The most significant factors in his study in order of influence are product and cell characteristics, manufacturing strategy, capacity utilization, and material delay. Given controlling factors of high level of capacity utilization (92-95%) or significant material availability delay MRPII with DBR control offers lower average product unit cost than either MRPII with SPC or MRPII with Kanban control. However, with governing factors of higher levels of capacity utilization (87-95%) or significant material availability delay, MRP-II with shop floor control also offers lower average product unit cost than MRP-II with Kanban control.

In 1998, Carrigo (1998) of Texas Tech University did his study comparing MRP, JIT, and TOC with a new manufacturing concept named the Adaptive Model (combination of selected aspects of JIT and TOC) using SLAM simulation package. In his study, three different manufacturing systems of five, nine, and fifteen stations with different buffer sizes are simulated in a period length of six months. He found the adaptive model to be the one that provides sporadic results when compared with the other philosophies, but with higher costs of larger WIP, increased time-in-the system, and the cost of operating at an accelerated pace. Consequently, he further concluded that TOC is the best overall manufacturing philosophy for flow shop environment.

3. RESEARCH METHODOLOGY

Many researchers agree that the use of analytical or mathematical models that rely on assumptions, may produce unrealistic results (Chaharbaghi, 1990; Savsar and Al-Jawini, 1995) Therefore, many researchers advocate the use of simulation software to improve or design a manufacturing system. However, simulation also has a major limitation in that it does not provide a solution (Chaharbaghi, 1990). One of the strengths of the simulation technique, nevertheless, is that it gives the user the freedom to experiment with any desired configuration for a system or environment. The simulation model is a central element in a manufacturing decision support system, which could address a wide range of decision situations in planning, operation and control (Starr, 1991).

Consequently, this research will be conducted using a SIMAN simulation code, written on an Arena5 platform, to investigate the performance differences between the manufacturing strategies, JIT and TOC, under different scenarios. Some of the basic block diagrams used in this study are:

- CREATE: the block used to create the entities to the system
- ASSIGN: attributes and variables of an entity are assigned under this block
- GROUP: the entities are temporarily combined to be one single entity
- SPLIT: an entity that is temporarily grouped together will be split to an individual entity again
- BRANCH: conditions used to route an entity to a single block
- QUEUE: waiting area for an entity before proceeding to another block

- MATCH: two entities are matched and permanently combined to be one single entity
- SEIZE: a specified resource is seized by an entity for processing
- DELAY: delay simulation clock time as the time specified
- RELEASE: a specified resource is released and set free for another entity to process next
- IF, ENDIF: a condition statement

These are some of the blocks that have been used in constructing the models under study. The detailed description of each of the SIMAN blocks, elements, and commands can also be found in Pegden et al. (1990), Banks et al. (1995), Kelton et al. (1998).

3.1 MODEL CONSTRUCTION

The model constructed for the study is based upon the use of a hypothetical model. The reason for using a hypothetical model in this study instead of an actual system is that the results of the study will be more generalizable than those of a specific factory. Moreover, it is easier to do the analyses on a hypothetical model since the study is looking at different process structures and it might be difficult or at least time consuming to find systems that are comparable to each other.

Once a hypothetical model for each plant is constructed, it will then be studied based upon the set of experimental designs, which will be discussed later. However, in order to simulate each hypothetical model under JIT or TOC production systems, the differences of JIT and TOC will need to be defined. Basically, what makes JIT and TOC different from each other is how they strive for continuous improvement. In JIT, every single process will be searched for improvement opportunities and efforts are to improve the whole system. In contrast, TOC will attack the current constraint resource for any improvement that can be made. Once the current constraint has become a non-constraint, its focus will then move to the next emerging constraint. However, this study will not look at different improvement stages of JIT and TOC.

Other major difference between JIT and TOC that will be studied in this research is how they schedule the production process and their differences in buffer management. Consequently, the working conditions of JIT and TOC will be defined as follows:

- JIT - the production system where only the smallest amount of possible inventory is kept at every production stage in term of a Kanban card. Putt (1995) states at least two Kanbans are required between adjacent workstations. The production scheduling under JIT is based on the MPS (Master Production Schedule) using a pull technique throughout the plant from the last workstation.
- TOC - the production system where the buffer (or time buffer) will be of strategic use to absorb any variation that might occur in the system, which typically will be placed before the bottleneck resource and final assembly. The scheduling under TOC is tied to the bottleneck resource by pulling upstream from the bottleneck and pushing downstream beyond that.

Therefore, under the JIT and TOC setup in this simulation study, there will be two major differences in the model setup:

1. Under JIT, each work station will have an inventory level of two Kanban cards, while only the bottleneck station in TOC will have an inventory level equal to two Kanban cards; the rest will have half the inventory of the bottleneck location, one Kanban card.
2. In JIT production, only a pull technique will be associated in pulling the part from each workstation, but a hybrid push/pull technique, pulling before the bottleneck and pushing beyond the bottleneck, will be employed in TOC.

Even though the concept of Kanban allocation techniques have been widely discussed in the literature (Mitra and Mitrani, 1990; Andijani and Clark, 1991; Wang and Wang, 1991; Fukukawa and Hong, 1993; Tayur, 1993; Andijani, 1998; Nori and Sarker, 1998; Sengupta et al., 1999) this study will be done using only two Kanbans at each work station to allow for comparison between alternatives. The size and time buffer in Theory of Constraints have also been extensively studied in the literature (Radovilsky, 1994 and 1998). However, this study will not provide detail about this subject.

The most important thing in building a simulation model for both the JIT and TOC production systems is to make some assumptions for the model in order to simplify the study. Hence, the following assumptions are made in this study:

- Every product produced can be sold to a customer.
- There will never be a shortage of raw materials.
- The same product mix will be used throughout the study. Every stage of production will produce only one piece of product at a time.
- A single-piece flow will be used where possible.
- Material moving time can be neglected.

- If a single-piece flow is not suitable, parts will then be gathered and transferred in a batch.
- In the case of a single-piece flow, a transfer batch size for both JIT and TOC will be one; if not, a transfer batch size will be equal to the production batch size.
- Product is scheduled to be delivered based on its arrival or first-come-first-serve (FCFS).
- No additional variations such as machine breakdown or defect rate will be introduced into the study.

Following are some of the simulation model setups to be conducted in this study:

- The system operates in an eight-hour shift, 1 shift per day, 20 days per month or 9,600 minutes per month.
- The model is set to run for an eight-month period. The first two months are disregarded as a warm-up period for the system to achieve the steady state condition; thus, only six-months of data is collected.
- Each simulation scenario is run for 10 independent replications.
- Each process structure, V, A, and T, is capable of producing four different product types.
- A production schedule of 80 products will be released daily, which will be sub-batched into production batches of 20 parts for each part type.
- The mean processing time at any workstation that has to produce more than just one part type will be divided by the number of different part types that go through that particular machine.

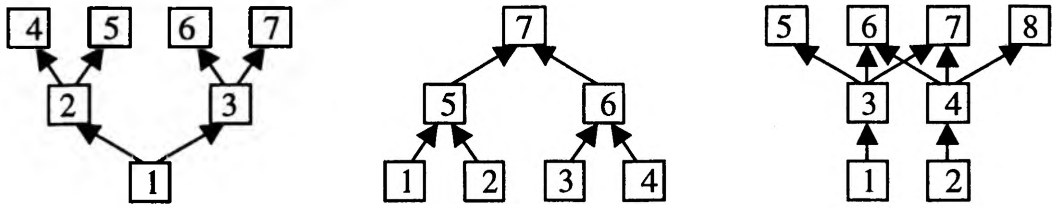
- The setup will occur every time a single batch is completed, regardless of the part type.
- Based on a mean processing time of the constraint resource; triangular distribution of 18, 24, and 30, disregarding any variation the system, each system should be able to ideally produce 1,600 parts of products in one month based on a 9,600-minute working month, or a total of 9,600 parts for all four different product types in a six-month period.

There are also some model setup differences between V, A, and T plants. Since there is a chance that two different downstream processes will simultaneously pull from one upstream process at the same time at a diverging point in V and T plants under a pull scenario for both JIT and TOC; thus, instead of using a single-piece flow, the batch flow will be used instead as discussed earlier to avoid the repeated setups scenario. Under an A plant, however, a single-piece flow can be used throughout the plant because no such scenario will ever happen. The simulation codes used in this study will be given as a supplement upon request.

3.2 DESIGN OF EXPERIMENT

This is a study of the performance of different manufacturing systems utilizing either JIT or TOC philosophies operating in different manufacturing conditions. There have been many studies that try to make the comparison between JIT and TOC systems, as previously discussed in the review of literature section. However, most studies have been done on a simple flow shop and mostly on just one product type. In this study, the different process structures of V, A, and T plants that produced four different part types are studied to see if JIT and TOC have different effects on different kind of plants in a mixed model simulation.

However, instead of using very sophisticated V-A-T plants as shown in Figure 1.2, very simple V-A-T plants as shown in Figure 3.1 below will be used instead.



V-Plant A-Plant T-Plant

Figure 3.1 Hypothetical Models of V-A-T Plants Used in the Study

Many studies have been done to investigate the effect of line balancing on JIT production systems (Plenert, 1997; Shin and Min, 1991a; Shin and Min. 1991b; Sarker and Harris, 1988; Sparling, 1998; Villeda et al., 1988). They report that JIT works best under a balanced line situation. However, it seems to be an ideal case to have a manufacturing process that is perfectly balanced. There are no studies concerning line balance and TOC, since TOC is based on the assumption that each system should have at least one constraint that needs to be managed effectively. Based on this fact, a balanced line situation will not be included in this study even it is an important aspect of JIT that might lead to better results than TOC. Consequently, only systems with the bottlenecks will be studied here.

It is nonetheless doubtful whether or not different locations of a constraint in the system will affect the system performance. Similar results between JIT and TOC are expected when the constraint is at the very end of the production line. As previously mentioned TOC operates under pull logic from the constraint resource backward to the beginning of the process, thus in such a circumstance when a constraint resource is the last workstation, both JIT and TOC will operate under the same pull logic throughout the system. However, with different inventory level setups for JIT and TOC, different performance can also be presented.

In this study, several factors that create system variations are introduced into the model to study their effects. Such variations are given as follows:

- Setup time
- Degree of processing variation

Even though both JIT and TOC are said to be able to reduce inventory and improve profit to an organization, not every organization operates under the same environment. Thus, it would be hard to say that an organization will always gain benefit if either of these two systems were to be implemented. Generally, each organization possesses a unique manufacturing environment, which in turn makes it best suited for a specific management system. Consequently, this research will simulate several manufacturing conditions to see if any manufacturing strategies will be favored under specific conditions.

Thus, this study attempts to see the effects associated with system variations in different production systems operated under different strategies. Such system variations introduced are shown in Table 3.1.

Table 3.1 Design of Experiment

<table>
<tr><th>Manufacturing Strategies</th><td colspan="2">JIT (Just in Time)</td><td colspan="2">TOC (Theory of Constraints)</td></tr>
<tr><th>Process Configuration</th><td>V</td><td colspan="2">A</td><td>T</td></tr>
<tr><th>Bottleneck Location</th><td>HLL</td><td colspan="2">LHL</td><td>LLH</td></tr>
<tr><th>Process Variation</th><td colspan="2">Low</td><td colspan="2">High</td></tr>
<tr><th>Setup</th><td colspan="2">Low (1)</td><td colspan="2">High (5)</td></tr>
</table>

Process Configuration

As discussed earlier for different plant classifications based on product structure; V, A, and T plant (see Figure 3.1)

Bottleneck Location

- High-low-low (HLL): the system with high mean processing time, in the first, low in between, and low at a final stage
- Low-high-low (LHL): the process that has low mean processing times at the front and final stages and high in the middle
- Low-low-high (LLH): the system with low, low, and high mean processing time at first, middle, and last stages respectively

Degree of Process Variation

- Low: Low process variation means the process with a symmetrical triangular distributions of 18, 24, and 30, and 6, 8, and 10 for H and L, respectively
- High: High process variation is the process with an asymmetrical triangular distribution that tends to skew to the right or triangular distributions of 18, 24, and 48, and 6, 8, and 16 for H and L, respectively

Setup

- Low setup of 1 means the setup time is equal to the mean processing time at such workstation
- High setup of 5 means the setup time of such workstation multiplies by five

3.3 PERFORMANCE MEASURES

The performance measurements in this study are make span and WIP inventory level. The definition of each measurement are as follows:

- Make span is defined as the period of time used to produce a specified amount of products.
- WIP inventory level is the money that is tied up in the product that cannot be sold which is a burden of the company.

Machine utilization, the rate that machines are utilized, will also be observed to see if the model is performing properly as it is intended for a verification purpose.

A make span variable is very easy to measure in nature. It is the total time a production uses to complete a specified amount of demand. This kind of variable is normally reported automatically when a simulation is run completely without having to write a specific code for it. WIP level, however, is difficult to measure since it can be observed in many ways, depending upon how an individual looks at it. Under this study, WIP is measured as the average value of WIP that currently resides in a production system. It will increase every time a single part entered a production system and decrease once a finished part leaves the system. However, it is not necessary for WIP to increase and decrease one by one every time. The number of WIP to be decreased when a finished part leaves a system depends on the structure of the product. For example, WIP will be decreased by four when a finished part leaves the last process of an A-plant since it takes four single parts to produce one finished part in an A process structure. The process structure in Figure 3.1 may give a clearer idea for how much WIP will be increased and decreased under a specific plant character.

Since the goal of an organization is to make as much money as possible, make span is used in this study to measure the making money performance of each manufacturing system. The faster the completion of demand, the faster the collection of money. WIP level is used to determine how much money is tied up in the system without generating any return under different strategies. Machine utilization is used to confirm that the workstation that is intended to be the bottleneck really is the bottleneck of the system. Machine utilization, in other words, can also determine if the system still has excess capacity that can be relocated to improve the system for maximum throughput. However, this study will not deal with the off-load bottleneck problem, so machine utilization will be used only as a model indicator, not a performance measure. The off-loaded bottleneck study can be found in Meinert and Taylor (1998).

4. DISCUSSION AND ANALYSES

Once all 72 different scenarios of the simulation were run completely and all data was collected, the ANOVA table was constructed using the statistical software package, Design Ease Student Version 6.B2.1a (Beta). Since the ANOVA tables alone might not give a clear picture of what really happened with respect to statistically significant factors, graphs and tables of means are presented to give a better picture of how these factors affect the response variables. It should be noticed though that the mean values in an individual graph or table are not the mean values directly collected from the simulation results, but the values averaged across the factors that were not significant.

As discussed in a previous chapter, the two response variables of make span and work-in-process (WIP) are used as the performance measures in the study. Make span measures how long a production system would take in order to finish the production of a specified amount of demand. WIP, on the other hand, measures the average amount of the inventory that circulates in the system during a production period. Consequently, the analyses of the results are discussed separately for each performance measure based upon the results given in the ANOVA tables and additional graphs and tables as necessary.

4.1 MAKE SPAN

The factors that were shown to be statistically significant in the full ANOVA table (shown in Appendix A) for the response variable make span are shown in Table 4.1. From Table 4.1, the main effects of strategy, setup, and process variation, and the interaction effects of strategy*plant type, plant type*bottleneck location, plant type*setup, plant type*process variation, bottleneck location*setup, bottleneck location*process variation, setup*process variation, strategy*plant type*bottleneck location, strategy*plant type*process variation, and strategy*plant type*bottleneck location*process variation are statistically significant at 0.05. For high order interactions that are significant, lower order interactions and main effects of factors that appear in that interaction will not be discussed, since the interpretation of these effects might be misleading due to the fact that they have already been influenced by other factors.

Table 4.1 The ANOVA Table for Response Variable Make Span

Source	Sum of Squares	Prob > F
Strategy	15,886,500	0.0029
Setup	27,142,400,000	< 0.0001
Process Variation	46,028,600,000	< 0.0001
Strategy*Plant Type	50,304,200	< 0.0001
Plant Type*Bottleneck Location	43,980,000	< 0.0001
Plant Type*Setup	11,225,200	0.0435
Plant Type*Process Variation	26,827,700	0.0006
Bottleneck Location*Setup	19,670,600	0.0042
Bottleneck Location*Process Variation	71,974,200	< 0.0001
Setup*Process Variation	878,473,000	< 0.0001
Strategy*Plant Type*Bottleneck Location	42,001,400	0.0001
Strategy*Plant Type*Process Variation	33,355,300	< 0.0001
Strategy*Plant Type*Bottleneck Location*Process Variation	22,531,600	0.0137
Pure Error Sum of Squares	1,154,150,000	
Correlated Total Sum of Squares	75,619,100,000	

Therefore, the analyses was done solely on the four-way interaction of strategy*plant type*bottleneck location*process variation and another three two-way interaction effects of plant type*setup, bottleneck*setup, and setup*process variation. It is noticed that the interaction effects of plant type*setup, bottleneck*setup, and setup*process variation all have setup as part of these effects. The following three figures (Figure 4.1, 4.2, and 4.3) show the interaction effect plots of the three two-way interactions.

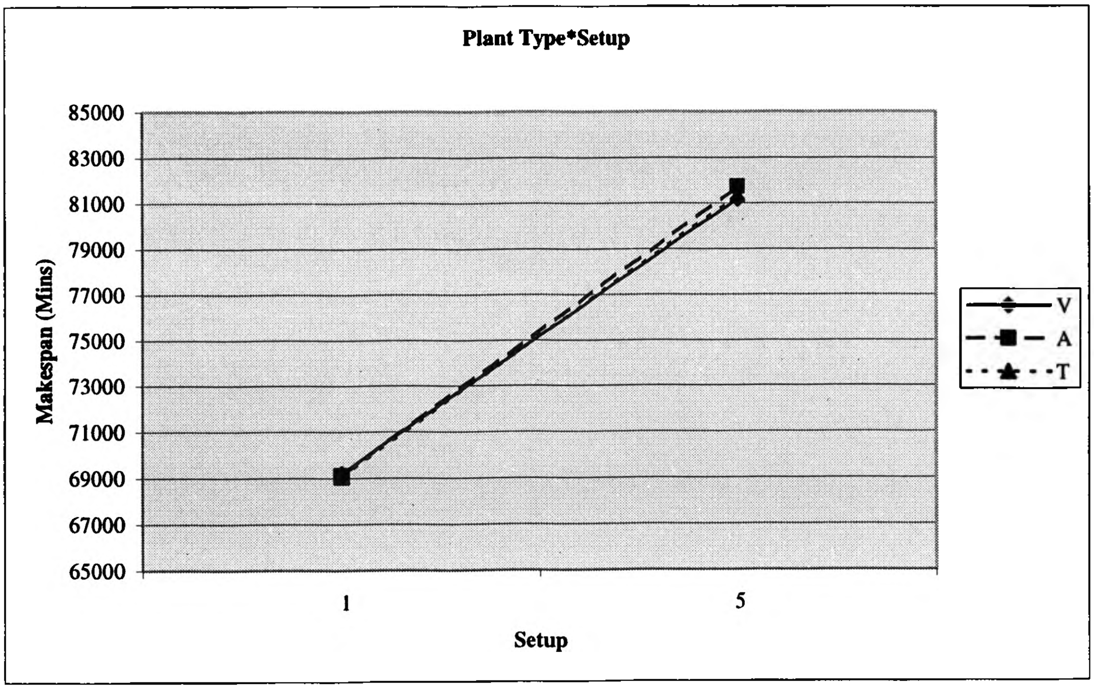


Figure 4.1 The Effect of the Two-way Interaction Plant Type*Setup on Make Span

From Figure 4.1, 4.2, and 4.3, apparently setup has a similar practical effect over different factors, the higher the setup, the longer it takes for the production to be completed. This result, however, is pretty intuitive in the sense that it is always true for a process that has a larger setup to take a longer time to finish the production, regardless of any other factors.

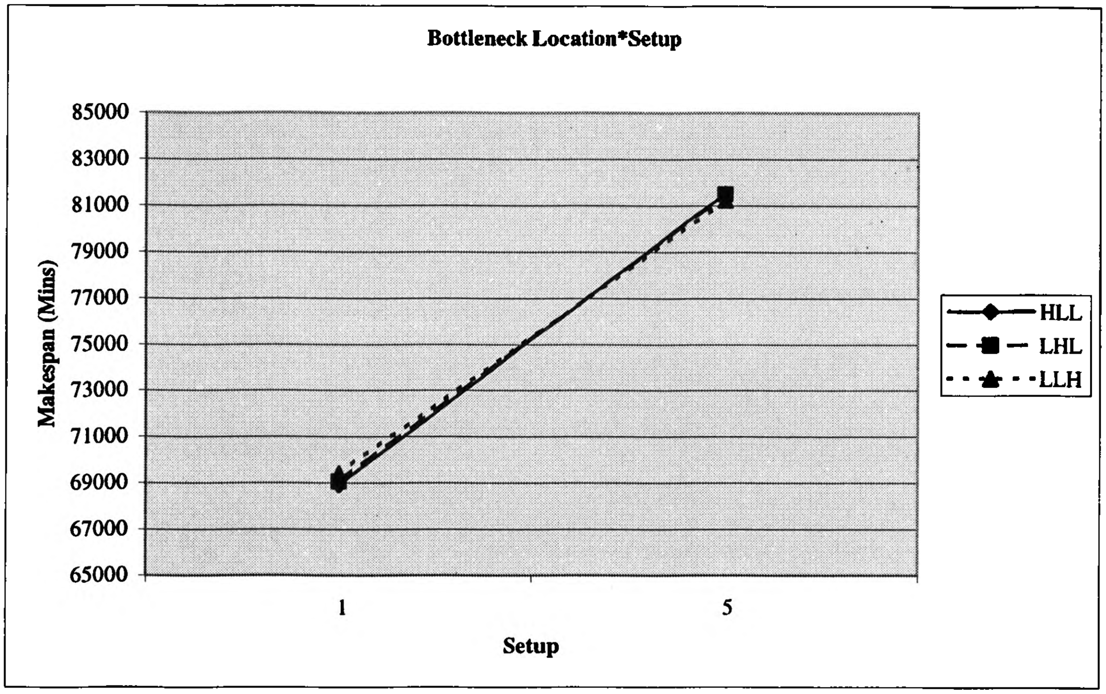


Figure 4.2 The Effect of the Two-way Interaction Bottleneck Location*Setup on Make Span

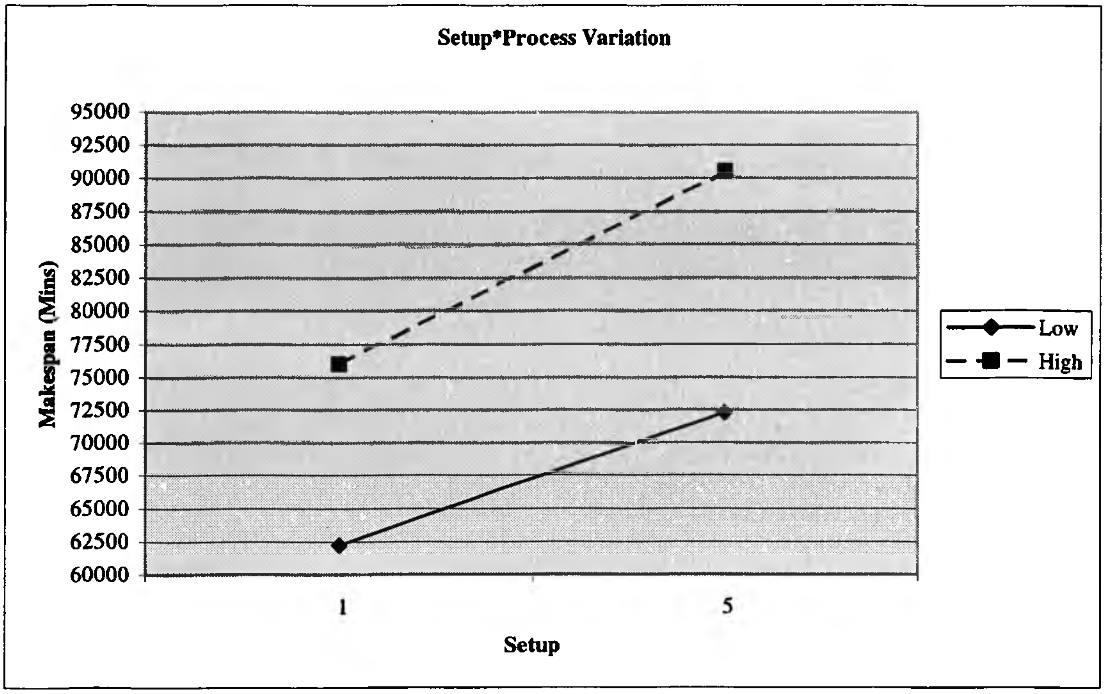


Figure 4.3 The Effect of the Two-way Interaction Setup*Process Variation on Make Span

The significant two-way interactions suggest a statistically significant change in this effect of setup at different levels of plant type and bottleneck location (Tables 4.2 and 4.3), but this chance seems to be of negligible practical importance.

Table 4.2 Mean Comparison of a Two-way Interaction (Plant Type*Setup)

Setup	Plant Type	Make Span (Mins)
1	V	69,195.31
	A	69,131.86
	T	69,051.51
5	V	**81,163.62***
	A	81,711.55
	T	**81,342.59*****

* indicates significant difference between V and A at 0.05

*** indicates significant difference between A and T at 0.05

Table 4.3 Mean Comparison of a Two-way Interaction (Bottleneck Location*Setup)

Setup	Bottleneck Location	Make Span (Mins)
1	HLL	**68,905.99****
	LHL	69,060.50
	LLH	69,412.19
5	HLL	81,502.54
	LHL	81,479.46
	LLH	**81,235.76** *****

** indicates significant difference between HLL and LLH at 0.05

*** indicates significant difference between LHL and LLH at 0.05

Note: Setup of 1 and 5 refers to the setup time of each workstation equal to a mean processing time of the workstation multiplies by 1 and 5, respectively.

Setup, however, seems to have a larger impact when associated with a high process variation, as shown from the differences in slopes of the graph in Figure 4.3. This clearly results from that setup was a function of mean processing time. Since it is typical for a process with high variability to have a higher mean processing time; thus, a high process variation also results in a high setup, which eventually leads to a very long make span compared to a relatively low process variation.

Another significant factor that is very difficult to interpret is a four-way interaction of strategy*plant type*bottleneck location*process variation. Apparently, from Figure 4.4, it shows the same trend for a make span to increase with a process with high variability, similarly to a process with high setup. This result is simply predictable, as mentioned earlier, that a process with high variability will most likely have a larger mean processing time than the process with low variability. Therefore, a process is prone to take a longer time to satisfy the specified demand when it has a high mean processing time. In addition, it can be seen in Figure 4.4 that two groups of data under different degrees of process variation are entirely separated from each other, one group on a lower side and another group on a higher side. As a result, looking at the graph in Figure 4.4 alone does not give any inside information about the system since those results may have already been overwhelmed by the process variation factor. It would be more interesting instead to break down the graph in Figure 4.4 to see how other factors might respond differently under different degrees of process variation, low and high (Figures 4.5-4.16).

Since it is already clear how process variation affects the system performance, the next three tables, Tables 4.4, 4.5, and 4.6, were constructed to show how the other three factors in this four-way interaction affect the system performance. These tables show the results of a paired t-test for the means under the four-way interaction effect based upon strategy, plant type, and bottleneck location, respectively.

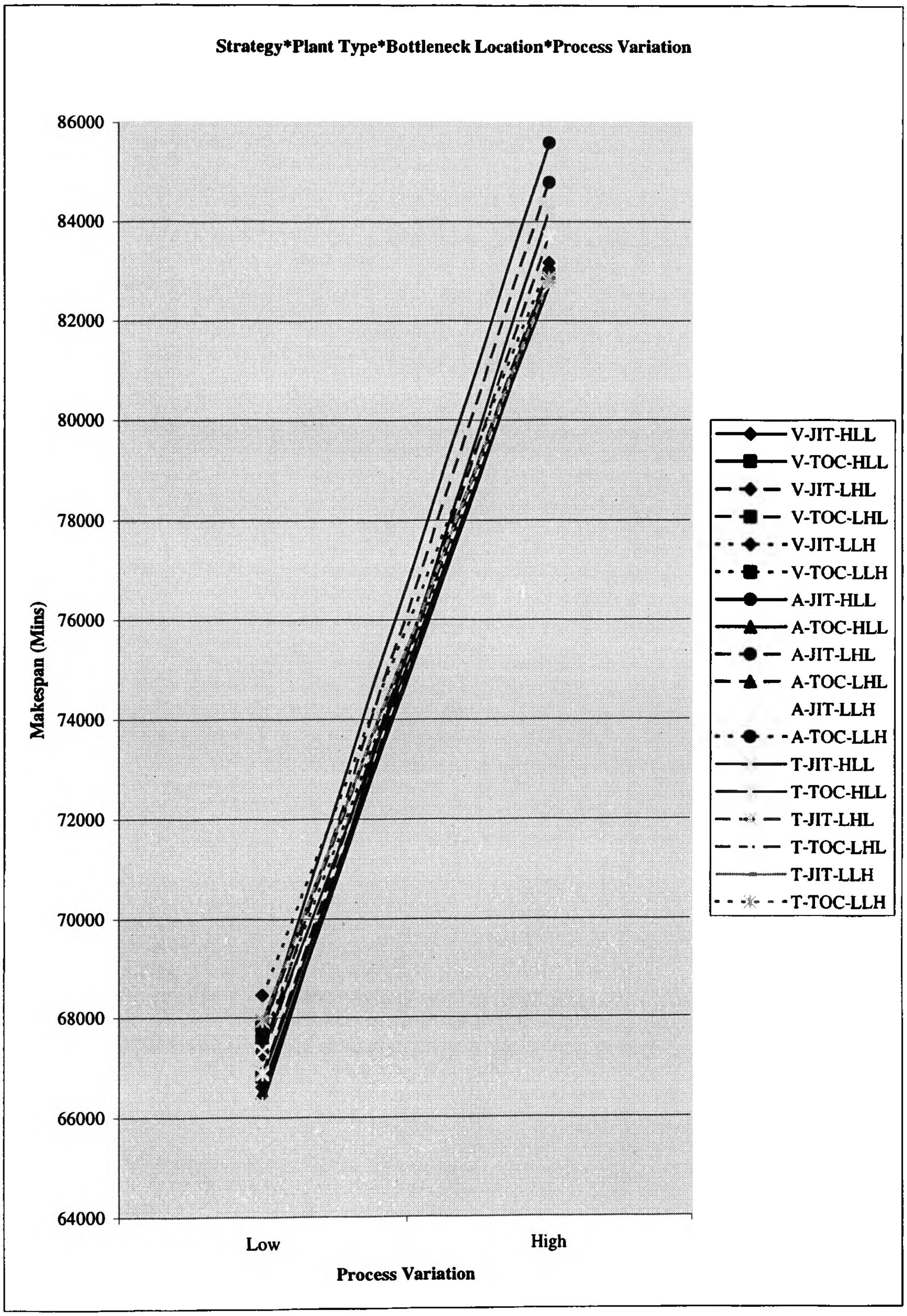


Figure 4.4 The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

Table 4.4 Mean Comparison of a Four-way Interaction (Strategy*Plant Type*Bottleneck Location*Process Variation) on Different Strategies

Plant Type	Bottleneck Location	Process Variation	Strategy	Make Span (Mins)	Plant Type	Bottleneck Location	Process Variation	Strategy	Make Span (Mins)	Plant Type	Bottleneck Location	Process Variation	Strategy	Make Span (Mins)
V	HLL	Low	JIT	66,607.17	A	HLL	Low	JIT	67,729.14	T	HLL	Low	JIT	67,335.20
			TOC	66,802.60				TOC	**66,493.71****				TOC	**66,281.17****
		High	JIT	82,813.41			High	JIT	85,585.57			High	JIT	**82,692.70****
			TOC	82,827.05				TOC	**83,057.21****				TOC	84,226.21
	LHL	Low	JIT	67,260.92		LHL	Low	JIT	67,362.94		LHL	Low	JIT	66,900.25
			TOC	67,816.23				TOC	66,903.96				TOC	66,858.78
		High	JIT	83,051.19			High	JIT	84,788.00			High	JIT	**82,783.71****
			TOC	82,945.42				TOC	**82,879.18****				TOC	83,689.22
	LLH	Low	JIT	68,450.48		LLH	Low	JIT	67,314.30		LLH	Low	JIT	67,937.47
			TOC	67,563.61				TOC	67,314.30				TOC	67,937.47
		High	JIT	83,173.35			High	JIT	82,816.06			High	JIT	82,861.21
			TOC	82,842.19				TOC	82,817.06				TOC	82,861.21

** indicates significant difference between JIT and TOC at 0.05

Table 4.5 Mean Comparison of a Four-way Interaction (Strategy*Plant Type*Bottleneck Location*Process Variation) on Different Plant Types

Bottleneck Location	Strategy	Process Variation	Plant Type	Make Span (Mins)	Bottleneck Location	Strategy	Process Variation	Plant Type	Make Span (Mins)	Bottleneck Location	Strategy	Process Variation	Plant Type	Make Span (Mins)
HLL	JIT	Low	V	66,607.17	LHL	JIT	Low	V	67,260.92	LLH	JIT	Low	V	68,450.48
			A	67,729.14				A	67,362.94				A	67,314.30
			T	67,335.20				T	66,900.25				T	67,937.47
		High	V	**82,813.41***			High	V	**83,051.19***			High	V	83,173.35
			A	85,585.57				A	84,788.00				A	82,816.06
			T	**82,692.70*****				T	**82,783.71*****				T	82,861.21
	TOC	Low	V	66,802.60		TOC	Low	V	67,816.23		TOC	Low	V	67,563.61
			A	66,493.71				A	66,903.96				A	67,314.30
			T	66,281.17				T	66,858.78				T	67,937.47
		High	V	**82,827.05* ****			High	V	**82,945.42****			High	V	82,842.19
			A	**83,057.21*****				A	**82,879.18*****				A	82,817.06
			T	84,226.21				T	83,689.22				T	82,861.21

* indicates significant difference between V and A at 0.05

** indicates significant difference between V and T at 0.05

*** indicates significant difference between A and T at 0.05

Table 4.6 Mean Comparison of a Four-way Interaction (Strategy*Plant Type*Bottleneck Location*Process Variation) on Different Bottleneck Locations

Plant Type	Strategy	Process Variation	Bottleneck Location	Make Span (Mins)	Plant Type	Strategy	Process Variation	Bottleneck Location	Make Span (Mins)	Plant Type	Strategy	Process Variation	Bottleneck Location	Make Span (Mins)
V	JIT	Low	HLL	**66,607.17****	A	JIT	Low	HLL	67,729.14	T	JIT	Low	HLL	67,335.20
			LHL	**67,260.918*****				LHL	67,362.94				LHL	66,900.25
			LLH	68,450.48				LLH	67,314.30				LLH	67,937.47
		High	HLL	82,813.41			High	HLL	85,585.57			High	HLL	**82,692.70* ****
			LHL	83,051.19				LHL	**84,788.00***				LHL	82,783.71
			LLH	83,173.35				LLH	**82,816.06** *****				LLH	82,861.21
	TOC	Low	HLL	**66,802.60***		TOC	Low	HLL	66,493.71		TOC	Low	HLL	**66,281.17****
			LHL	67,816.23				LHL	66,903.96				LHL	**66,858.78*****
			LLH	67,563.61				LLH	67,314.30				LLH	67,937.47
		High	HLL	82,827.05			High	HLL	83,057.21			High	HLL	84,226.21
			LHL	82,945.42				LHL	82,879.18				LHL	83,689.22
			LLH	82,842.19				LLH	**82,817.06****				LLH	**82,861.21** *****

* indicates significant difference between HLL and LHL at 0.05

** indicates significant difference between HLL and LLH at 0.05

*** indicates significant difference between LHL and LLH at 0.05

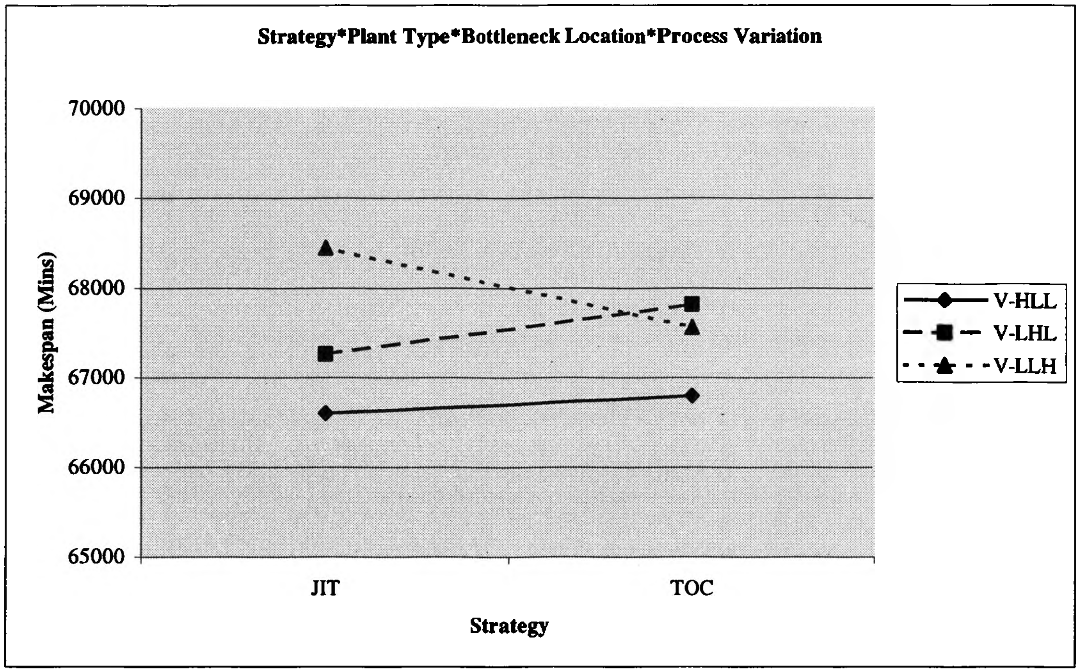


Figure 4.5 V-plant with Low Process Variation Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

From Table 4.4, the mean comparison shows no significant difference between JIT and TOC for a V-plant with low process variation. However, some trends of the system performance between the strategies can be observed from Figure 4.5. Neither JIT nor TOC seem to have much impact on a V-plant that has a bottleneck at the beginning of the process (V-HLL) under a low process variation environment. An interaction result between V-plants that have a bottleneck located at the middle and at the end of the process (V-LHL and V-LLH) to operate under different strategies can be observed. From Table 4.6, the results show significant differences of the bottleneck location over different strategies. It appears that when a bottleneck is present at the beginning of the process both JIT and TOC seemed to be working the best. However, when a bottleneck is moved toward the end of the line, JIT is the worst for all scenarios; while TOC has the worst performance, compared to itself, when a bottleneck is located in the middle station.

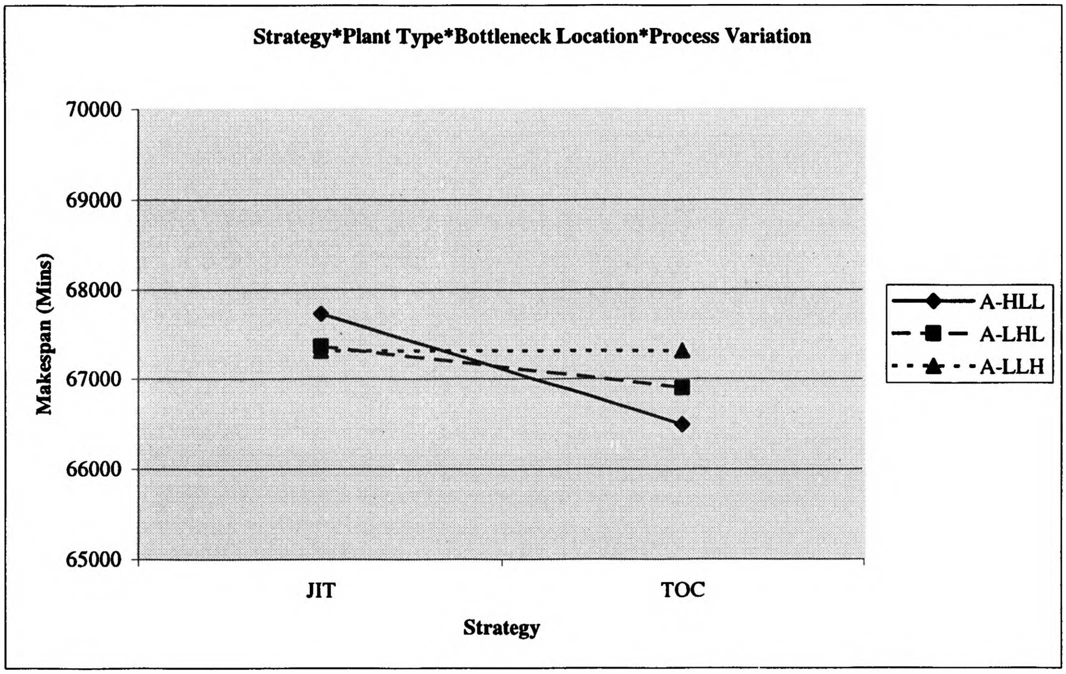


Figure 4.6 A-plant with Low Process Variation Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

From Table 4.6, when the process has low variability, there is no statistical significance on make span, compared within each strategies, JIT and TOC, on the bottleneck location differences in the A-plant. However, when comparisons were made within each bottleneck location at low process variation (Table 4.4), there is a significant difference between the strategies. The results in Table 4.4 show TOC has superior performance over JIT only when a bottleneck moves toward the first station (A-HLL).

The graph in Figure 4.6 also shows that TOC performs somewhat better than JIT in most cases.

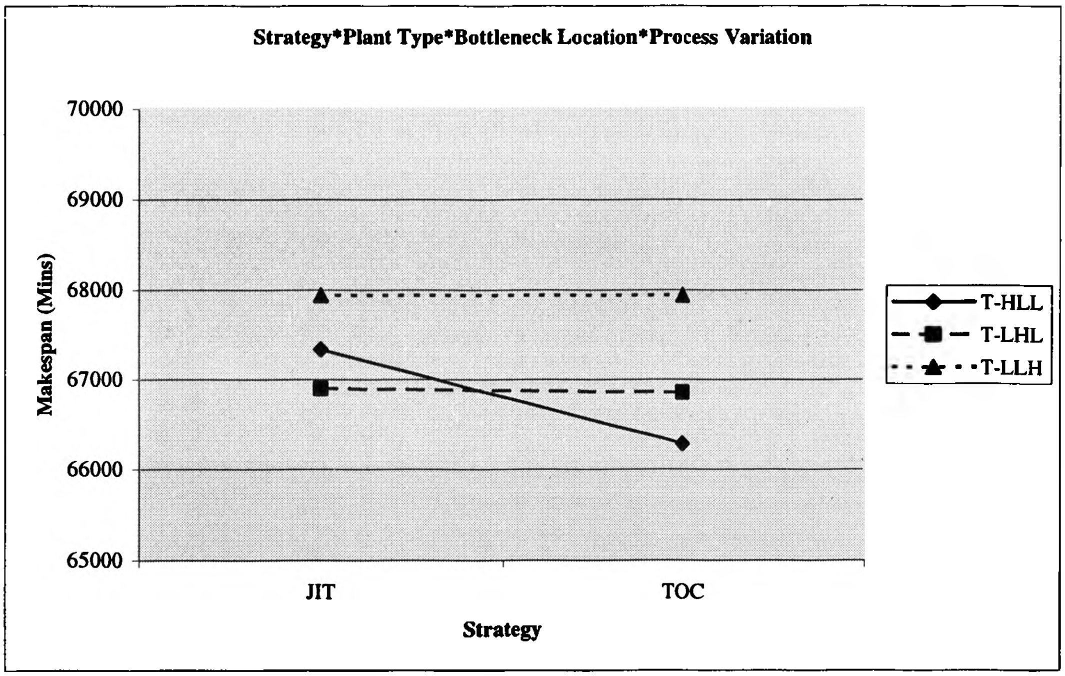


Figure 4.7 T-plant with Low Process Variation Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

From Table 4.4, the similar results for an A-plant can also be observed in a T-plant with low process variation where the favor of TOC is shown when a bottleneck is located at the first process (T-HLL). When comparisons were made within each strategy, the results from Table 4.6 show that, no matter where a bottleneck of the system is, JIT does not seem to have a significant effect on the system performance at all, in contrast to TOC where the worst performance is observed when the bottleneck is at the last process (T-LLH).

One common result for a process that operates under a low process variation is that there is a trend for a process that has a bottleneck at the end of the production line to have the worst performance, while the process that has a bottleneck at the beginning of the production line will perform best especially under the TOC strategy.

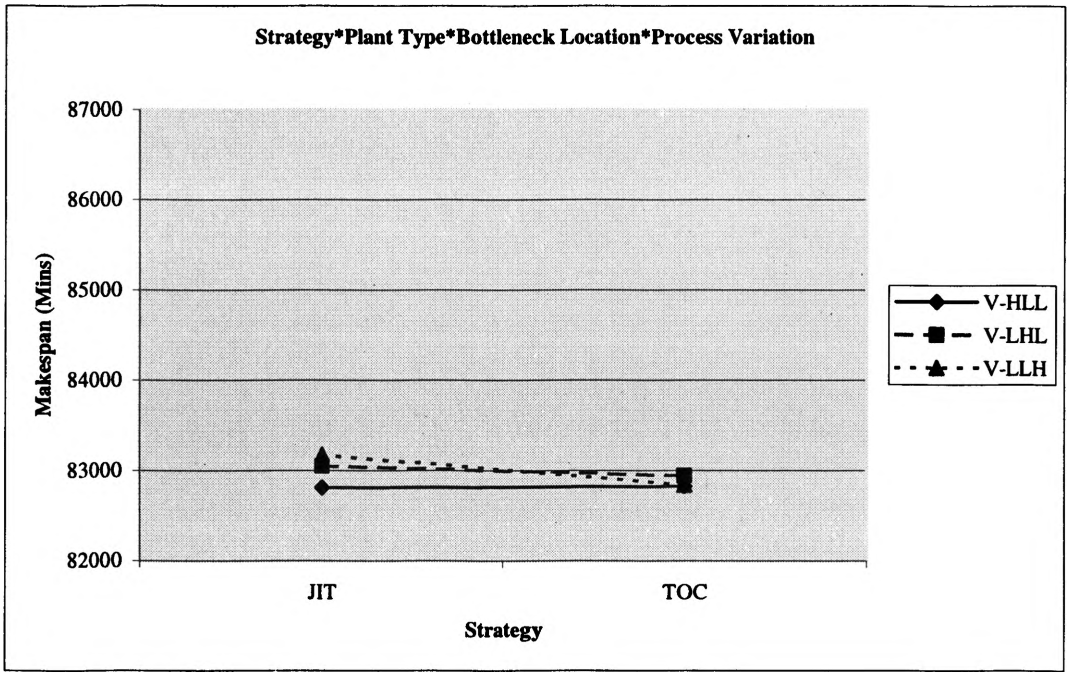


Figure 4.8 V-plant with High Process Variation Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

With high process variability, from the results in Tables 4.4 and 4.6, no significant difference is found in a V-plant regardless of the comparisons made within strategy or bottleneck location. Figure 4.8 above also supports this finding. This might be because all other effects might again have all been ruled out by the high variation of the process as mentioned earlier. Nevertheless, from both Table 4.4 and Figure 4.8, TOC still performs slightly better compared to JIT, but might not be practically significant.

According to the results from Table 4.4, different strategies seem to have the greatest effect when a high level of process variation is presented in an A-plant, except when a bottleneck is located at the end station (A-LLH). Figure 4.9 provides the same picture as TOC always outperforms or at least performs equally to JIT in such a condition. The results in Table 4.6 report statistical significances of JIT and TOC within different bottleneck locations where both JIT and TOC have the best performance when a bottleneck is found at the last process.

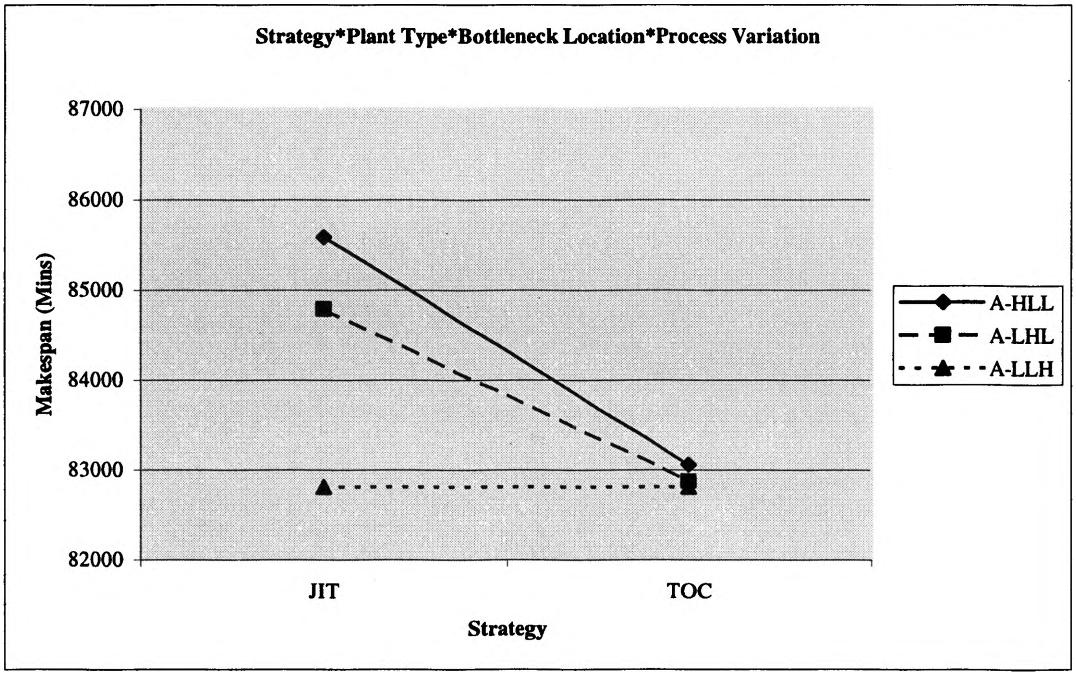


Figure 4.9 **A-plant with High Process Variation Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span**

However, the difference in TOC is of practically negligible while a larger impact is observed under JIT. JIT can only equal the performance of TOC in an A-plant with high process variation when the bottleneck is at the end of the production line.

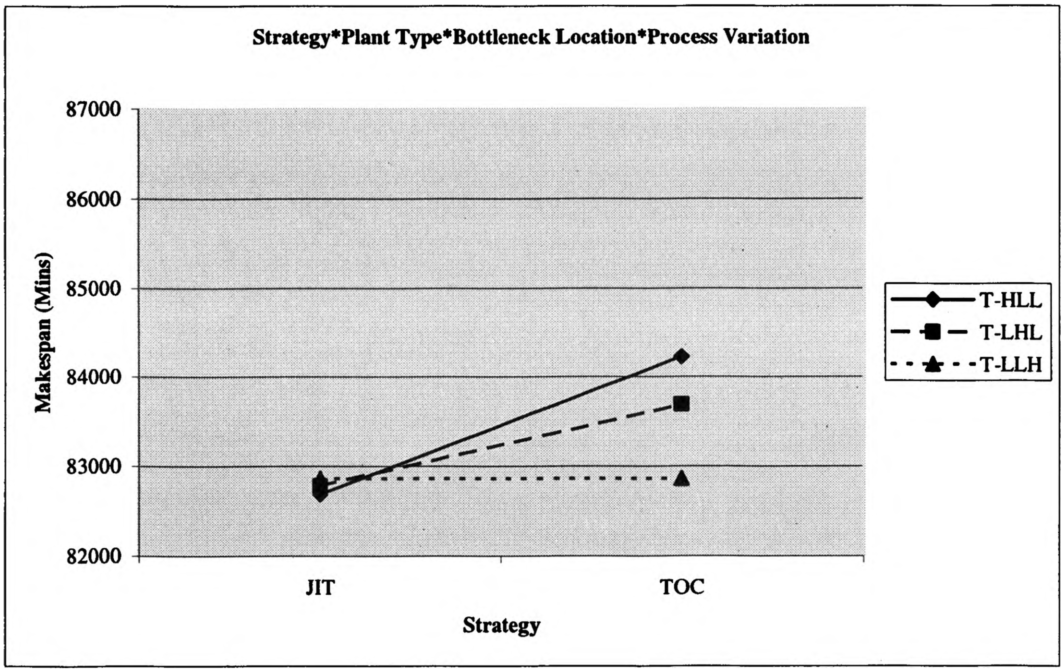


Figure 4.10 T-plant with High Process Variation Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location* Process Variation on Make Span

Contrastingly to an A-plant, in the case of a T-plant with high process variability, it is shown in Table 4.4 that JIT always outperforms TOC, except when the bottleneck moves to the end of production line (T-LLH) where the two strategies essentially become the same. Figure 4.10 shows the JIT strategy seems to handle the bottleneck location differences very well compared to TOC. The result from Table 4.6 indicates a significant difference of JIT strategy within different bottleneck locations, but it is negligible.

Moreover, Table 4.6 also reports a surprise finding for JIT, which performs best when a bottleneck is present at the first process (T-HLL), whereas TOC was the worst in the same condition. This resulted from the characteristic of a T-plant in this study that one diverging operation has to produce three different product types to feed to three succeeding stages in combination with converging operations where two parts have to be assembled together to complete the product at the end of the production line.

Another important thing to notice is that in a process with high variation, a process with a bottleneck at the end of production will have the best performance. This is contrast to a process under low variation where the process with a bottleneck at the first stage of production seems to have the best performance.

Table 4.7 summarizes the likelihood of the best manufacturing strategy for different plant types under different process variations. From Table 4.7, it appears that TOC is almost always shown superior to JIT except for a few cases.

Table 4.7 The Summary Table for the Best Strategy in Different Plant Types under Different Process Variations

Process Variation	Plant Type	Best Strategy
Low	V	Depends upon bottleneck location
	A	TOC
	T	TOC
High	V	Both perform equally
	A	TOC
	T	JIT

For a V-plant with low process variability, the differences in bottleneck location will influence the decision to determine which manufacturing system should be used.

However, for the V-plants with high process variability, different strategies have no implication in system performance in terms of make span. For a T-plant with high variability in the process, JIT is somehow better than TOC as previously discussed.

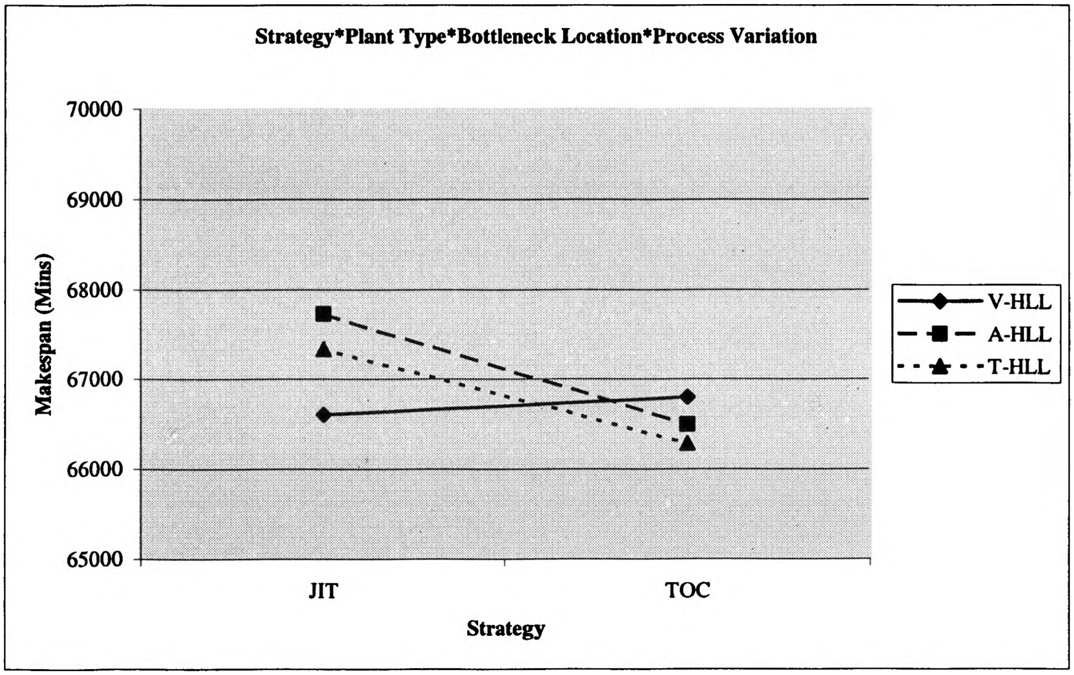


Figure 4.11 Low Process Variation with Bottleneck at the First Process Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

Under low process variability, when the mean comparisons were made in Table 4.5 within the factor of plant type, it is shown that different process structures do not have any impact on the system performance regardless of other factors. With high process variability, on the other hand, some differences are shown to be of significant statistically. However, when a bottleneck is located at the last process, no significant difference have been found whatsoever. Figures 4.11, 4.12, and 4.13; nevertheless, show some differences in both JIT and TOC for different conditions. Based on a previous discussion, though it appears that only the differences in strategy and bottleneck location distinguishes the system performance.

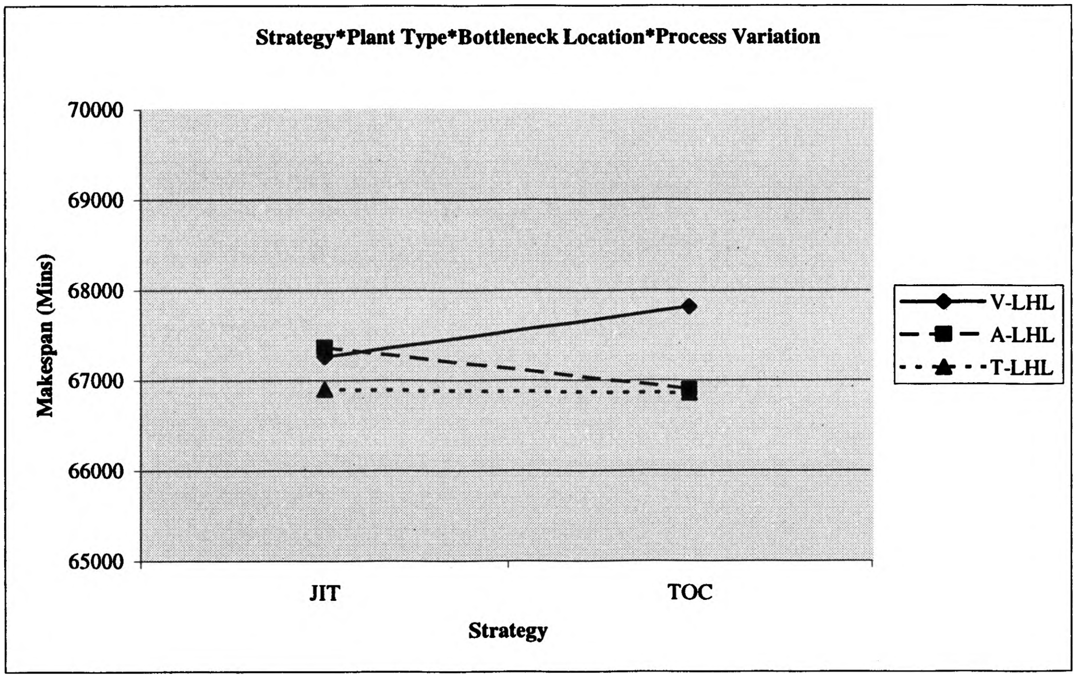


Figure 4.12 Low Process Variation with Bottleneck at the Middle Process Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type* Bottleneck Location*Process Variation on Make Span

When a high process variation is involved in the system and a bottleneck is found at the beginning or middle process, the results from Table 4.4 shows that TOC is more suitable to an A-plant while JIT, on the other hand, works best for a T-plant. A V-plant, nonetheless, does not seem to be affected much by different strategies under various circumstances. However, when the bottleneck is located at the last process and high process variation is involved, none of the differences are significant. Table 4.5 also shows the systems that have a bottleneck at the first and middle process having a similar effect within the two strategies and plant types. This suggests that each plant type has its own characteristics and does affect the system in its own way.

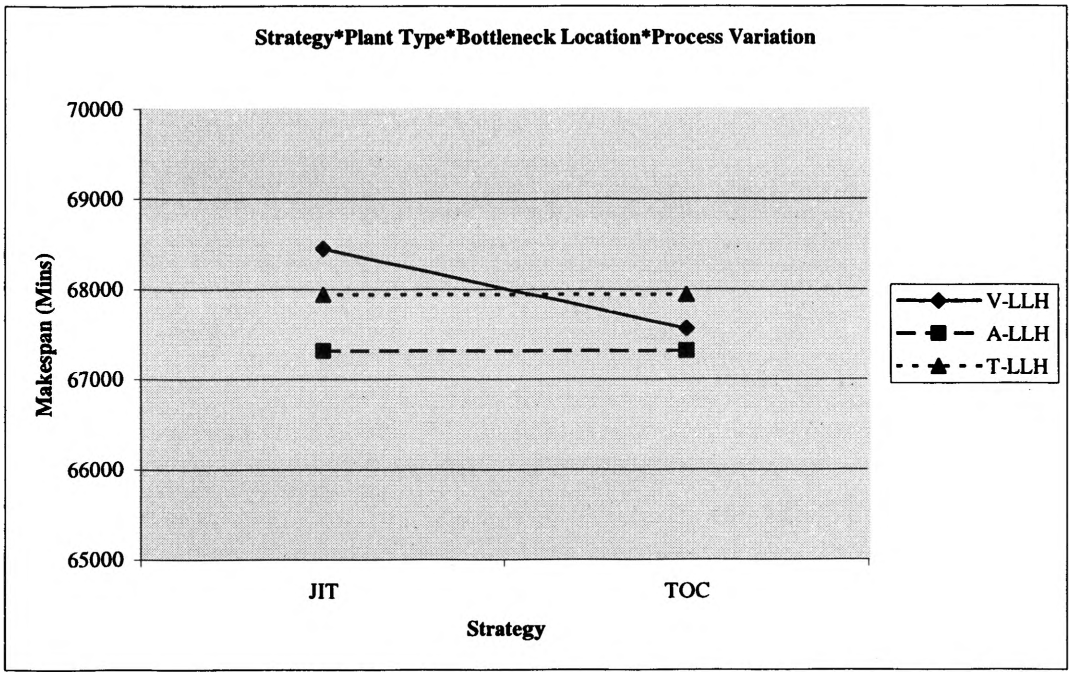


Figure 4.13 Low Process Variation with Bottleneck at the Last Process Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

Figures 4.14 and 4.15 also confirm the results from Table 4.5 that each process structure with a bottleneck at the front and at the middle of a production line is affected similarly by both strategies. Figure 4.16 supports the findings in Table 4.4 where no significant difference is found when a process has a bottleneck at the last workstation. This once again supports the finding that when a production system has a bottleneck at its last workstation, both JIT and TOC strategies happen to work fundamentally the same.

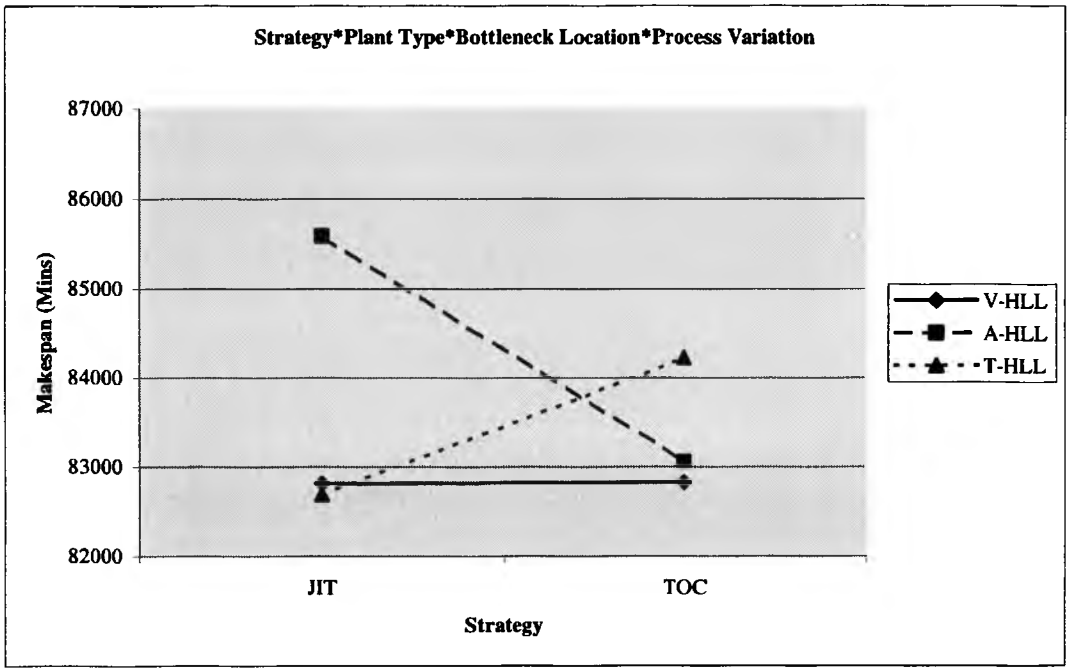


Figure 4.14. High Process Variation with Bottleneck at the First Process Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

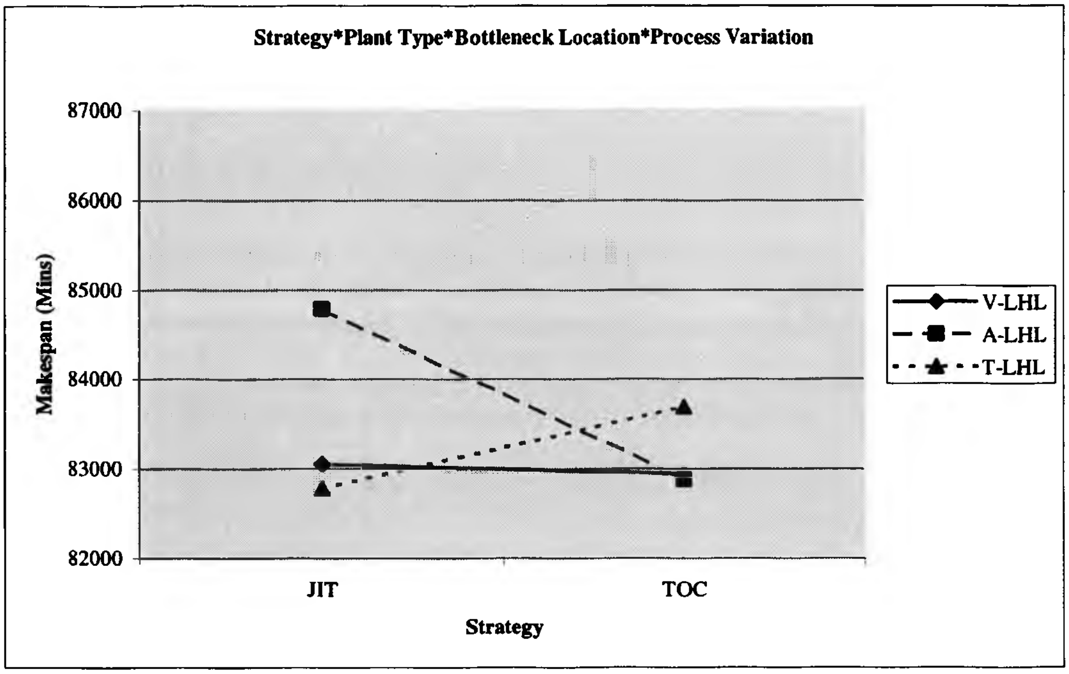


Figure 4.15 High Process Variation with Bottleneck at the Middle Process Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

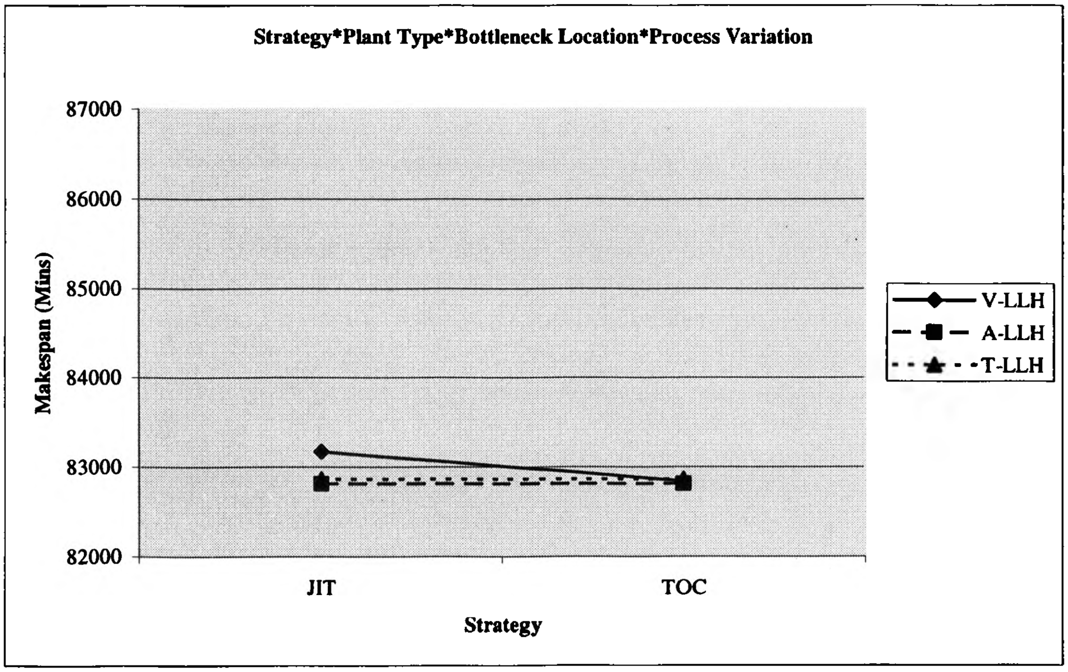


Figure 4.16 High Process Variation with Bottleneck at the Last Process Sub-graph: The Effect of the Four-way Interaction Strategy*Plant Type*Bottleneck Location*Process Variation on Make Span

Table 4.8 shows the summary for possibly the best manufacturing strategy in a process with different bottleneck locations with different process variabilities.

Table 4.8 The Summary Table for the Best Strategy in Different Bottleneck Locations under Different Process Variations

Process Variation	Bottleneck Location	Best Strategy
Low	First	TOC
	Middle	Depends upon process structure
	Last	TOC
High	First	Depends upon process structure
	Middle	Depends upon process structure
	Last	TOC

TOC again appears to be the best strategy, especially when the bottleneck is located at the end of the process. Process structure also has an influence on the system performance in order to determine which manufacturing system should be considered implementing.

Finally, by taking a closer look at Tables 4.4, 4.5, and 4.6, it appears that those significant differences in the values of make span range from less than a production day to more than one production week. This simply implies that not all of the cases that are statistically significant will be practically significant.

4.2 WIP (work-in-process)

All of the factors that are shown to be statistically significant in the full ANOVA table (shown in Appendix B) for the response variable WIP are shown in Table 4.9. For any low order interaction and main effect factors that are part of higher order interactions shown to be significant, only the higher order interaction will be discussed so the interpretation of the ANOVA table will not be misleading. Therefore, only the effects of strategy*plant type*bottleneck location, strategy*plant type*setup, strategy*plant type*process variation, strategy*bottleneck location*setup, and strategy*bottleneck location*process variation will be discussed.

It is interesting to look at the interaction effects that include setup and process variation due to the fact that these two factors are similar as they are both quantitative factors. Moreover, since they both have the same impact on make span variable as already discussed in the previous section; therefore, it is interesting to see if such quantitative factors create the same impact on WIP. The three-way interaction effects that include setup and process variation are shown graphically in Figures 4.17-4.20.

Table 4.9 The ANOVA Table for Response Variable WIP

Source	Sum of Squares	Prob > F
Strategy	21,622	< 0.0001
Plant Type	953,937	< 0.0001
Bottleneck Location	1,283,250	< 0.0001
Setup	4,278	0.0333
Strategy*Plant Type	301,506	< 0.0001
Strategy*Bottleneck Location	234,281	< 0.0001
Strategy*Setup	12,842	0.0002
Strategy*Process Variation	18,171	< 0.0001
Plant Type*Bottleneck Location	746,755	< 0.0001
Strategy*Plant Type*Bottleneck Location	153,608	< 0.0001
Strategy*Plant Type*Setup	7,942	0.0150
Strategy*Plant Type*Process Variation	7,032	0.0242
Strategy*Bottleneck Location*Setup	6,943	0.0254
Strategy*Bottleneck Location*Process Variation	9,637	0.0062
Pure Error Sum of Squares	609,077	
Correlated Total Sum of Squares	4,411,240	

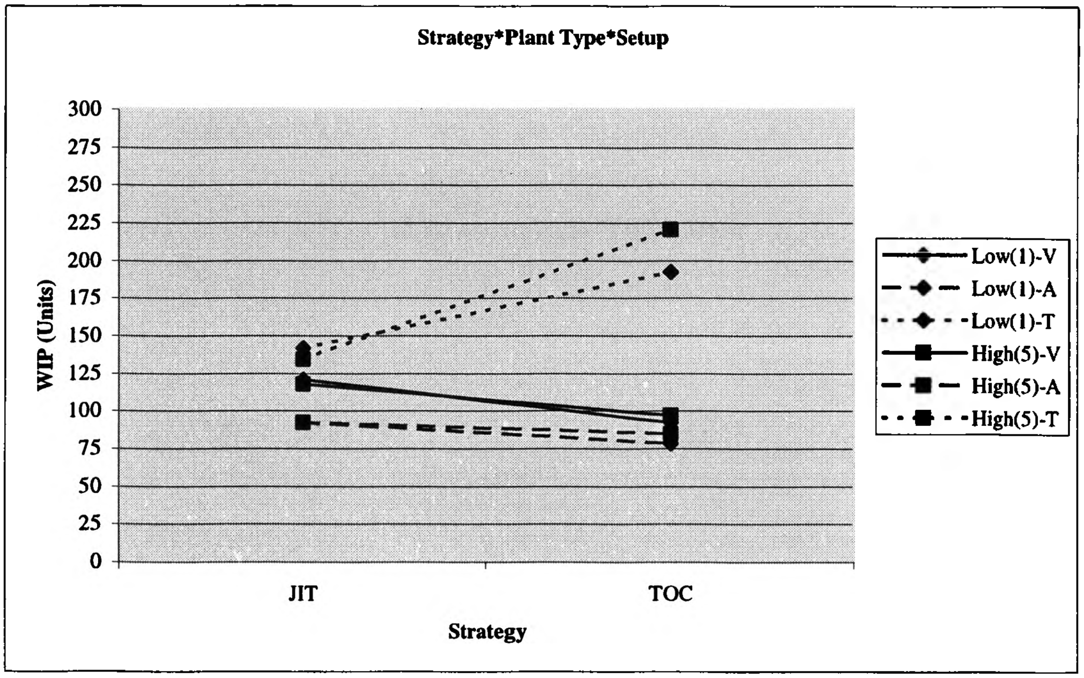


Figure 4.17 The Effect of the Three-way Interaction Strategy*Plant Type*Setup on WIP

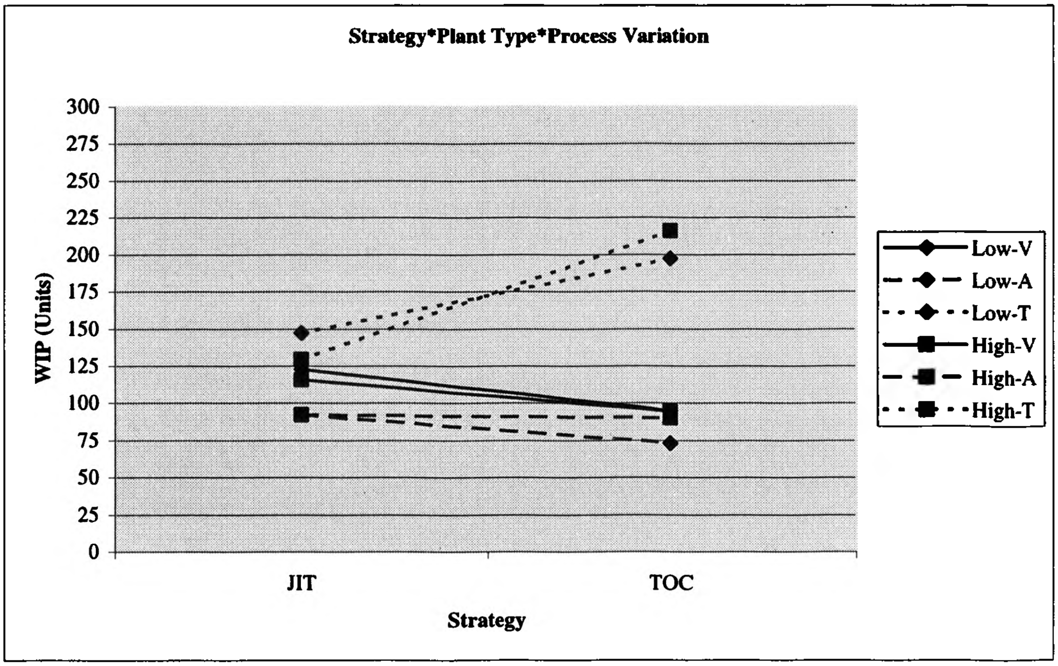


Figure 4.18 The Effect of the Three-way Interaction Strategy*Plant Type*Process Variation on WIP

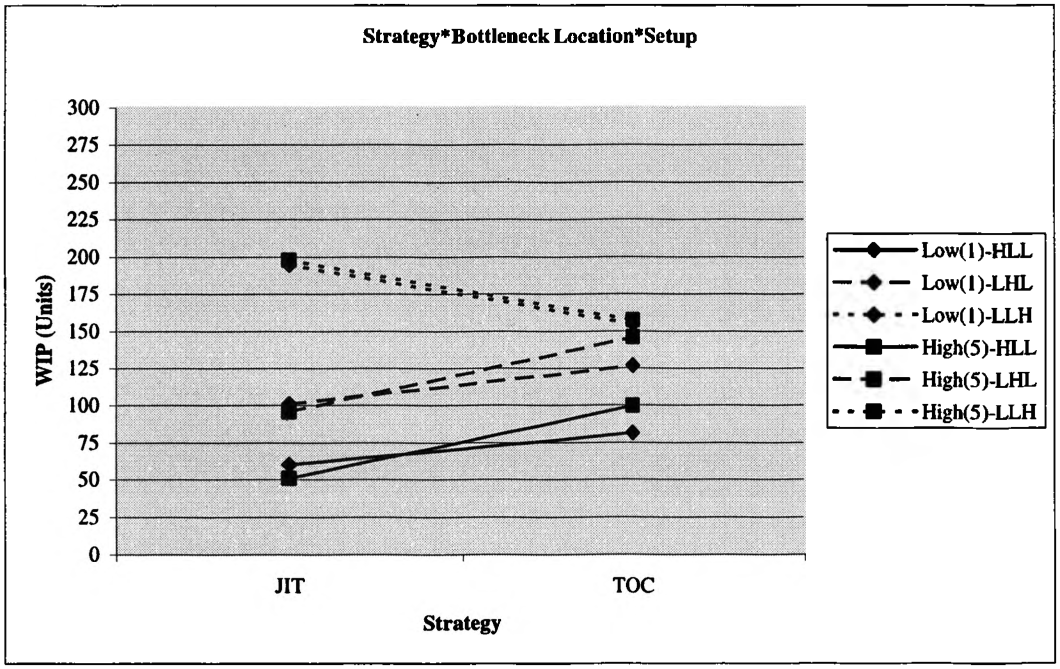


Figure 4.19 The Effect of the Three-way Interaction Strategy*Bottleneck Location*Setup on WIP

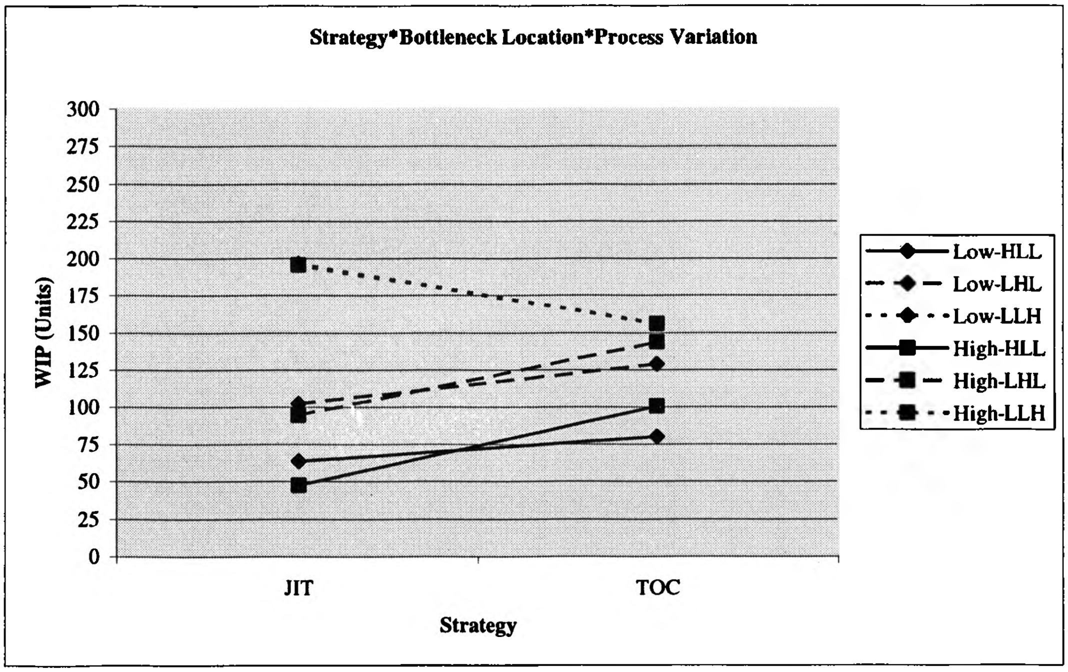


Figure 4.20 The Effect of the Three-way Interaction Strategy*Bottleneck Location*Process Variation on WIP

Figures 4.17-4.20 show that the factors of setup and process variation, within themselves, have no effect on WIP level. This result is different to those found in the make span analysis where the higher the quantitative factor, the higher the response variable. For a response variable WIP, the quantitative factors of setup and process variation do not seem to have as much impact as they do on make span. The reason for both quantitative factors not affecting the level of WIP is because both JIT and TOC were purposely designed to control WIP level. JIT uses a Kanban card system while TOC uses what called "rope" to limit the releasing of raw materials to the system based on the pace of a constraint resource.

On the other hand, from Figures 4.17-4.20, the WIP level seems to be only affected by the factors of strategy and bottleneck location. Figures 4.17 and 4.18 show

JIT works best with a T-plant, while TOC has a little less inventory level in V and A plants than JIT. Figures 4.19 and 4.20 show that the benefits of JIT are observed when the bottleneck is found either at the beginning or at the middle of the process. In contrast, when the bottleneck is shifted to the end, TOC performs better.

Another significant factor is strategy*plant type*bottleneck location. By looking at Figure 4.21, a trends favoring JIT can be observed for T-plants with a bottleneck at the front or middle of the process (T-HLL vs. T-LHL). Both V and T-plants that have a bottleneck at their last workstation (V-LLH and T-LLH) also show a decrease in WIP level when operated with TOC. The graph in Figure 4.21, however, will again be broken down into several sub-graphs (Figures 4.22-4.27) for a clearer picture of how each factor will affect the level of inventory differently.

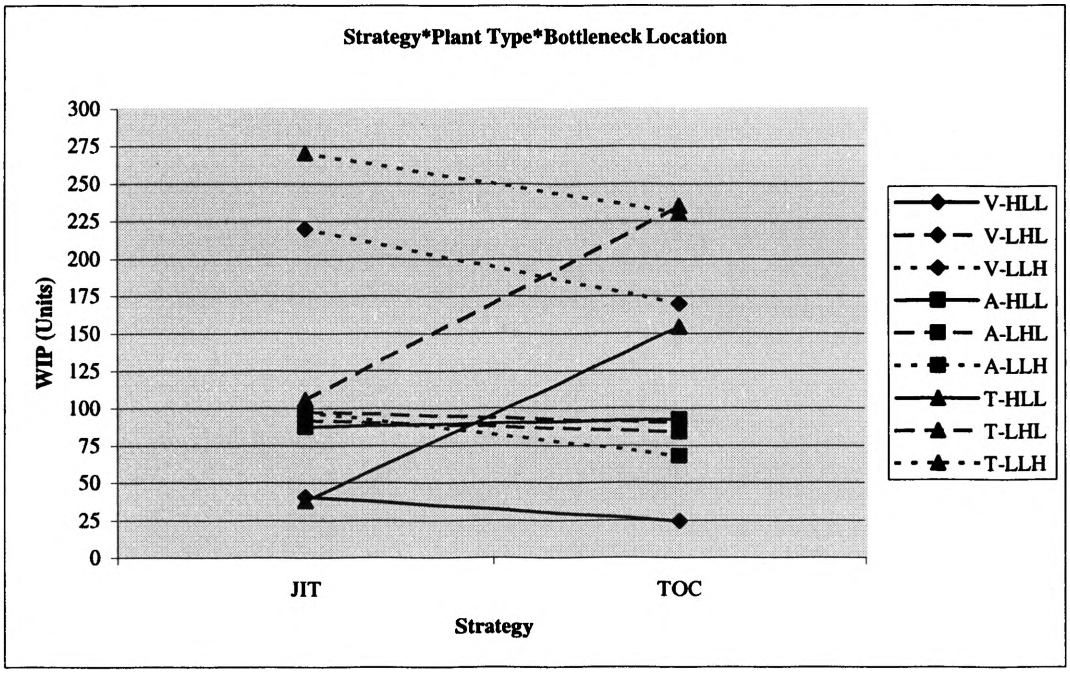


Figure 4.21 The Effect of the Three-way Interaction of Strategy*Plant Type* Bottleneck Location on WIP

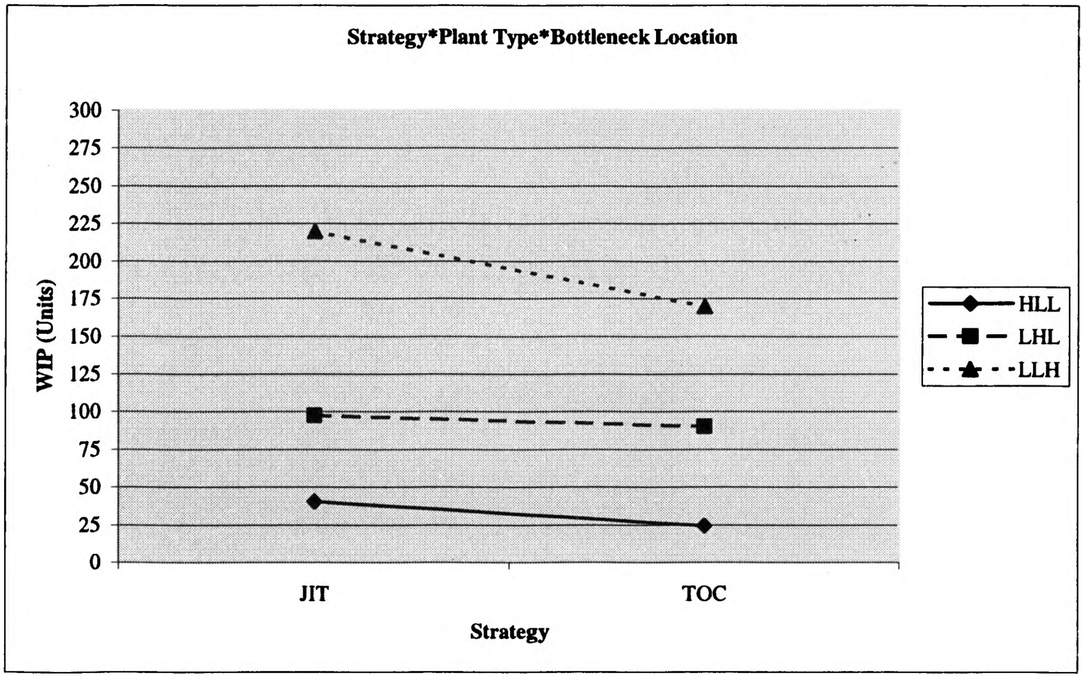


Figure 4.22 V-plant Sub-graph: The Effect of the Three-way Interaction Strategy*Plant Type*Bottleneck Location on WIP

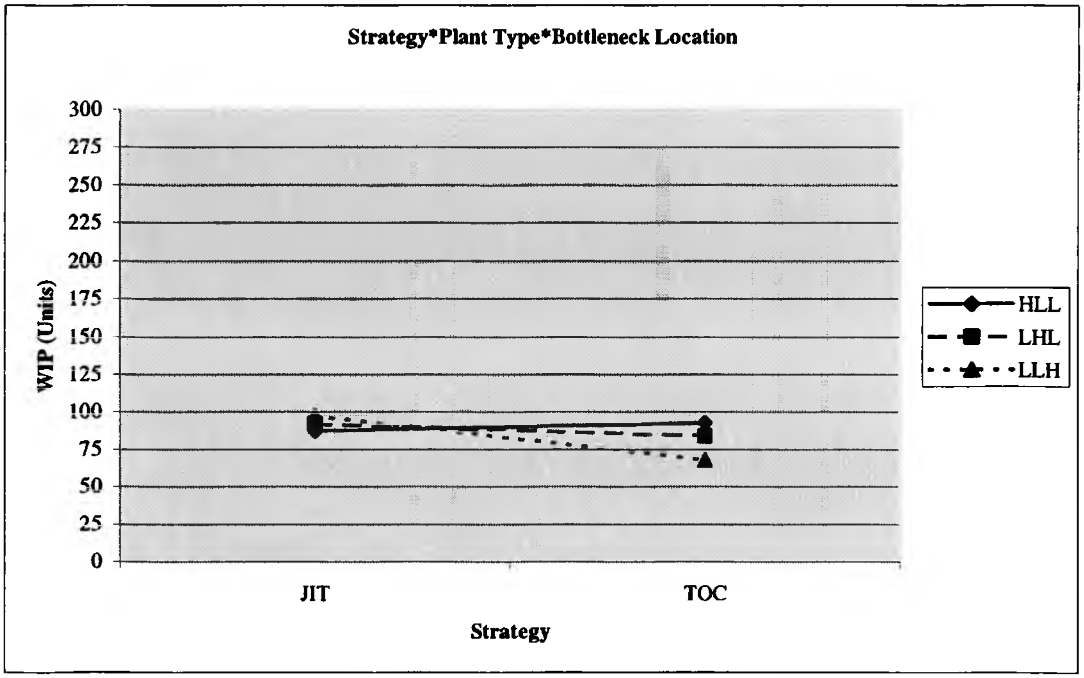


Figure 4.23 A-plant Sub-graph: The Effect of the Three-way Interaction Strategy*Plant Type*Bottleneck Location on WIP

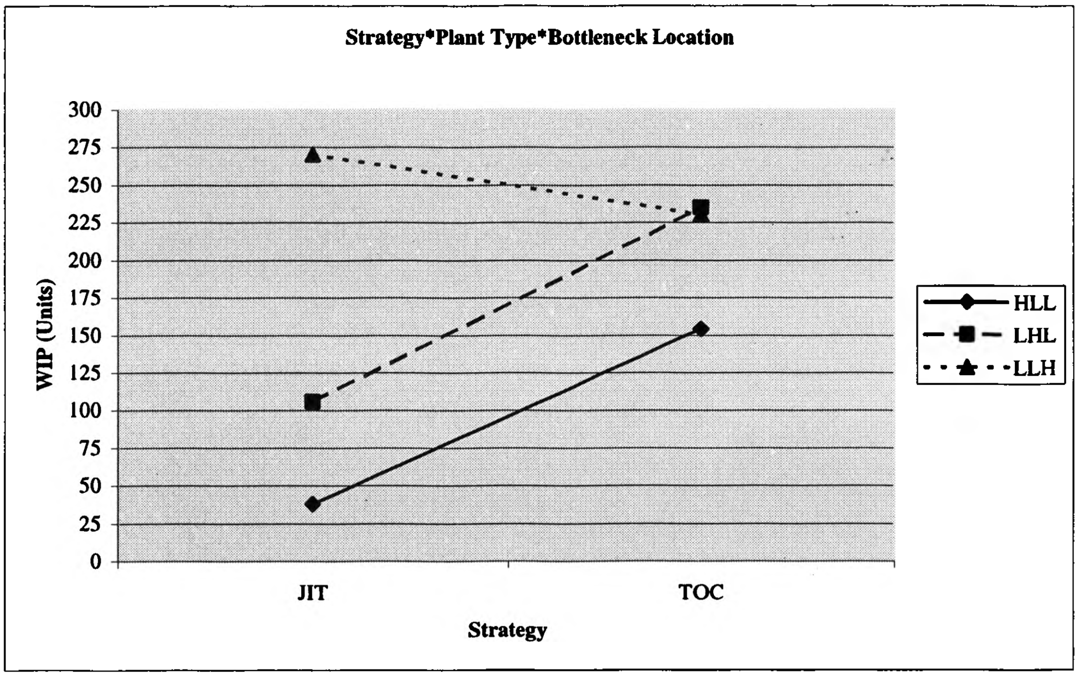


Figure 4.24 T-plant Sub-graph: The Effect of the Three-way Interaction Strategy*Plant Type*Bottleneck Location on WIP

From Figures 4.22, the JIT system seems to have a slightly higher level of WIP than the TOC system in all cases. Moreover, under a V-plant, the level of WIP increases when the bottleneck is moved towards the end of the process for both strategies.

From Figure 4.23, A-plants seem to have the least effect on the level of WIP regardless of bottleneck locations or strategies. The level of inventory of the T plant, as shown in Figure 4.24, under the JIT strategy seems to be dramatically decreased when a bottleneck is located at either the front or middle of the process. The level of inventory for the T-plant is also increased by moving the bottleneck towards the end of the production line as it does in a V-plant.

It is somewhat surprise to see such a low level of WIP in the JIT system for both V and T plants. This might be because in a JIT system when the early process appears to be a bottleneck, an incapability of the preceding stage to release the parts to catch up is created. A push technique used in TOC also resulted in this phenomenon where parts are pushed beyond the bottleneck and accumulated at the last workstation to be assembled together. However, had the production ever come to complete stop with no more demand, WIP level of JIT system should end up higher than of TOC due to the fact that it began the production with a significant larger amount of WIP than TOC in each workstation.

The summary of which strategy is likely to be the best for different kinds of plant with respect to WIP level is shown in Table 4.10 below. From Table 4.10, TOC is the best strategy to operate for V and A-plants. The bottleneck location will determine whether JIT or TOC will be the best for a T-plant.

Table 4.10 The Summary Table for the Best Strategy in Different Plant Types

Plant Type	Best Strategy
V	TOC
A	TOC
T	Depends upon bottleneck location

Figures 4.25 and 4.26 show that a different strategy alone does not have an effect on WIP level for both V and A-plants when the bottleneck is found at the first station. For a T-plant, JIT results in a lower level of WIP than TOC. An A-plant shows a significantly higher level of WIP compared to a V-plant when a bottleneck is located at the first process (Figure 4.25), while a V-plant has a slightly higher level of WIP than an A-plant when a bottleneck is found at the middle of the production (Figure 4.26).

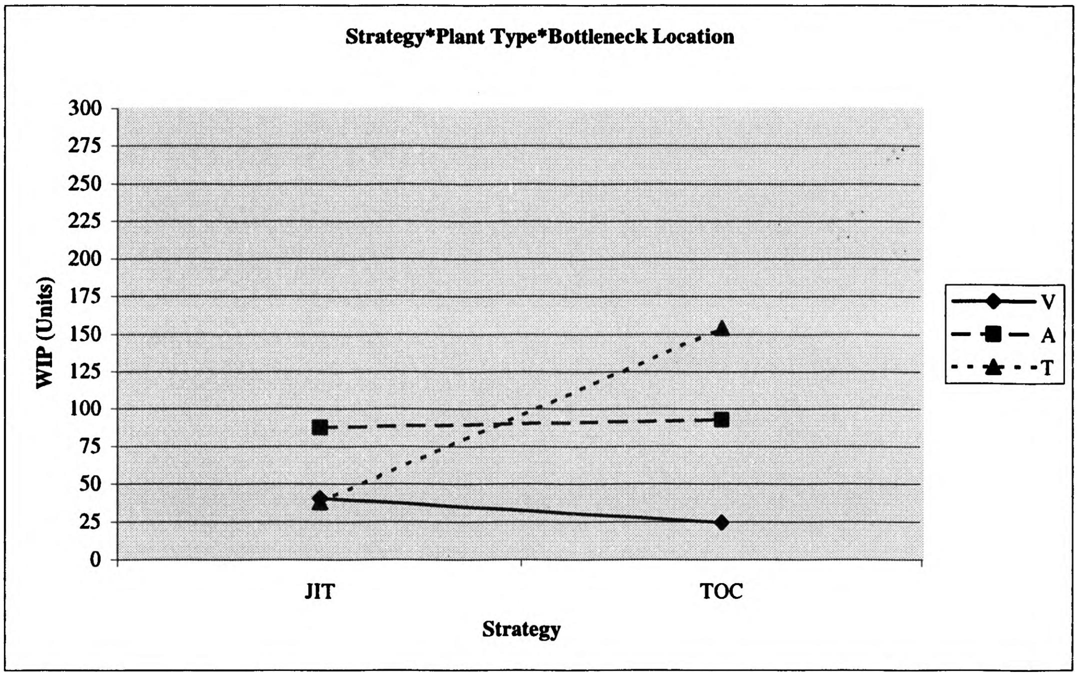


Figure 4.24 Process with Bottleneck at the First Process Sub-graph: The Effect of the Three-way Interaction Strategy*Plant Type*Bottleneck Location on WIP

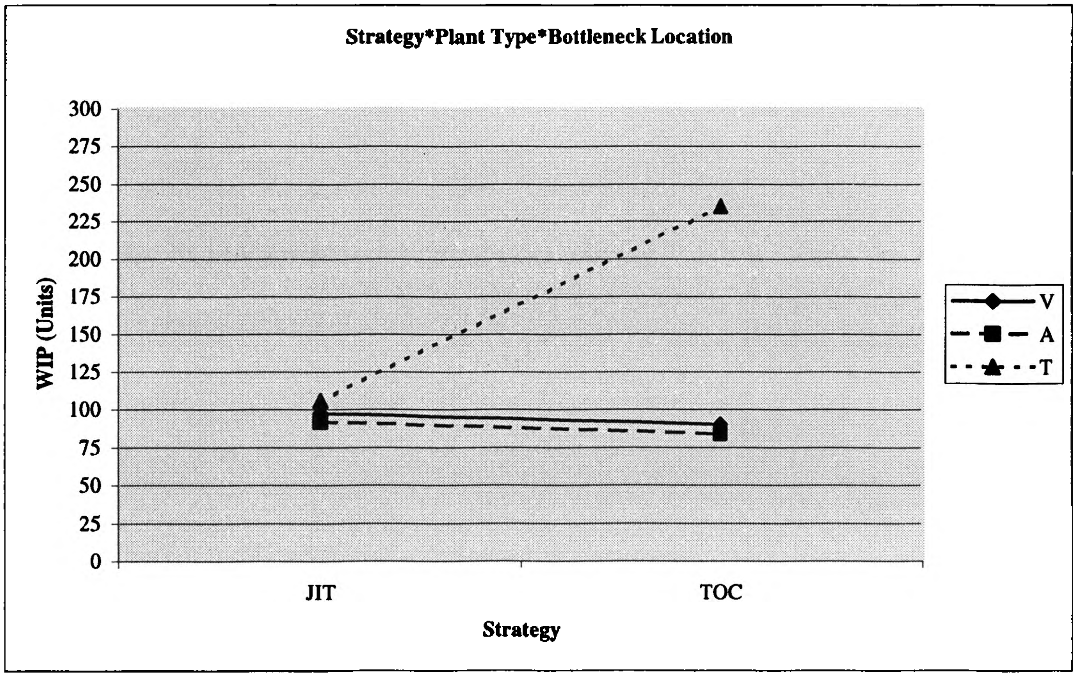


Figure 4.26 Process with Bottleneck at the Middle Process Sub-graph: The Effect of the Three-way Interaction Strategy*Plant Type*Bottleneck Location on WIP

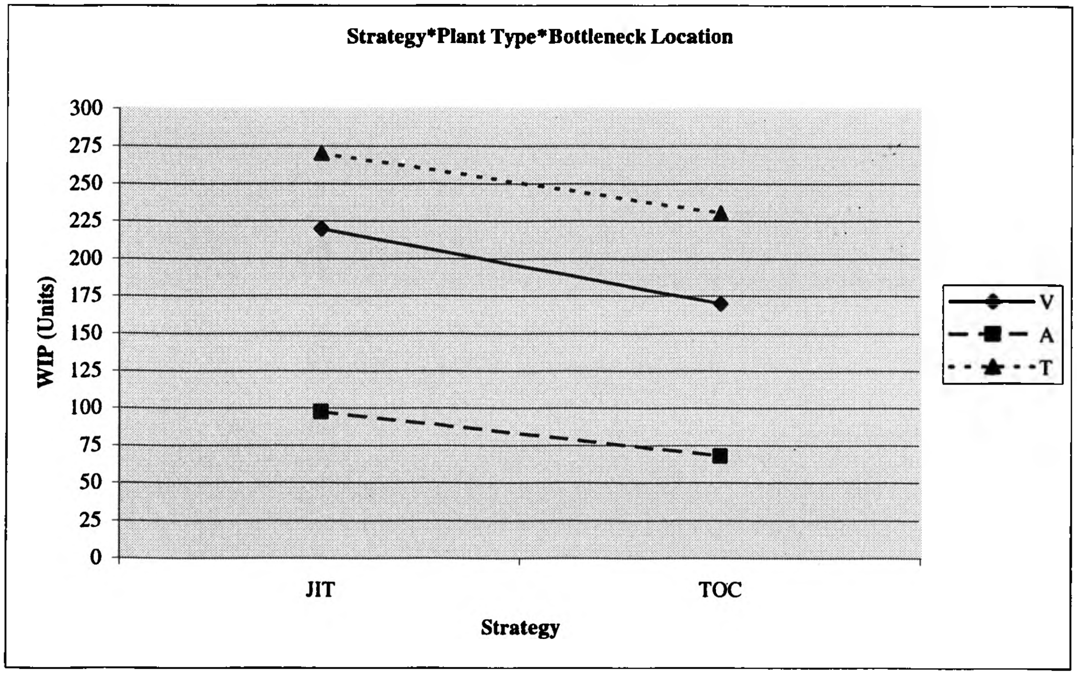


Figure 4.27 Process with Bottleneck at the Last Process Sub-graph: The Effect of the Three-way Interaction Strategy*Plant Type*Bottleneck Location on WIP

The reason for JIT to have such a low WIP level in both V and T plants was explained earlier. However, TOC shows another surprise result to have a remarkable higher level of WIP when a bottleneck is found either at the front or middle process. The reason is because of its push technique and convergent points at the end where parts are pushed to wait for another part to begin the production at the last process.

Figure 4.27 shows that when the bottleneck is at the last process, JIT results in a slightly higher inventory than TOC, and a T-plant appears to have the highest level of inventory where V and A-plants show lesser level, respectively.

The summary of which strategy is most likely the best for different kinds of plant with respect to WIP level is shown in Table 4.11.

Table 4.11 The Summary Table for the Best Strategy in Different Bottleneck Location

Bottleneck Location	Best Strategy
First	Depends upon process structure
Middle	JIT
Last	TOC

The summary in Table 4.11 shows that TOC and JIT are the best strategy when a bottleneck resource is located at the end or middle of the process respectively. However, when a bottleneck is presented very early in the production process, it is the plant type that will determine which strategy would be the best.

The mean comparison of WIP level under the three-way interaction of strategy, plant type, and bottleneck location are shown in Tables 4.12, 4.13, and 4.14. The process that has a bottleneck located at the first process tends to have lower levels of WIP except in case of an A-plant operated under TOC strategy. Typically, an A-plant will have the least inventory while a T-plant will have the most inventory.

In most cases, TOC has a lower level of WIP than JIT, except for a T-plant where the bottleneck is at the front or the middle of the process. The reason for this was already discussed. Even though JIT has been designed purposely to attack the issue of inventory and was believed to be the system that provides smallest inventory level and TOC, on the other hand, was considered as having throughput as its main objective; however, TOC also attacks an inventory issue by strategic placement of a buffer where it feels essential to the system such as prior a constraint resource or a final assembly. By doing so, the inventory level for TOC is also dramatically decreased. This practice results in TOC having a lower level of WIP than JIT in this study.

Table 4.12 Mean Comparison of a Three-way Interaction (Strategy*Plant Type*Bottleneck Location) on Different Strategies

Plant Type	Bottleneck Location	Strategy	WIP (Pieces)	Plant Type	Bottleneck Location	Strategy	WIP (Pieces)	Plant Type	Bottleneck Location	Strategy	WIP (Pieces)
V	HLL	JIT	40.68	A	HLL	JIT	87.51	T	HLL	JIT	38.04**
		TOC	24.35**			TOC	92.93			TOC	153.96
	LHL	JIT	97.58		LHL	JIT	92.02		LHL	JIT	105.80**
		TOC	90.02**			TOC	84.13**			TOC	234.96
	LLH	JIT	219.73		LLH	JIT	97.74		LLH	JIT	270.59
		TOC	169.65**			TOC	67.97**			TOC	230.34**

** indicates significant difference between JIT and TOC at 0.05

Table 4.13 Mean Comparison of a Three-way Interaction (Strategy*Plant Type*Bottleneck Location) on Different Plant Types

Bottleneck Location	Strategy	Plant Type	WIP (Pieces)	Bottleneck Location	Strategy	Plant Type	WIP (Pieces)	Bottleneck Location	Strategy	Plant Type	WIP (Pieces)
HLL	JIT	V	40.68*	LHL	JIT	V	97.58**	LLH	JIT	V	219.73**
		A	87.51			A	92.02* ***			A	97.74* ***
		T	38.04***			T	105.80			T	270.59
	TOC	V	24.35* **		TOC	V	90.02**		TOC	V	169.65**
		A	92.93***			A	84.13* ***			A	67.97* ***
		T	153.96			T	234.96			T	230.34

* indicates significant difference between V and A at 0.05

** indicates significant difference between V and T at 0.05

*** indicates significant difference between A and T at 0.05

Table 4.14 Mean Comparison of a Three-way Interaction (Strategy*Plant Type*Bottleneck Location) on Different Bottleneck Locations

Plant Type	Strategy	Bottleneck Location	WIP (Pieces)	Plant Type	Strategy	Bottleneck Location	WIP (Pieces)	Plant Type	Strategy	Bottleneck Location	WIP (Pieces)
V	JIT	HLL	**40.67* ****	A	JIT	HLL	**87.51* ****	T	JIT	HLL	**38.04* ****
		LHL	**97.58*****			LHL	**92.02*****			LHL	**105.80*****
		LLH	219.73			LLH	97.74			LLH	270.59
	TOC	HLL	24.35		TOC	HLL	92.93		TOC	HLL	**153.96* ****
		LHL	90.02			LHL	84.13			LHL	234.96
		LLH	169.65			LLH	**67.97** *****			LLH	230.34

* indicates significant difference between HLL and LHL at 0.05

** indicates significant difference between HLL and LLH at 0.05

*** indicates significant difference between LHL and LLH at 0.05

5. CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 CONCLUSION

This study discussed some major differences between JIT and TOC. There have been misconceptions about their differenced. For example, TOC is said to be better than JIT in the sense that it can transfer a partial lot to the next station while JIT will have to wait and transfer a whole lot. Actually, this has proven to be a false impression since most companies now, for all practical purposes, transfer partial lots instead of whole lots regardless of what manufacturing strategy they are using. The study also discussed briefly an issue of V-A-T analysis. This analysis is a very powerful tool in analyzing and solving the problems of manufacturing systems. However, it has been received little attention by few researchers.

In this study, the different manufacturing environments of process structures, bottleneck locations, and system variations were tested between Just-in-Time (JIT) and Theory of Constraints (TOC) philosophies over two response variables, make span and work-in-process (WIP). From the study, the performance of TOC with respect to both make span and WIP was shown to be superior to JIT in most environments, even though not all of them were shown to be statistical significant. However, there are also cases where JIT and TOC have no performance differences and even a few cases where JIT can outperform TOC.

One interesting finding is for JIT and TOC systems that have a bottleneck located at the last processing step have equal performances with respect to make span. As expected, both JIT and TOC do not have any performance difference with respect to make span in a plant that has a bottleneck at the last process, since both JIT and TOC will operate as a pull system in this situation. Due to this, TOC can perform equally to JIT with respect to make span with a smaller inventory. This supports the TOC concept of strategic use of inventory at the critical resource, but minimizing it elsewhere. This also shows that it is not necessary for every workstation to have at least two Kanban cards, as they normally do in the JIT system, for the system to perform at its best.

The study overall shows the relationship of different factors and performance measures on generalized V, A, and T plants, enabling most managers to use them as a guideline in implementing different manufacturing philosophies in their organizations, depending upon what aspect of the manufacturing system management hopes to improve.

Based on this study, if manager wished to reduce WIP rather than make span, then the factors of plant type and bottleneck location will need to be taken into consideration. If the manager, on the other hand, consider WIP less significant in terms of performance compared to make span, he or she will then have to take every factor; plant type, bottleneck location, setup, and process variation, into consideration.

The manager must try to reduce setup time and process variability in the system as much as possible if the make span performance needs to be improve. Even though this sounds intuitive, this study strengthens the statement. Another important finding is WIP performance is not going to be improved by this effort. A process structure appears to be what is unique to the production system itself, which may be rather difficult or sometimes even impossible to alter. However, what managers can do is try to reload or alter a bottleneck in the system to the location where it provides the best result.

In addition, the study strongly suggests a plant that has mostly converging operations (A-plant) and constraint resources early in the production line should not consider implementing the JIT system since this plant characteristic allows for variability in the process to be accumulated, which eventually leads to a longer time to complete the production. A plant that has only diverging operations (V-plant) is, on the other hand, the least complicated operation and suitable to either JIT or TOC to be implemented. However, careful consideration has to be given in choosing a strategy for the most complex plant where both converging and diverging operations are present, such as a basic T-plant. However, the results may vary in more sophisticated V, A, and T plants, which has to be further investigated.

The results from this study show that not one system is perfect in every condition. It is a manufacturing environment that dictates the performance of a manufacturing system, not the management technique. Another important finding in this study is that WIP level will be reduced dramatically, if a single-piece flow can be used throughout the production system as in the case of an A-plant where a single-piece flow was used everywhere.

The key contribution this study makes is to tell managers not to follow what has been claimed to be the best manufacturing system in the literature, since typically only one particular set of manufacturing environments is included in the literature. Instead managers should consider using simulation as a tool to evaluate changes of the production system if each particular technique were to be implemented prior to deciding if it is the best for current manufacturing conditions. Instead of altering the whole manufacturing process to observe the performance difference when the new strategy or some minor changes were to be implemented, all of these changes can be examined through using a simulation so the current process will not be halted. Without simulation, it may not be possible for the researchers and managers to understand how a new manufacturing philosophy will affect the production systems.

In searching for the best manufacturing strategy to improve system performance, many techniques have been touted in the literature, including JIT and TOC. What managers should take into consideration prior deciding to implement any system is the specifics of their own organizations structure and the impact of system environments. By following the latest fad without knowing if it is best suited to an organization, managers could likely face an implementation failure, which often comes with a huge investment. Managers may even consider combining the strength from different philosophies to best suit an organization and create a competitive edge by responding to customer demand faster with lower inventory.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

One major limitation in this study is that it is an initial effort to compare JIT against TOC using three different process structures of V, A, and T. This makes the study more one of breadth rather than depth since the focus of the study was on the big picture of how the strategy will react differently in different process structures. Consequently, some factors that may prove to be significant may not have been included, due to the time constraint and the scope of the research. Moreover, each process structure will have its own characteristics, which means that sometimes a comparison against each other may not be completely accurate. Therefore, a particular plant characteristic may need to be further investigated in detail.

Another limitation is that the study was done on hypothetical models of different manufacturing environments. There are both advantages and disadvantages to using hypothetical models. Even though a hypothetical model has the advantage of giving more generalized results, it lacks the ability to fully represent the "real world." Moreover, the lack of the data and randomness in hypothetical models leads to many assumptions. These assumptions may cause an ambiguous result such as the four-way interaction shown to be significant in this study.

Therefore, the recommendations for future research will focus on two main issues, to narrow the scope of the research and improve the design of the experiment and to conduct the study on a real factory. The future research should focus solely on one particular kind of plant so more factors can be studied in order to better compare JIT and TOC. Some factors that might be interesting to look at are the degree of bottleneck severity (in fraction compared to another process), batch size, number of Kanban cards, buffer size, arrival rate, and others. More process variability should also be implemented in the system in different ways.

If possible, a real factory that represents each process structure should be used in developing a model so the number of assumptions can be reduced to make the outcome of the study more reliable. The real data acquired from an actual system may create randomness that may result in fewer factors being significant. However, researchers should keep in mind that there are also some drawbacks in doing research on an actual factory. First of all, the cost and time of the study will increase dramatically due to the fact that the real system will need to be altered, so the comparison can be made. All these things can be done with simulation in significant less time. Second, it is difficult or almost impossible to find the real factory where any changes can be made by the suggestion of a researcher. Consequently, it would be desirable if the study could be done in an actual factory, but due to these drawbacks it is doubtful it can be done on a large scale.

It would also be interesting to observe a specific improvement of either JIT or TOC over a production system on different stages of implementation since JIT and TOC have different approaches in striving for a continuous improvement.

Appendix A

The ANOVA Table for the Response Variable of Make Span

Response: **Make Span**

ANOVA for Selected Factorial Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F-Value	Prob > F
Model	74,465,000,000	71	1,048,800,000	588.8530	< 0.0001
A = Strategy	15,886,500	1	15,886,500	8.9195	**0.0029**
B = Plant Type	8,756,530	2	4,378,270	2.4582	0.0864
C = Bottleneck Location	1,725,250	2	862,626	0.4843	0.6163
D = Setup	27,142,400,000	1	27,142,400,000	15,239.2000	**< 0.0001**
E = Process Variation	46,028,600,000	1	46,028,600,000	25,842.9000	**< 0.0001**
AB	50,304,200	2	25,152,100	14.1217	**< 0.0001**
AC	4,200,320	2	2,100,160	1.1791	0.3082
AD	323,304	1	323,304	0.1815	0.6702
AE	141,453	1	141,453	0.0794	0.7782
BC	43,980,000	4	10,995,000	6.1732	**< 0.0001**
BD	11,225,200	2	5,612,600	3.1512	**0.0435**
BE	26,827,700	2	13,413,900	7.5312	**0.0006**
CD	19,670,600	2	9,835,300	5.5221	**0.0042**
CE	71,974,200	2	35,987,100	20.2050	**< 0.0001**
DE	878,473,000	1	878,473,000	493.2210	**< 0.0001**
ABC	42,001,400	4	10,500,300	5.8954	**0.0001**
ABD	9,439,010	2	4,719,500	2.6498	0.0714
ABE	33,355,300	2	16,677,600	9.3637	**< 0.0001**
ACD	2,020,230	2	1,010,110	0.5671	0.5674
ACE	4,695,040	2	2,347,520	1.3180	0.2684
ADE	3,448,100	1	3,448,100	1.9360	0.1646
BCD	6,728,440	4	1,682,110	0.9444	0.4377
BCE	5,505,520	4	1,376,380	0.7728	0.5431
BDE	234,466	2	117,233	0.0658	0.9363
CDE	6,925,420	2	3,462,710	1.9442	0.1439
ABCD	6,593,580	4	1,648,400	0.9255	0.4485
ABCE	22,531,600	4	5,632,900	3.1626	**0.0137**
ABDE	2,631,950	2	1,315,970	0.7389	0.4781
ACDE	6,906,830	2	3,453,420	1.9389	0.1447
BCDE	3,019,200	4	754,800	0.4238	0.7915
ABCDE	4,534,650	4	1,133,660	0.6365	0.6366
Pure Error Sum of Squares	1,154,150,000	648	1,781,090		
Correlated Total Sum of Squares	75,619,100,000	719			

Appendix B

The ANOVA Table for the Response Variable of WIP

Response: **WIP**

ANOVA for Selected Factorial Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F-Value	Prob > F
Model	3,802,170	71	53,552	56.9738	< 0.0001
A = Strategy	21,622	1	21,622	23.0039	**< 0.0001**
B = Plant Type	953,937	2	476,969	507.4490	**< 0.0001**
C = Bottleneck Location	1,283,250	2	641,626	682.6290	**< 0.0001**
D = Setup	4,278	1	4,278	4.5514	**0.0333**
E = Process Variation	607	1	607	0.6457	0.4219
AB	301,506	2	150,753	160.3870	**< 0.0001**
AC	234,281	2	117,140	124.6260	**< 0.0001**
AD	12,842	1	12,842	13.6631	**0.0002**
AE	18,171	1	18,171	19.3322	**< 0.0001**
BC	746,755	4	186,689	198.6190	**< 0.0001**
BD	2,823	2	1,411	1.5015	0.2236
BE	4,652	2	2,326	2.4747	0.0850
CD	534	2	267	0.2840	0.7529
CE	522	2	261	0.2779	0.7574
DE	663	1	663	0.7059	0.4011
ABC	153,608	4	38,402	40.8561	**< 0.0001**
ABD	7,942	2	3,971	4.2247	**0.0150**
ABE	7,032	2	3,516	3.7409	**0.0242**
ACD	6,943	2	3,471	3.6931	**0.0254**
ACE	9,637	2	4,818	5.1263	**0.0062**
ADE	2,971	1	2,971	3.1606	0.0759
BCD	1,812	4	453	0.4819	0.7491
BCE	5,173	4	1,293	1.3760	0.2407
BDE	164	2	82	0.0874	0.9164
CDE	349	2	175	0.1859	0.8304
ABCD	4,785	4	1,196	1.2726	0.2794
ABCE	3,341	4	835	0.8888	0.4702
ABDE	4,068	2	2,034	2.1642	0.1157
ACDE	2,360	2	1,180	1.2555	0.2856
BCDE	482	4	121	0.1283	0.9721
ABCDE	5,052	4	1,263	1.3438	0.2522
Pure Error Sum of Squares	609,077	648	940		
Correlated Total Sum of Squares	4,411,240	719			

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VITA

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