INVESTIGATING THE APPLICATION OF THE
THEORY OF CONSTRAINTS TO THE
SCHEDULING ENVIRONMENT
OF THE IAF'S DEPOTS

THESIS

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THESIS

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Preface

The purpose of this research was to examine the application of a revolutionary management philosophy known as the Theory of Constraints to the scheduling environment of the depots of the Israeli Air Force (IAF). The challenge of military application of many business theories and approaches is that they are designed for profit-oriented commercial enterprises. Often in teaching management in the military, little attention is placed on bridging the gap between what is considered good management in the private sector and what is needed for good management in the military. Part of the challenge of this research was to bridge the gap for a specific military environment. The ongoing challenge is to strengthen that bridge.

It is common practice in the preface to express acknowledgement to those members of the faculty connected with the thesis regardless of whether or not thanks is truly felt. I wish it to be publicly known that I express the most sincere and honest gratitude to the tremendous guidance and wisdom given to me by my thesis advisor and teacher Lieutenant Colonel R. Moore and to my teacher Professor D. Reynolds. More than the formal knowledge passed on to me, both these men have demonstrated to me the meaning of being a "gentleman and scholar".

Sincere thanks is also expressed to the Avraham Goldratt Institute, and in particular Dr. E.M. Goldratt, for permitting me to participate in their academic seminars.

Like so many of the AFIT students the thesis could never become a realization without the unselfish support of their spouses. My wife Tali has given far more to the completion of this research than is reflected by the words on this page.

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Abstract

This research investigated the application and merits of the Theory of Constraints (TOC) to the scheduling environment of the Israeli Air Force's (IAF) maintenance depots. TOC was extensively reviewed including an elaboration of the TOC paradigm and the scheduling procedures developed for a commercial manufacturing settings. Background information was also presented on the IAF depots and traditional scheduling rules. An experiment was designed and conducted that simulated a simplified version of the process flow of the armaments depot. The simulation compared the performance of the depot using a schedule based on TOC as opposed to the traditional depot schedule. The results of the simulation clearly favored the TOC schedule in terms of lower inventory and makespan. The experiment did not conclusively show any difference in standard throughput hours as a result of the TOC schedule. These results were statistically validated. It was concluded that the core scheduling procedures of TOC, specifically the concept of drum-buffer-rope and buffer management were applicable to the depot environment and provided advantages over the traditional depot schedule. Difficulties were found in defining a uniform measurement for throughput and inventory for the depot environment.

INVESTIGATING THE APPLICATION OF THE THEORY OF CONSTRAINTS TO THE SCHEDULING ENVIRONMENT OF THE IAF'S DEPOTS

I. Introduction

The General Issue

The external military threat to Israel's survival is perceived by the Israeli society as being ominously real. Given this threat, the Israel Defense Forces (IDF) constantly strive for better performance. Often efforts are made in the military to adapt commercially-oriented management theories and procedures to the military environment. The Theory of Constraints (TOC) is a recent management theory that has reported to have had success among a number of leading U.S. commercial firms (Melton, 1986:13). Its most publicized contribution has been in the development of synchronized schedules for the challenging job shop scheduling environment.

The scheduling environment of the Israeli Air Force's (IAF) maintenance depots is similar to a job shop. Typically the depots are required to fulfill a variety of demands that require the synchronization of depot resources. The challenge of synchronization is compounded by the constant changes in both the priority and work content of the demands. These changes are in response to the dynamic nature of the military threat that Israel faces. Given these challenges, the depots are perceived as having at times difficulty in effectively and efficiently meeting the demands placed upon them. It is widely believed among the depot's top management and the logistic's command that the inability of the depots to achieve synchronized schedules prevents the effective utilization of their resources (Maiere, 1990; Ben-Israel, 1990). Given the primary role that the depots play in the maintenance and upgrading of the IAF's weapon systems, the success of the depots has a direct impact on the IAF's combat capability.

In light of the publicized success of TOC in developing schedules for the job shop environment, it is appropriate to investigate the applicability and merits of TOC to the depot's scheduling environment.

The Specific Problem

This research will attempt to determine whether TOC can substantially contribute to the scheduling environment of the IAF's maintenance depots.

Assumptions

1. The scheduling environment of the depots is classified as a job shop environment.

2. The depots some times experience difficulties in meeting the demands and expectations placed on them.

3. The depots currently have difficulty in achieving synchronized schedules.

4. A depot's inability to achieve a synchronized schedule significantly contributes to its performance difficulties.

Investigative Questions

1. What is TOC?

2. What is TOC's contribution to the job shop scheduling environment?

3. What are the differences between the commercial manufacturing and depot's scheduling environment?

4. If differences do exist between the two environments, are they significant enough to warrant changes in the TOC procedures?

5. How is depot performance measured?

6. How does one validate the contribution of a theory to the scheduling environment of the depot?

7. If changes are required to the TOC procedures, do those adapted procedures significantly contribute to the depots performance? (The same question can be asked if changes are not required to the TOC procedures.)

8. How do the depots currently schedule their operations?

9. Are TOC procedures, adapted or otherwise, more effective than the current scheduling approach?

10. If modifications are required in the TOC procedures, would those modifications constitute a change in the inherent nature of TOC?

Scope of the Research

Due to the security classification of data related to depot operations, all data used has been created through a simulation of an IAF depot. The simulation is of a simplified version of the IAF's armaments depot. Detailed data such as specific weapon system problems or type and number of weapons will be avoided. The issue of validity of the simulation experiment will be discussed in the body of the research.

II. Background

The aircraft maintenance depots of the Israeli Air Force (IAF) provide direct support to the flying units agencies providing the front line support of the state of Israel. This chapter presents background information related to the IAF depots. In addition research related to scheduling and TOC is reviewed.

The IAF Depots

The IAF's logistics organization encompasses five major maintenance depots that maintain and upgrade the IAF's weapon systems. There are three levels of maintenance in the IAF. The most extensive maintenance is conducted at the depot level, and usually requires the transfer of weapon systems and their components from the operational base to the depot for an extended period.

A functional separation is what distinguishes each of the depots from one another. For example, one depot specializes in electronics, another in engines. Different components from the same weapon system can be maintained by different depots. The fire and control unit of an F-16 fighter plane, for example, is maintained in the electronics depot, while the fighter's engine is the supported at the aircraft configuration depot. The armaments depot is the subject of the simulation experiment in the thesis. The weapon systems that are supported by this depot are primarily missiles and anti-aircraft systems.

The structure, organization, and logic of work flow is essentially the same for all the depots. The structure and work flow of a depot is centered around its workshops. Each workshop is assigned direct responsibility for a specific weapon system. In addition to the specialized workshops, there are a number of departments that provide common services to all the workshops. These departments include the Common Service department that provides welding, sheet metal, and painting services.

Job Shop Scheduling

Scheduling has been defined in the literature in several ways. McClain and Thomas define scheduling as "the process of assigning a starting time for each job on each machine" (McClain and Thomas, 1985:341). A more encompassing definition is supplied by Chase and Aquilano through their description of a schedule as being:

> a timetable for performing activities, utilizing resources, or allocating facilities. The purpose of operations scheduling in the job shop is to desegregate the master production schedule into time-phased weekly, daily, or hourly activities--in other words, to specify in precise terms the planned workload on the productive system in the very short run. (Chase and Aquilano, 1985:580)

Scheduling can be applied to different working environments: projects, services, and production. The production environment can be further divided into either a job shop/intermittent system or an assembly/continuous system. The nature and treatment of the scheduling problem in each of these environments is different (Cook and Russell, 1984:415). The IAF depots can be described as classic examples of job shop environments. Both the academic and manufacturing community acknowledge that job shop scheduling is the most difficult of scheduling environments (Chase and Aquilano, 1985:580).

The term job shop needs to be defined:

> A job shop is a functional organization whose departments or work centers are organized around particular types of equipment or operations, such as drilling, forging, spinning, or assembly. Products flow through departments in batches corresponding to individual orders. (Chase and Aquilano, 1985:580).

A complex job shop is characterized by multiple machine centers processing a variety of different jobs arriving at machine centers in an intermittent fashion throughout the day (Chase and Aquilano, 1985:588).

Why is there a need for scheduling? In a working environment where resources are constrained (time, manpower, facilities, materials) appropriate scheduling allows for the effective and efficient utilization of the organizations resources to meet its goals. According to Meridith, appropriate scheduling ensures ". . . that the right tasks are conducted at the right time on the right items to produce the output" (Meridith, 1987:368). How is appropriate scheduling achieved? In one word--orchestration. However, it is no simple matter to orchestrate the hundreds of simultaneous activities that constitute a typical day's schedule in a complex job shop.

Part of that orchestration requires a control system. Control entails monitoring job order progress, and where necessary, expediting orders and/or adjusting system capacity to make sure that the master schedule is meet (Chase and Aquilano, 1985:580).

Functional Considerations. The first step in gaining control of job shop schedules is the design of an appropriate scheduling and control system. The design must provide for the efficient performance of the following functions:

1. Allocating orders, equipment, and manpower to work centers--short-term capacity planning.

2. Determining the sequence of order performance (i.e. establishing job priorities).

3. The dispatching of orders. "Dispatching is the selecting and sequencing of available jobs to be run at individual work stations and the assignment of these jobs to workers" (Wallace and Dougherty, 1987:9).

4. Shop floor control involves: reviewing the status and controlling the progress of orders as they are being worked; expediting late and critical orders.

5. Revising the schedule in light of changes in order status (Chase and Aquilano, 1985:580-581).

Priority Rules. Priority rules are at the core of any scheduling system. The process of allocating jobs to work centers is known as work center loading. Determining which dispatching rule to use is a key scheduling decision and is the focus of much attention. According to Meridith (1987:342), researchers present fairly consistent results. However, a detailed review of research into priority rules is beyond the scope of this research. This review will limit itself to an overview of the traditional dispatching rules. The Theory of Constraints dispatching rules will be explained later. The following is a summary of the more common rules:

1. First come, first served: This rule selects the first job to arrive at each work station, from among those waiting (McClain and Thomas, 1985:342; Chase and Aquilano, 1985:584; Cook and Russell, 1984:439).

2. Shortest operation time: This rule always selects the task with the shortest time requirement on the machine, from among those waiting (McClain and Thomas, 1985:342; Chase and Aquilano, 1985:584; Cook and Russell, 1984:439).

3. Truncated shortest operation time: This rule selects according to the shortest operation time, unless a job has been waiting longer than a specified truncation time, in

which case that job goes to the front of the waiting line (McClain and Thomas, 1985:342).

4. Dynamic slack per remaining operation (DS/RO): For each job waiting, this rule computes the DS/RO value as the amount of slack remaining (time until due minus remaining processing time on all machines), divided by the number of operations remaining. The job with the lowest DS/RO value is chosen to work on first (McClain and Thomas, 1985:342; Chase and Aquilano, 1985:584).

5. Slack time remaining: Same as DS/RO without dividing by the number of remaining operations (Chase and Aquilano, 1985:584; Cook and Russell, 1984:439).

6. Due dates: Run the job with the earliest due date first (Chase and Aquilano, 1985:584).

7. Critical ratio: This ratio is calculated as the difference between the time remaining before the due date and the current date divided by the work remaining. Orders with the smallest critical ratio are run first (McClain and Thomas, 1985:343; Chase and Aquilano, 1985:584; Cook and Russell, 1984:439).

Schedule Evaluation Criteria. Several different measurements are used to evaluate priority rules. The standard measurements include:

1. Meeting due dates of customers or downstream operations.

2. Minimizing idle time of machines and workers.

3. Minimizing work in process and average waiting time for jobs.

4. Minimizing the amount of time a job spends in the shop (Chase and Aquilano, 1985:585; Cook and Russell, 1984:437).

<u>Approaches to Scheduling</u>

There are several different schools of thought in both the business and academic community. Manufacturing Resource Planning (MRP II) and Just-In-Time (JIT) are two of the more widely-known scheduling approaches. MRP in particular has experienced a very rapid growth and level of acceptance among practitioners (Cook and Russell, 1984:381). The Theory of Constraints is a very recent addition to the scheduling literature. Although it is not widely publicized, it seems to be having an increasing impact on a number of leading U.S. firms (Melton, 1986:13). There are some basic differences between these approaches.

<u>MRP II</u>. This computer-based approach focuses on the timing of the release of materials to the shop floor as well as indicating where there is a capacity problem in the planned schedule. The logic of the release of materials is based on backward scheduling. By this term it is meant that scheduling starts from the due dates and schedules backwards in time. Production requirements are developed

from a bill of materials "explosion." MRP II allows the user to select from a number of preselected decision rules for sequencing. The question of which decision rule should be used at individual work centers, is left to the discretion of the user and is rarely changed once the rule is selected.

Just-in-time (JIT). It should be noted that JIT is more than a scheduling technique, it is a whole a managerial approach to a production organization that includes the fostering of worker-employer relationship, customer-vendor relationship, abhorrence of wastefulness, close to immediate response to customer demands, quality at the source. In the context of scheduling, JIT is considered as a pull system. Materials are not fed into the production cycle until the finished product is actually required. Production requirements and not forecasts, trigger production. JIT takes its name from the idea of having materials arrive just when they are needed and not before or after (Meridith, 1987:392; Plenert, 1986:23). The "just-in-time" release of materials into the shop floor infers the use of small batch sizes. To make small batches economically feasible, setup times need to be reduced significantly. In addition a high level of preventive maintenance is required to reduce the need for buffer inventory. The JIT approach reduces much of the complexity of the scheduling environment. Instead of having to constantly decide what to work on first and how to schedule and synchronize the numerous work centers, the foreman and production worker need merely be concerned with working on whatever WIP is released to them.

TOC. Since this research is concerned with the application of TOC, it is necessary to have an extensive explanation as to this theory. Chapter IV of the thesis is dedicated to a detailed explanation of TOC.

The scheduling procedures are only a portion of TOC. TOC is primarily a system's approach to problem solving. The procedures which evolve from TOC, are the result of a systematic methodology rooted in experience, common sense, and intuition. The scheduling procedures for the manufacturing shop floor have similarly evolved from the TOC paradigm which is elaborated on in chapter IV. TOC claims that a synchronized, effective schedule is achieved by focusing management effort on the constraints in the system. Materials are only released on to the shop floor in accordance to the production rate of the system's constraint. An inventory buffer is placed in front of the constraint to protect the production flow of the constraint from disruptions. The protection of the constraint's production flow is critical since its production rate ultimately controls the entire system's production. By releasing less material onto the shop floor than is required to maintain the inventory buffer, the ultimate throughput of the entire production system is threatened by starving the constraint for work. By releasing more inventory than is necessary in order to protect the buffers, the system is unable to maintain a synchronized flow of materials throughout the plant. A synchronized schedule is achieved through focusing on the constraint's production capacity. All improvement efforts can only be meaningful if they are able to positively impact the productivity of the system's constraint.

Like JIT, TOC seems to have greatly simplified the scheduling environment. No longer is it necessary to decide which scheduling rule or what job should be worked on first for the numerous work center. The only work center that needs to be scheduled is the constraint work center. After the decision has been made as to the master schedule, materials are released on to the shop according to the capacity of the constraint and the length of the time buffer before the constraint. The remainder of the work centers, are left to work on what ever job is released to them in the order of their arrival. At times it will be necessary for management to interfere through expediting, however such involvement should be the exception rather than the rule.

TOC strength in terms of scheduling lies in its ability to provide effective, simple solutions that are capable of bridging the gap between a local action and its global impact. One of the major criticism's of the traditional scheduling rules is that they fail to achieve a system's perspective of a scheduling decision and instead are only capable of viewing the local impact of their decision which may or may not be in the interests of the organization as a whole.

Concluding Remarks

In concluding the discussion on scheduling it should be emphasized that many jobs shops are characterized by chaos, with jobs being typically late, large quantities of work-in-process inventory congesting the work areas, and schedules that are constantly rearranged through a bargaining process between production supervisors and expediters (McClain and Thomas, 1985:343). TOC sources claim to have largely overcome the difficulties of achieving an orchestrated job shop schedule through simplified procedures. This thesis examines this claim in detail as TOC relates to the operations of the IAF depots.

III. Methodology

The thesis research combined several methodologies: interviews with interviews with IAF personnel who are familiar with depot operations; an exhaustive literature review of TOC and current production scheduling theories; conducting an expe:iment based on a scheduling simulation model of the armaments depot; statistical analysis of the results.

The research can be classified into a number of areas.

The Literature Review

An extensive literature review of TOC was conducted to investigate the application of TOC to the depot scheduling environment. In addition to analyzing written material concerning TOC, the researcher attended a number of seminars conducted by The Goldratt Institute. In addition, extensive use was made of The Goldratt Institute's educational simulator programs.

Since the maintenance of weapon systems and their components in the depot can be classified as a job shop manufacturing process, the literature review included background on job shop scheduling.

Defining the Area of Investigation

Knowledge of the IAF's depot operations was collected in part as a result of past assignments. Assistance in defining the area of investigation was provided by IAF personnel familiar with the depot. This personnel included the former head of the armaments depot as well as the former head of the planning branch from the logistics HQ. The interviews were of an informal nature. The following subject areas were discussed: the planning, scheduling, and work flow of the depots; similarities and differences between the shop floor of the depot and a commercial manufacturing firm; the impact of scheduling on depot performance; similarities and differences between the depots; capacity constraint resource candidates. The lack of a rigid structure in the interviews both created opportunities to "tap" into new information as well as expose the research to bias (with the interviewer becoming a potential error source (Emory, 1985:93). To minimize the risk of bias the research relied on collaboration and cross reference of the information obtained from the interviews.

Documentation of the Work Flow

Informal interviews with IAF personnel were used to document the depot work flow. The documentation of the work flow served as an input to the construction of the scheduling simulation. Since the simulation was based on a simplified version of the armaments depot it was not necessary to use real data, but rather to use data that reflected the main elements of the work flow. The topics covered in these interviews were: routings, processing times, work centers capacities, requirements, and team sizes.

The Simulation Experiment

A simulation experiment was designed and conducted in order to investigate the application and merits of TOC to the scheduling environment of the depots. Simulation aids in the design of a system by evaluating the system's response to changes in its structure. It is an appropriate methodology to situations in which the size and or complexity of the problem makes the use of optimizing techniques difficult or impossible (Chase and Aquilano, 1985:444-445). It has proved to be particularly well suited for job shop environments which are characterized by complex scheduling problems. Such is the case in our research problem. The simulation was based on a simplified version of the shop floor of the armaments depot. The TOC scheduling rules were employed, and the output was compared to the output resulting from the employment of traditional scheduling procedures. The details of the simulation are outlined in chapter V. This section will confine itself to the methodology of designing and running a simulation. The following steps were covered:

1. The first step is to define the scope of the system, i.e. its boundaries and contents. The scope of the system

is a function of the purpose of the simulation (Pritzker, 1986:2). As part of the system's contents, the system's goal needs to be specified. Next, performance measurements need to be defined. These measurements are required to evaluate the effectiveness and efficiency in achieving the system's objective. Next controllable and uncontrollable variables need to be identified. The controllable variables will be the variables connected to the decision rules. Uncontrollable variables will include the processing times of weapon systems, the arrival time of weapon systems at work centers, the resources of a work center that are available to process a weapon system.

2. Constructing the model:

a. Determining the type of model used. Models are classified as being either discrete or continuous. A discrete model was chosen for the experiment. A discrete simulation occurs when dependent variables change discretely at specified points in simulated time, meaning that the system state changes discretely (Pritzker, 1986:52). The purpose of a discrete simulation is to reproduce the activities that the entities engage in and thereby learn something about the behavior and performance potential of the system (Pritzker, 1986:54). The advantage of using a discrete simulation is that it is process-oriented, meaning that it is a time ordered sequence of events that encompasses several activities.

b. Determining which properties of the system should be fixed (e.g. routings, work standards) and which should be allowed to vary through the simulation runs. A simpler model was constructed to begin with to accommodate debugging and to validate the model during trial runs. Once the program was tested, additional variables were added to make the simulation more representative of the complexity of the system under study.

c. Specification of the decision rules: These rules were the focus of the simulation study. The "drum-buffer-rope" approach constituted the decision rule used in the case of the TOC schedule. The decision rule were then changed to reflect the current traditional scheduling procedures of the depot.

d. Another task is the specification of probability distributions of the uncontrollable variables. On the basis of previous experience in production environments, an exponential distribution was used as an approximation of the real world scenario.

3. Computerizing the model: The computer language chosen was SLAM II. SLAM II is a powerful simulation language that is well-suited to the construction of discrete simulation models.

4. Running the model: Determining the starting conditions for the variables is a major tactical decision in simulation because of the potential for bias. Different approaches can be taken which were considered on the basis of the range of the output data expected (run till equilibrium; set period; till a sufficiently large sample is gathered) (Chase and Aquilano, 1985:453-454). It was decided to run the simulation until steady state was achieved.

Evaluating the Results

1. Statistical inference: Each simulation run provided observations for samples of results that were subjected to formal statistical analysis. A 95% confidence interval was constructed around each of the statistics of the samples. This method assessed if there was a statistically significant improvement in depot performance through the application of TOC scheduling procedures as compared to using the depot's current scheduling rules.

2. Internal validity: The simulation model is a key measurement instrument of the research and as such was tested for internal validity. The validity of this measurement instrument was viewed from two perspectives. First, did the model adequately predict a real world process? This is known as criterion-related validity. Secondly, did the objectives specified in the simulation

study (e.g. throughput in the form of standard maintenance hours) adequately reflect what is meant by good or bad performance of the depot? This validity test is known as criterion adequacy.

3. External validity: The simulation was a simplification process of one depot in the IAF. Can those findings be generalized for the other depots?

IV. The Theory of Constraints

Introduction

Given the Socratic style of the Theory of Constraints (TOC) writings, it is appropriate to begin this discussion with a question, "What is the definition of TOC?" More than one definition has been uncovered in the course of this research. Each definition cited below illuminates a different yet complementary side of this multi-faceted body of teaching. The Goldratt Institute, a private educational institution that promotes TOC, defines TOC as "an intuitive framework for managing an organization. Implicit in the framework is a desire to continually improve performance--to have a process of ongoing improvement" (Avraham Y. Goldratt Institute, 1990:1). Oded Cohen has taken an even broader approach, describing TOC as "an overall management approach for running a system" (Cohen, 1988:51). Schragenheim and Ronen (1989b:3) regard TOC as ". . . a comprehensive management methodology. It aims to focus on the crucial issues."

Cox and Blackstone, have utilized TOC to advance a management theory they call Resource Management which is described as:

> the effective scheduling and control of organization resources to produce a product or service which provides customer satisfaction and supports the organization's competitive edges and ultimately the organization's goals. (Cox and Blackstone, 1990:4)

Their definition emphasizes the necessity to focus all organizational efforts in achieving the organization's goals. Each of these definitions emphasizes different aspects of TOC. An all-encompassing definition is as follows: TOC is an intuitive framework for effectively managing a system. The presentation in this literature review is designed to illuminate this definition.

What will <u>not</u> be attempted in this review is to address the question of whether or not TOC is a theory in the strictest sense of the word. Rather than be concerned with what it is not, it is far more constructive to be concerned with what it is. Nor will the literature review try to determine to which academic discipline TOC "belongs." A broader integrated picture is missed in trying to categorize this body of learning. For the sake of reference alone TOC will be addressed within the confines of operations management.

Consider for a moment the name itself, the Theory of Constraints. Why did the TOC's founder, Dr. Goldratt, choose this name? Dr. Goldratt, who by training is a physicist, chooses his words carefully. The choice of this name sheds light on understanding the meaning of TOC. The central theme of Dr. Goldratt's approach is to focus on a system's constraint(s). Every "living" system is limited by one or more constraints. To break out of our inertia of thinking, we need to address those constraints through a highly focused methodology. Constraints may not necessarily be physical. The constraints in most organizations involve policies and a resistance to change. The constraint can be in thinking, in believing that there is a conflict when in fact there is none. It is particularly this constraint in the thinking process, that Dr. Goldratt spends considerable energy addressing.

TOC is a contemporary addition to the body of operations management, with its beginnings being as recent as the late 1970s. Since then it has continued to evolve, with many of its procedures being hailed as major breakthroughs by practitioners and academics alike. Its greatest impact has been in the scheduling of the shop floor of an increasing number of U.S. firms, including such names as Ford, General Electric, General Motors, Westinghouse, and RCA (Melton, 1986:13).

The approach to be used in presenting TOC is to initially familiarize the reader with the paradigm of TOC--what Dr. Goldratt refers to as the thinking process. Using the paradigm as a foundation, the review will address some of the very powerful procedures that have evolved from the thinking process and have proved themselves on the shop floor. There is not always a clear distinction between the paradigm and the procedures in the minds of those that have had some exposure to TOC. This distinction is needed to appreciate the power of this theory and its ability to develop unconventional effective solutions to longstanding problems.

Historical Background

The beginnings of TOC are traced backed to Israel, in the early 1970s, in a setting far removed from the environment of the manufacturing plant. Eli Goldratt, a physicist, applied a technique for predicting the behavior of a heated crystalline atom. This technique was later adapted to optimize a large number of variables in a manufacturing environment. A computer scientist helped program the procedure, and a small business, Creative Output Limited, was established in Israel in the late 1970's to market the product (Melton, 1986:13). The primary product of Creative Output Limited was a software scheduling package known as Optimized Production Technology (OPT). The software evolved in the span of a few years reflecting the evolution of the thinking process of synchronized manufacturing. Initially the package began as a computerized Kanban and eventually evolved to the computerization of the Drum-Buffer-Rope technique (Goldratt, 1988:443). Even though the schedules were reported to be feasible and accurate and could be run on a computer in a fraction of the time that an MRP system took, OPT failed to have a large success in the market place. Among the reasons for OPT's lack of success was the absence of a concerted effort to disseminate to the market the thoughtware behind the software. Instead, any potentially interested company was presented with a "black box" that it was expected to trust. Even though the software package was reported to produce excellent results, the "black box" image of OPT together with its half a million dollar price tag, was enough to discourage the interest of many potential users. To quote one critic:

> One must pay up to $500,000 for a system whose operation is a mystery and hope that it works as claimed. . . . . It is difficult to trust ones production facilities to a system whose mechanics are a guarded secret. (Melton, 1986:13,19)

In light of OPT's lack of general acceptance, Dr. Eli Goldratt shifted the emphasis of his efforts to the development and dissemination of the thoughtware that today constitutes the mainstay of TOC. The Avraham Y. Goldratt Institute was formed by a nucleus of unconventional, zealous, industrial practitioners and theoreticians, including the senior partners Bob Fox and Eli Goldratt. Even though one of the main aims of the Institute is to develop and promote TOC's thrust of continual improvement for all types of organizations, most of its efforts have been directed towards the commercial manufacturing environment.

In addition to the ongoing seminars and workshops of the Institute, a number of TOC works have been published in recent years. *The Goal*, published in 1984, has had a tremendously wide success with over 500,000 copies sold as of May 1990 (Goldratt and Fox, 1990:back cover). Part of book's success is attributed not only to its powerful message of the need for continual improvement and how to begin achieving it, but also to its totally unconventional style. Classified by the publishing community as a business book, it is written in the first person as a novel in which the main character Alex Rogo is given three months to turn his plant around while at the same time trying and save his marriage. In the course of his struggle he meets Jonah, the thinly-disguised alter ego of Eli Goldratt, who through the Socratic approach, assists Alex in finding his own solutions. The reader is drawn into the plot, personally experiences the same intuitive, common sense, thought process that TOC endeavors to develop. During that "experience," the reader gains a sense of ownership of the ideas developed, which is one of the primary reasons behind writing of *The Goal* (Goldratt and Fox, 1986:146).

Following *The Goal, The Race* was published in 1986. The objective of *The Race* was to provide the manufacturing organization, in particular the shop floor, with more detailed procedures than was presented in *The Goal*. The last book to be published *Theory of Constraints*, returns the reader to the fundamental thinking process that is at the heart of TOC. Quoting from the book:

> *The Goal* provided brilliant simple solutions when what is really needed is the process that will enable management to generate such solutions on their own. Moreover, *The Goal* may have highlighted, but certainly did not address, the major problem of changing the nature of a company. Changing it to the extent that change itself will become the norm, not the exception. (Goldratt, 1990a:x)

In addition to these three works, the Goldratt Institute periodically publishes a journal whose aim is to provide a sequel of thoughts to *The Goal*. The focus of the journal is on Alex's two problems, namely what to change and how to cause the change. Each edition contains two articles dealing with these subjects. The existence of the journal is testimony in itself of the evolutionary nature of TOC.

Dr. Goldratt will be soon release his next work, entitled *The Haystack Syndrome*. This book lays the theoretical foundations of The Goldratt Institute's partially developed decision support system *Disaster*. *Disaster* is an enhanced scheduling software package that will be discussed in detail later. Dr. Goldratt and his associates have learned well from past experiences. Disaster is only being released after considerable effort and thought have been put into preparing the managerial cultural changes that a potential user of is required to adopt.

The selection of the name *Disaster* is interesting in and of itself. Should an organization use this package without having made the necessary managerial cultural changes induced by TOC, then the program would spell disaster for that organization.

Before discussing cultural changes provoked by TOC, the methodology's paradigm needs to be introduced.

The Paradigm

The purpose of the paradigm is twofold:

1. To precipitate the individuals ability to create a vision of the broader solution to his/her system's problem.

2. To harness that individual's ability to translate that vision into effective, practical procedures. These procedures are referred to by Eli Goldratt as the "leg on the ground" (Goldratt, 1990b).

Defining the Goal. Inherent to the paradigm are a number of steps. The first step is to define the system's goal. By definition all living systems--an organization or an individual--must have a goal, a purpose. Why does TOC place such importance on defining the goal? The effectiveness of any decision or action can only be judged by its impact on the system's goal. Since our concern is the improvement of performance it now becomes obvious the requirement to define the system's global goal.

Performance Measurements. Of course, it is not enough to simply define the goal to determine the effectiveness of our actions. Performance measurements provide the bridge between an action and its impact on the system's goal. Normally the impact on the goal of any system can be judged through more than one set of measurements. TOC requires more than simply measurements from performance "measurements". What is sought are measurements that not only can be used to judge the attainment of the goal, but also direct the system's action towards the attainment of that goal (Goldratt and Fox, 1988b:13).

The three measurements postulated by TOC that meet the above criteria are throughput, inventory, and operating expense. The reader may be surprised by these three terms since they conjure up the image of measurements that are used for a commercial manufacturing organization. Up to this stage in the discussion it has been emphasized that the purpose of building the paradigm is to provide a universal framework. When Goldratt uses these terms in the context of the paradigm he is referring to them in a universal sense. Later, in the procedures that are developed for manufacturing, these terms take on a literal meaning. These terms are defined generically follows:

1. Throughput: The rate output is generated by the system.

2. Inventory: The inputs to the system that are eventually transposed into outputs.

3. Operating expenses: The resources needed to convert the inventory into throughput.

The terms output, input, and process are not new and are often used to describe the process flow of any system. What is new in Goldratt's approach is the manner in which he elevates these terms so that they are used not only as classifications of the elements of a process but in also as measurements and guidelines to improved performance.

It is difficult to prove that the three performance measurements in their universal sense are appropriate for all systems. In the later discussion on the procedures of a manufacturing setting, the appropriateness of these three measurements is easily demonstrated. However, this application only validates but does not prove the universal application of these measurements. Their universal application is assumed. This assumption is in fact the only assumption made in TOC. The strength of this assumption should not be underestimated since, according to Goldratt, everything else in TOC is derived logically from that assumption (Goldratt, 1990a:28).

Focusing on the Constraints. Up to this point the paradigm provides a methodology for determining the impact of our decisions as well as some guidance on the type of decisions required to perform better. What is still missing is a means to better focus a company's efforts. In any system there is normally a multitude of variables that can be changed. How do managers decide where to focus their attention to make the most significant change, and, once having determined the variable of interest, what is the right change to make? The key to opening the door of this puzzle is in the recognition of the important role of the system's constraint(s).

The term constraint is defined as ". . . anything that limits a system from achieving higher performance relative to its goal" (Schragenheim and Ronen, 1989a:4). The constraint becomes the key to controlling the system's performance. This key operates in two ways:

1. The most obvious way is by "breaking" the constraint to elevate the system to a new level of performance. 2. A more subtle approach, and one which has more powerful implications, is to "exploit" the constraint. It is clear that thinking in terms of processing an input (i.e. inventory) through a process so as to obtain an output (i.e. throughput), that throughput is controlled by the rate of the constraints capability to process. The exploitation of that constraint would in part mean ensuring that there is always input to work on, otherwise throughput is lost. This insight is the meaning behind Goldratt's claim that an hour

of production lost at a bottleneck[1] is in fact an hour lost for the entire system. In terms of a manufacturing plant the cost would be that of the entire plant, being idle for a whole hour (Goldratt and Cox, 1984:157-158). Another important aspect of exploitation of the constraint is ensuring that the constraint processes only those inputs that need to worked on. If the constraint was being used to its full capacity but was processing what needs to be processed in the distant future at the expense of what is required now, then clearly the constraint is not being correctly exploited.

Since the key to improved performance is to focus on the constraints, it would defeat the purpose of this strategy if there were many constraints in the system. As it turns out the opposite is the case. In Goldratt contends that no system can survive with too many interacting constraints (Goldratt and Fox, 1989a:6-14). Hence, by definition, living systems are characterized by few constraints. Traditional management has intuitively recognized that there are very few elements of an organization that actually

[1]A bottleneck is defined as any resource whose capacity is less than the demand placed upon it (Chase and Acquilano, 1989:799). In the earlier writings of OPT, the constraint was expressed in terms of capacity with such terms as bottleneck and capacity constrained resource. In today's writings the more universal term constraint is used since not all the constraints are in the form of capacity and the same paradigm is used regardless of the type of constraint.

control the output. Pareto's law (Chase and Acquilano, 1989:605), the 20/80 rule, is testimony to this belief. According to TOC, however, the "true" Pareto ratio is closer to .1/99.9, meaning that just a fraction of a percent is responsible for almost all the end result. The implications of such a reduced ratio is far-reaching, allowing managers to tremendously simplify solutions to what have traditionally thought off as being intractable. The scheduling world is one such problem. With this new insight on the reduced ratio of controlling factors on a system's performance, it is now possible to greatly improve the output of a system by focusing the improvement effort on a fraction of the system's variables, namely the constraints.

Statistical Fluctuation and Dependent Resources. In order to have a clearer understanding of how constraints have occupied such a leading role in the formulation of TOC, it is important to deliberate on the statistical phenomenon Goldratt refers to as statistical fluctuations and dependent resources (SFDR). Every process is subject to variation or fluctuations. The act of transferring inputs into outputs creates a dependency between different resources or elements of the system and develops a system of dependent resources. In almost every system, and certainly in all organizations, these two phenomena exist (Goldratt and Fox, 1989a:6). The fact that they exist together is what creates so much havoc in the operations of organizations, causing traditional management to constantly resort to "fire fighting" in order to maintain some semblance of product flow.

An illustration of this statistical phenomenon will assist in making it more concrete. Take the scenario of a job shop floor. Typically, what is observed is a difficulty to meet due dates of orders; not because materials weren't released on time to the shop floor but rather because of work in process (WIP) being "stuck" at some work station that is processing WIP of a lower priority. The every day occurrence of such scenes can not be simply dismissed as incompetence on the part of the worker, foreman, or scheduler. Normally what has occurred in a traditionally well-scheduled plant is that WIP was in fact scheduled to arrive at a certain work station "A" after having been processed by an earlier work station "B". There exists a dependency between the work stations. The assigned WIP did not arrive as planned due to process variation at the earlier work station "B" (e.g. a machine broke down). Since other WIP was available to work station "A", even though it was less urgent, work station "A" began processing this less urgent WIP. When finally the originally scheduled and now urgent work arrives at the work station "A", the dependent resource, it waits in line for the less urgent WIP to be finished. Since there are hundreds if not thousands of WIP operations on the shop floor at any one time, no control system has yet been designed that is capable of constantly reassigning priorities to work stations before a problem is created. The reassigning of priorities is normally the result of a problem already encountered.

Goldratt has described in his writings *Gedunken* experiments[2] that illustrate the damage caused to the product flow of a process due to SFDR (Goldratt and Cox, 1984:102-109; Goldratt, 1989b:6-13). What these simple yet seemingly powerful experiments demonstrate is that through the existence of SFDR, nearly every process, including the shop floor, that introduces inventory (i.e. inputs) into a process, is hampered by a buildup of WIP between work stations, a slowdown of throughput (which in the manufacturing environment is translated as missing due dates), and an increase in operating expense.[3]

In *The Goal* the description of the hike was used to show again the damaging impact of SFDR. In this case Throughput is described as the rate at which the last hiker completes

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[2]A Gedunken experiment is a technique commonly used among physicists, meaning literally a "thinking experiment". The idea behind this term is that an experiment, tnat is typically simple yet logically sound, is constructed so as to validate or refute an assumption. Goldratt, himself a physicist, uses the term in his seminars (Goldratt, 1990b)

[3]All three terms, inventory, throughput, and operating expense are used in their universal sense.

the trail, inventory is the amount of trail between the leader and the last person in the troop, and operating expense is the energy that is expended in catching up to the rest of the troop (Goldratt and Cox, 1984:96-101). The hike is meant to be more than an analogy. It shows the universal application of the TOC concepts that go far beyond the processes of the manufacturing shop floor.

Having clarified SFDR, it is appropriate to examine its implications for TOC. Only after one has understood the underlying cause of a problem can he progress to a solution. SFDR explains why the performance of even traditionally well managed systems is impeded. That insight, together with the knowledge of the critical role played by constraints, enables construction of seemingly simple, effective, common sense solutions. There should be allowed into the system only an amount of Inventory that is required to buffer the constraint against probable disruptions that could "starve" the constraint of work. By focusing our attention on managing mainly the constraint to protect it against the disruptions of SFDR, an apparent workable solution to better performance is achieved. The solution to the problem of product flow becomes vastly simplified. This solution is the cornerstone of the scheduling procedure known as buffer management that will be dealt with in more detail in the section on procedures.

Another implication of SFDR for TOC is that the resulting damage of SFDR ensures that the number of interacting constraints in any system is very few. In one of Goldratt's *Gedunken* experiments it was demonstrated that as the number of interacting constraints increase there is a exponential growth of WIP in the system with a corresponding rapid decline in throughput. The results are so devastating that they prevent any system from being able survive such as situation (Goldratt and Fox, 1989a:6-13). In terms of a manufacturing environment, interacting constraints cause a flood of WIP on the shop floor which limits the ability to meet due dates. With so much capital tied up in standing inventory and the loss of revenue from missed due dates, Goldratt concludes that this situation will eventually leads to bankruptcy.

> Since we are dealing with organizations that exist, we must conclude that at least one of the assumptions in our little example does not exist in reality. What is left to remove besides the assumption that we are dealing with interactive resource constraints? (Goldratt and Fox, 1989a:14)

The main point that should be learned from Goldratt's illustration is that living systems cannot tolerate any more than a very limited number of interactive constraints.[4]

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[4]Even though Goldratt's suggestion is that there can never be interactive constraints, one should be wary to accept that as an absolute. In reality there are systems, such as shop floors, that do have a limited number of interactive constraints. When that is the case management is inevitably considerably occupied with "fire fighting".

With this conclusion, the practitioner of TOC can feel confident that his efforts to improve his system's performance need mainly be focused on a limited number of constraints thereby simplifying considerably effective management.

Ongoing Improvement. The need for ongoing improvement is a central tenant of the TOC paradigm. All living systems exist within a dynamic environment. Failing to adapt to the changes of this environment will eventually spell disaster. The only way to ensure not only growth but also survival is through instituting a process on ongoing improvement. Much of TOC's focus has been directed specifically to the U.S. manufacturing firms. The environment that these firms are placed is dynamic. According to TOC, failure to continually improve has spelled the end of many U.S. firms as well as the loss of markets of entire industries. The importance of ongoing improvement in this environment is passionately presented in *The Race*:

> The marketplace today is more crowded, faster-changing and more fiercely competitive than at any time in history. Industrial manufacturing is witnessing an intensification of the race for market-dominance: the life-cycles of products is shortening; zero-defects is becoming the goal of quality; new machine technology is being introduced each year and systems to control production replace each other at an unprecedented rate. What was once relatively gradual change has in recent years turned into a race of exponentially increasing intensity. Those unable to continually improve are falling behind, since success in this environment requires more than a one-time investment. . . . Clearly, something far greater than a few sporadic improvements is

> now needed. Indeed the only way to secure and improve one's competitive position today is by instituting a process of ongoing improvement. (Goldratt and Fox, 1986:144)

It is no coincidence that the Goldratt Institute uses the term Jonah to describe those participants who have completed training in TOC with the Institute. Just as Jonah was the successful agent of change from the Old Testament, so it is hoped that these new "Jonahs" will be successful agents of change in their respective organizations.

The Five Steps. The reader has been introduced up to this point in the presentation with some of TOC's key concepts. What is lacking though, is a framework that will direct the power of TOC's concepts. The five focusing steps are meant to provide that framework (Avraham Y. Goldratt Institute, 1990:2). The five steps are summarized as follows (Goldratt, 1990a:7):

1. Identify the system's constraints.
2. Decide how to exploit the system's constraints.
3. Subordinate everything else to the above decision.
4. Elevate the system's constraints.
5. If in the previous steps a constraint has been broken, go back to step 1, but do not allow inertia to cause a system constraint.

Elaborating on these steps (Goldratt, 1990a:5-6; Fox, 1989:47-52):

1. Identification: Care should be taken to avoid allowing trivial points to attract our attention. Ranking the constraints is required in the case of several constraints.

2. Exploitation: Since the constraint controls the rate of the system's throughput it is essential not to waste its capacity.

3. Subordination: The focus of the management effort is on the constraints. The implication of this effort for the non-constraints, which is the majority of the resources, is that they should only input the amount of inventory that the constraint itself can process. To produce any more than that is wasteful since it can not be processed by the constraint. Furthermore any additional output from the non-constraints will endanger throughput by clogging the product flow with WIP that is not required in the time period of operations.

4. Elevation: Since constraints are not acts of nature over which we have no control, there are always improvements that eventually "break" the constraint.

5. Go back to step one: According to TOC advocates, one of the greatest difficulties in applying TOC is inertia. It would appear that many times when a constraint is broken, management fails to review those policies which at the time

they were written made sense. These policies in turn become system constraints.[5]

In the earlier writings of OPT reference is made to the "Nine Rules of OPT." The underlying principles for rules are included in the more generalized procedure of the five focusing steps.[6]

Even though the logic of the five focusing steps is based on common sense, it can be argued that there is a tendency to ignore steps two and three when confronted by a constraint. Typically in a manufacturing setting it can be heard that the only way to boost production is with additional investment in resources. One of the major strengths of the five focusing steps is that the procedure opens up solutions of improved performance through a focused reshuffling of existing resources without having to incur additional expenses.

The Process of Change. The five focusing steps uses the terminology of the system that TOC is trying to improve. As powerful as these steps are, they are insufficient to ensure a process of ongoing improvement. For this reason the

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[5]The problems posed by policy constraints is demonstrated in The Goal. The oven and the NCX-10 didn't lack the capacity required to supply the demands. Alex didn't have to buy any additional capacity. All that was required was to change some of the production policies in his plant (Goldratt, 1990a:6).

[6]For details on the nine rules refer to Cohen, 1988, pages 57 to 62.

methodology of the process of change (i.e. what to change, what to change to, and how to change it) is introduced to provide a framework for dealing with change. This change process complements the five focusing steps, using the terminology of the improvement process itself (Goldratt, 1990a:75-76; Avraham Y. Goldratt Institute, 1990:2).

1. What to change? Management efforts should be focused on the core problems. Often there is a tendency to address what we feel most familiar with rather than what actually needs to be addressed.

2. To what to change? Solutions should be simple and practical. TOC has an aversion to complicated solutions, claiming that the more complicated a solution is the less chance it has of succeeding.

3. How to create change? Since we are dealing with people, it is expected that this step will be difficult to achieve. Interestingly enough much of the operations management and certainly nearly all of the management science literature ignores this topic even though it is clear that every solution to a system's problem involves the human psychology of the system. Goldratt, recognizing the importance of this issue, devotes considerable space to this topic in his most recently published work *The Theory of Constraints* (Goldratt, 1990).

Goldratt "sets the stage" to his proposed solution by taking the reader on a path of logical progression which is summarized as follows:

> Any improvement is a change. Leading to: Any change is a perceived threat to security. Leading to: Any threat on security gives rise to emotional resistance. Leading to: Emotional resistance can only be overcome by a stronger emotion. (Goldratt, 1990a:10-11)

The stronger emotion that Goldratt refers to is the emotion of the inventor a sense of ownership. No one expects to come up with inventors but rather to instill the emotion of the inventor among key individuals in the organization. That emotion is achieved through the Socratic method. Through this method the pupil is not given answers but rather is intellectually provoked through the master's questions at arriving at the solutions himself. Once this is achieved the pupil is endowed with the powerful emotion of the inventor, the emotion of ownership. Had the pupil been given the answer it is not only unlikely that he would be enthused with the emotion of the inventor but it is also unlikely that he would have implemented the solutions provided.

In the writing of *The Goal*, Goldratt hoped to imbue his reader with this sense of ownership. He wanted the reader to identify with Alex, his pressures from in and outside the office, with his groping for solutions, and most importantly with the emotional charge of finding an answer (Goldratt and Fox, 1986:146-147).

The other critical ingredient to implementing change in any system that is made up of a group of individuals is to gain group consensus. This idea in fact was part of the motivation behind writing *The Race* (Goldratt and Fox, 1986:149). Quoting from *The Race*:

> . . . merely presenting the appropriate rules and procedures to a group will not ensure their acceptance. Such a presentation needs to include the entire step-by-step derivation of this approach. Consensus will be reached only if this derivation starts from a generally agreed-upon picture of the situation . . . and proceeds using very precise, well defined arguments, making sure that no gaps or even perceived flaws leave an opening for misunderstanding. The logic must be so strong that it is perceived as common sense. (Goldratt and Fox, 1986:149)

There will be those who challenge Goldratt's lack of scientific rigor in the behavioral sciences. Goldratt reached his conclusions concerning the psychology of change based on his own experience and common sense. Even though this approach would be challenged in most academic circles, at least Goldratt addresses, an area that is so often sorely avoided by operations management, and certainly management science theoreticians. Organization theorists have always contended that those who propose solutions that involve people must address the issue of the human psychology of change.

<u>Techniques</u>. In Goldratt's latest published work *The Theory of Constraints* (Goldratt, 1990), he explains

techniques that assist those who wish to acquire the ability to think outside of their existing systems so as to be successful agents of change.

Goldratt's premise is that nearly all of us have the potential to find solutions to what are traditionally thought of as insurmountable barriers that hinder the progress of our systems. What is required from us is to verbalize our intuition. Quoting Goldratt:

> We grossly underestimate our intuition. Intuitively we do know the real problems, we even know the solutions. What is unfortunately not emphasized enough, is the vast importance of verbalizing our own intuition. As long as we will not verbalize our intuition, as long as we do not learn to cast it clearly into words, not only will we be unable to convince others, we will not even be able to convince ourselves of what we already know to be right. If we don't verbalize our intuition, we ourselves will do the opposite of what we believe in. We will just play a lot of games with numbers and words. (Goldratt, 1990a:3)

Three techniques are emphasized in TOC that assist one in his ability to verbalize intuition: Effect-Cause-Effect, Evaporating Clouds, and the Socratic method. Throughout all of Goldratt's writings these methods are employed as a matter of course. Each technique will be discussed in detail.

1. Effect-Cause-Effect: A technique, commonly used in physics, for finding core problems by verbalizing our intuitive sense of problems and their causes (Avraham Y. Goldratt Institute, 1990:2).

The way this technique works is to hypothesize the cause of a phenomenon. The investigator looks for solid evidence of other effects that are the logical extension of the initially hypothesized cause-effect relationship. The more effects that can be logically predicted and verified, the more powerful is the theory. More often this procedure results in the cause itself being regarded as an effect, thereby activating the question "what is its cause?" This process gives rise to a logical tree that explains many vastly different effects that grow from a single root cause (Goldratt, 1990a:32). Examples of this technique being put to use are illustrated in the "Visit" articles in the Institute's journal (Goldratt and Fox, 1987; Goldratt and Fox, 1988b; Goldratt and Fox, 1988a; Goldratt and Fox, 1989a Goldratt and Fox, 1989a; Goldratt and Fox, 1990).

An implication of being able to explain the core reason behind a problem is that it provides a building block from which to construct a solution that addresses the root cause of a problem rather than dispersing our efforts to attack symptoms of that root cause. Only after a problem has been correctly analyzed can it be properly addressed.

This understanding of the "why" a phenomena occurs is what Goldratt refers to as the highest stage of science. According to Goldratt, there are three distinct stages that every science has gone through: classification, correlation, and effect-cause-effect.

> The first step was always classification. There are often some practical applications from this stage but the major contribution is usually to create the basic terminology of the subject. The second step --correlation--is usually much more rewarding. It supplies us with procedures that are powerful enough to make some practical predictions about the future. . . . . But the most important stage--the one that is by far more powerful because it enables us to create things in nature--is the stage of effect-cause-effect. . . . . Only then does the question WHY bring into the picture the demand for a logical explanation. (Goldratt, 1990a:26)

2. Evaporating Clouds: The essence of this technique is to state a problem as a conflict and to proceed to isolate the assumptions to be challenged. When a faulty assumption is found, the problem disappears (Avraham Y. Goldratt Institute, 1990:3).

A good starting point to resolving a perceived conflict is to clearly state the problem. The defining of a problem properly must start with a declaration of a desired objective. Since we are facing a perceived problem that involves at least two competing needs, there must be at least two requirements involved to satisfy the objective. Since a conflict is perceived to exist there must be at least one thing that is competed for by the requirements. Either there isn't enough to share of whatever is needed, or, in order to satisfy the requirements the system is required to do conflicting things. Put more formally; to satisfy the requirements a prerequisite exists and it is within the framework of the prerequisites that the perceived conflict arises (Goldratt, 1990a:38).

After having defined the problem the next step of this technique is to verify the objective. According to Goldratt, too often we fool ourselves by struggling with problems that arise from trying to satisfy local objectives that do not match at all the global goal. In fact many of these local objectives can be at the expense of the global goal. For example resource utilization in a manufacturing plant environment. If the resource is a non-constraint we could unnecessarily build up WIP which is to the detriment of the overall goal of profit. Hence one of the first steps in the method of evaporating clouds is to verify the objective (Goldratt, 1990a:44-45).

After the objective has been verified, one proceeds to question the assumptions behind the perceived conflict. It is important realize that there are assumptions underlying one's perception of the conflict. The agent of change needs to question these assumptions (using Effect-Cause-Effect) until a suitable break of logic is revealed. By eliminating one of the assumptions the conflict vanishes and, in its place, takes a solution that potentially represents a win-win situation.

The classical economic batch quantity issue is a good example. Here the problem presents itself in trying to find the an optimal tradeoff between setup costs and carrying costs. An assumption that can be questioned is that setup costs are fixed. JIT has amply shown this assumption is false. All setups cost money is another assumption that can be proven to be false. In the case of the constraint resource the cost is not in operating expense but a decrease in throughput. In the case of a non-constraint there is no real cost to the extent that this resource is not turned into a constraint. With the breakdown of these assumptions the entire problem dissipates. What we are left with is a realization that there is no conflict of batch size but rather a distinction between process batches and transfer batches, whose sizes are determined by common sense. Small transfer sizes are used to reduce carrying costs and lead time as well as to provide greater flexibility to the scheduling of resources. Where setup time is significant, larger processing batches are used for constraint resources to protect throughput. Hence we see that the two prerequisites of reducing carrying costs and setup can be simultaneously satisfied thereby avoiding any conflict of prerequisites (Goldratt, 1990a:40-51).

The Evaporating Clouds technique takes a very different approach to traditional problem solving. Traditional solutions involve compromise by relaxing the requirements. What is a tolerable compromise is often called an optimum solutions. Consider the EOQ problem outlined above. The traditional optimum solution is a compromise on the size of the batch without regarding the distinction between process batch and transfer batch. Clearly the term optimum can be very misleading. If the requirements are real, any relaxation of them, by definition, reduces our ability to satisfy the objective (Goldratt and Fox, 1988b:3-4).

A different approach is opened up when it is realized that there is at least one underlying assumption behind each perceived conflict. Often these assumptions are erroneous or irrelevant in which case the corresponding arrow will no longer exist. By eliminating even one arrow the conflict simply vanishes. The problem is not just solved, it evaporates. This new perception significantly increases our ability to satisfy the objective over and above what was previously perceived possible.

Unfortunately such solutions are generally sporadic and rare. The challenge is to make them routine through a systematic approach outlined above. The key to that systematic approach is to verbalize the problem and the assumptions using the above format, and to make extensive use of the question "Why" (Goldratt and Fox, 1988a:4-5).

The Evaporating Clouds technique together with Effect-Cause-Effect provide a means of transposing what is perceived as being complex to what is, under TOC, far less complex. This reduction in complexity is achieved through a continual reduction of assumptions. What were originally perceived as independent events are in fact common events that can be subsumed under a common assumption. What originally appeared to be overwhelmingly complex is reduced to two sets of requirements whose prerequisites are in conflict. By questioning the final assumptions we "break" the conflict and reach an alternative solution.

Even with this technique one should not be misled into thinking that the "evaporation" of conflicts is an easy task. The most difficult part of this technique is to challenge the assumptions to the point that one of them is exposed as invalid. At times a "leap of faith" in this theorem is required so as to have the determination to seek a win solution and prevent reverting to compromising the requirements (Goldratt and Fox, 1988b:5-6).

3. The Socratic method is the third technique. This method was introduced in the discussion on how to implement change. It can be summarized as a technique for causing others to "invent" or discover answers and thereby engender ownership in them (Avraham Y. Goldratt Institute, 1990:3).

The discussion up to this point has dealt considerably with the TOC paradigm while purposely avoiding entering into any of the details of the procedures produced from the paradigm. Even though the specific problem that this thesis addresses is a scheduling problem, an area in which TOC has developed detailed procedures, the thesis can only do just service to this topic through presenting initially the paradigm through which TOC operates. The reason for this approach is best summed up by Goldratt:

> There are two distinct paths that companies can take in implementing the Theory of Constraints. One approach is to implement the procedures that have been developed. Excellent results typically are realized very quickly followed almost inevitably by a levelling off of improvement and stagnation. *The Goal* is a story of the procedure path. A second approach is to follow the thought process path. Results may occur somewhat more slowly at the start, but they then accelerate well beyond the procedures approach. Stagnation is avoided and a real process of ongoing improvement results. (Avraham Y. Goldratt Institute, 1990:3-4)

Procedures

Most of the procedures have been developed for profit-oriented manufacturing firms from the U.S. The more detailed procedures address the scheduling problems of the shop floor; in particular the complicated scheduling environment of the job shop. The discussion of TOC procedures will follow the same thought pattern that was presented in the explanation of the paradigm.

The Goal. Using the paradigm as our model, the first step to developing "a leg on the ground" (i.e. maintaining contact with reality) is to define the organization's goal. TOC writings have been consistent in their definition of the goal for commercial organizations, namely that their goal "is to make money in the present as well as the future" (Goldratt and Cox, 1984:10).

Performance Measurements. With the goal having been defined the next step is to define performance measurements for the firm.

The traditional measurements used by companies are net profit, return on investment, and cash flow. To be sure that the goal is in fact being achieved all three measurements need to be examined. Net profit is an absolute measurement. Even though this measurement is necessary, by itself it is not enough. What is needed is a relative measurement as well such as return on investment. Of course no company can exist without liquidity, so cash becomes a necessary condition (Goldratt and Cox, 1984:46-47).

Even though these measurements together give a clear indication of whether or not a firm is making money, are these measurements really adequate? Looking back on the earlier discussion in the paradigm, what is lacking in these measurements is their ability to bridge the gap between local actions, such as actions on the shop floor, and the global goal of the firm. The measurements that bridge that gap are throughput, inventory, and operating expenses. Goldratt and Fox (1986:29) provide the specific definitions of each of these terms are as follows:[7]

1. Throughput: the rate at which a system generates money through sales.

2. Inventory: all the money that the system has invested in purchasing things that it intends to sell.

3. Operational expenses: all the money that the system spends in order to turn inventory into throughput.

In order to determine the effectiveness of an action or the soundness of a decision, all three measurements need to be viewed simultaneously, i.e. to increase throughput while decreasing inventory and operational expenses (Goldratt and Cox, 1984:59-61). It is important to emphasize that every operation of the plant should be evaluated in terms of these performance measurements.

Many illustrations can be found in the TOC writing of the effectiveness of these performance measurements as a bridge between local actions on the shop floor and the global goal of a firm. In *The Goal* for example, Alex, the plant manager, is questioned by Jonah concerning the effectiveness of having introduced robots on to the shop floor. Initially

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[7]Even though the specific definitions are a derivation of the universal definitions, the reader should not confuse the two.

Alex was certain that the introduction of the robots was a wise investment. After all, there was a 36% increase in production which, by traditional cost accounting methods, meant a decrease in cost per part. Jonah proceeds to ask Alex three very simple yet insightful questions: Was there any decrease in inventory? Did operating expenses in the plant go down? Where any more products sold? The answers to all these questions were no! In terms of bottom line measurements the firms position was no more closer to its goal than before the introduction of the robots. In fact the introduction of the robots took the firm further away from its goal by introducing untimely WIP onto the shop floor, thereby further complicating what was already a chaotic scheduling situation on the shop floor (Goldratt and Cox, 1984:28-30).

In light of these new measurements, productivity is redefined. No longer is it measured in terms of output per labor hour, but rather "all the actions that bring a company closer to its goals" (Goldratt and Cox, 1984:32). What TOC attempts to do, is to realign management with common sense. The performance measurements are help management see through the fog of the of the financial "number games", to have a focused look at the impact of their actions on the global goal of their firm.

The definition of these bottom line performance measurements differs from the traditional cost accounting definition of these terms. Expanding on the earlier definitions:

1. Throughput (T) is measured by the money generated by the firm and should not be confused with sales. It is sales minus all the money paid per item to entities which are external to the system (i.e. purchased materials, money paid to sub contractors, royalties to an outside patent holder) (Goldratt and Fox, 1988a:6)

2. Inventory (I) does not consider any value added from the system itself, not even the direct labor used to produce the products. TOC claims that the approach of avoiding value added is a straightforward way of overcoming misleading traditional financial measurements associated with "inventory profits"[8] (Goldratt and Fox, 1988a:6-13).

3. Operating Expenses (OE) in TOC terms makes no distinction between what is traditionally regarded as fixed costs and variable costs, nor does it distinguish between overhead and direct costs. Since all these expenses are outlayed for the same purpose, namely converting inventory into throughput, any distinction only acts as a cost

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[8]The value added calculated for the WIP and finished inventory is considered by traditional cost accounting as an expense that is transferred to the next financial period thereby improving the profit picture for the present financial period.

accounting smoke screen. It is this smoke screen that misleads decision makers into thinking that expenses are investments that go on to be treated as assets. Such confusion in thinking arises through what TOC calls the "imaginary entity" of product costing (Goldratt and Fox, 1988a:13).

These new definitions account for all the items of the firm that can have a dollar value assigned: assets, liabilities, expenses, and revenues. The application of these definitions require a break from the traditional cost accounting classifications. The following examples clarify this point: Machine depreciation is now regarded as an operating expense and whatever portion that remains that can be sold is inventory. Carrying costs become an operational expense. Knowledge can either be an operational expense or inventory depending on what it is used for--if it provides a new manufacturing process then it turns inventory into throughput and as such it is an operational expense; if knowledge is to be sold, as in the case of a patent, then it is inventory. It is intended that these examples clarify that the TOC classification comes down to common sense (Goldratt and Cox, 1984:73-75).

The discussion on performance measurements up to this point has dealt with their definition and how they are used as a bridge in determining the effectiveness of local action on the global goal of the firm. The assumption has been that there is a logical link between the performance measurements T, I, OE, and the firm's global goal of making money. That assumption needs to be validated. It is already accepted, among the business community and business management academic circles, that there is a logical link between the three financial measurements (i.e. net profit (NP), return on investment (ROI), cash flow (CF)) and the global goal of making money. TOC validates the link of its performance measurements T, I, OE, through demonstrating a logical link between its performance measurements and the traditional financial performance measurements. Using a basic rule of logic:

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if   f(NP,ROI,CF) = global goal
&    f(T,I,OE)    = f(NP,ROI,CF)
then f(T,I,OE)    = global goal
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Oded Cohen offers an concise, comprehensible presentation of the link between T, I, OE, and NP, ROI, CF (Cohen, 1988:55-56).

As T goes up there is a corresponding positive impact on NP, ROI, and CF. If OE can be reduced without harming T and increasing I, then by the same logic used for T, all three financial measurements will be improved.

The full impact of lowering I is, however, not so direct. What is clear is that a decrease in I, without adversely affecting T and OE, will improve ROI (investment decreases) and CF (less cash is tied up). There is also an indirect link through the reduction of carrying costs which in turn lowers OE. However there is another indirect link which has far greater implications on the financial performance measurements, namely the impact through future throughput and to a lesser extent through OE.

The future throughput of a company is determined mainly by its ability to compete in the market. According to TOC, the competitive edge race among manufacturing firms is being fought in the areas of product (quality, engineering features), price (higher margins, lower investment per unit), and responsiveness (due date performance, shorter quoted lead times) (Cohen, 1988:55-56; Goldratt and Fox, 1990:8). The impact of lower inventory on each of these competitive areas should be explained in greater detail:

1. Quality: In a low inventory environment, when damage is detected, a relatively short period of time has elapsed since the damage was caused. The implications of this shortened time period are that it is easier to trace the source of the problem and rectify it; fewer products are damaged; fewer replacement parts are required; managerial efforts are freed to finding the root cause of the quality problem rather than being preoccupied with expediting as is the case in a high inventory environment (Goldratt and Fox, 1986:44).

2. Engineering features: Engineering changes are an increasingly common occurrence in the production life cycle of today's commodity. In a low inventory environment it is relatively simple to release the improved product to the market at an earlier date than what would have been the case in a high inventory setting. The normal reaction in a high inventory setting is to delay implementation of the changes until the present production run is completed, which in turn delays the release of the improved product to the market. Should management decide to scrap and rework the product, the expenses of a high inventory setting would certainly outweigh the expenses of a low inventory setting (Goldratt and Fox, 1986:48).

3. Higher margins: High inventory means long production lead times since WIP inventory and production lead times are really the same thing. If a competitive factor in the market is delivery time, then the firm with low inventory will be able to minimize having to expedite to meet due dates, which in turn means less overtime, thereby less operational expense, and higher margins (Goldratt and Fox, 1986a:50-52).

4. Lower investment per unit: In a high inventory environment, the end of the month syndrome[9] causes a peak

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[9]By this it is meant that there is a surge of product at the at the final operations that must be processed in the last week of the month in order to meet monthly quotas.

load on the capacity of machine resources and facilities. This phenomena is particularly true for the machinery and facilities involved in the last operations, even though the existing capacity is often several times higher than the average loads. The tendency in this scenario is to purchase more capacity. However by managing a low inventory environment, the load of the last operations is more uniformly spread and as such the firm is able to better handle expediting, if it occurs at all, without investing in additional resources (Goldratt and Fox, 1986:54-56).

5. Due date performance: It is a common complaint among plant managers that failure to meet due date performance is by and large out of their control. The primary reasons attributed to a deficiency in responsiveness are unreliable vendors, and customers changing their demands at short notice. However plants can impact these "outside" forces. WIP inventory has a strong impact on due dates via product forecast. A high inventory results in longer lead times which in turn is longer than the valid forecast horizon of the industry. As a result, the high inventory company's production plans are based more on guesses than reliable forecasts. Under these conditions it is expected that customers orders will differ from the production plans. The plant in turn changes its vendor requirements at short notice such that vendors cannot deliver in time. However

the scenario would be the opposite should production start with a valid forecast which is made possible by shorter lead times that result from low inventory (Goldratt and Fox, 1986:58-60).

6. Shorter quoted lead times: It was stated earlier that WIP inventory and production lead times are directly related. By lowering inventory, quoted production lead times can be similarly lowered, which in turn offers the firm an additional competitive edge (Goldratt and Fox, 1986:62-64).

In the earlier discussion of the paradigm's performance measurements, it was noted that one of the purposes of effective performance measurements is to guide the system as to what actions should be taken for improved performance. In the above presentation on the impact of T, I, OE on the global goal, it begins to become evident that a relative ranking exists among TOC performance measurements. Even though there should be a concerted effort to simultaneously increase throughput (T) while decreasing inventory (I) and operating expenses (OE), the priority of actions is to place T first followed by I and finally placing OE in last place.

The TOC ranking stands in contrast to the traditional priority of actions. According to traditional standards, OE is ranked in first place, followed by T, with I barely receiving attention. TOC explains traditional management's preoccupation with OE as being a derivative of the cost accounting procedures that strongly influence the decision-making process. Cost is after all operating expense. Cost accounting procedures focus on the tangibles, i.e. costs, that are under management's control. Throughput on the other hand is an intangible that is less controlled by management. There is a natural bias among people to focus on what they are most familiar with (Goldratt and Fox, 1990:6-7).

TOC readdresses that ranking of the three performance measures. It isn't enough to just examine short run improvements that result from cutting expenses. The firm needs to be concentrating on those actions that provide the greatest opportunity for improvement in the long run. Throughput provides those opportunities. In the long run the avenues of reducing inventory and operating expenses provide only a very limited number of opportunities (just how much can one save?) Throughput on the other hand, presents no limits (Goldratt, 1990a:91). As for the ranking of inventory before OE, traditional management has failed to recognize the immense impact that lowering of I has on the bottom line measurements by way of throughput and operating expense. This impact has been demonstrated above, showing that reducing inventory provides more opportunity than what is provided by directly lowering OE.

The simultaneous achievement of increasing T while lowering I and OE, or at the very least not worsening the position of I and OE relative to the improvement of T, could appear to some to be an unlikely accomplishment. Taking the issue of inventory alone, there could appear to be a perceived conflict. On one hand we would want to retain inventory in the system to protect current throughput against SFDR; on the other hand the above discussion elaborated on the benefits of reducing inventory for future throughput. How can this perceived conflict be resolved?

Employing the techniques that were presented in the paradigm, the first step to solving this conflict is to clearly state the problem using the evaporating clouds technique.

Rather than trying to solve the problem through compromising the requirements, TOC attacks what it claims to be the erroneous foundations of the traditional cost world that gave rise to the problem in the first place-- namely, that the shop floor is made up of independent variables.[10] By assuming that the shop floor is comprised of independent variables, one is led into believing that the only way to protect the current throughput is by buffering all the work centers with WIP inventory to protect the product flow from

[10]The widespread practice of product costing is testimony to the belief by traditional management in their mistaken assumption of independent variables.

the havoc caused by SFDR. At the same time though, it has been demonstrated above how high inventory levels compromise future throughput.

TOC refuses to accept the assumption of independent variables. In place of this assumption, TOC views the firm, including the shop floor, as a collection of dependent variables. In the case of such systems their higher performance is only contained by a very limited number of constraints.

> Putting Throughput to be number one forces the realization that our organizations operate as an assemblage of dependent variables. . . . In the configurations of dependent variables, the Pareto principle takes the form of 0.1/99.9 rule. Just a fraction of a per cent is responsible for almost all the end result. (Goldratt, 1990a:124)

Since the constraints of the firm control its performance, they in turn become the main tools of management, replacing the traditional tools of product cost. TOC's solution of what this author calls "constraint management," not only evaporates the problem of inventory size but appears to provide an overall solution to improved performance. By recognizing the critical role played by the constraint, it only becomes essential to buffer the constraint's throughput with high WIP inventory to protect the firms throughput from SFDR. As for the non-constraints, process inventory levels can be kept to a minimum without damaging current throughput. The additional capacity inherent in the non-constraints must be sufficient to absorb any disruptions to the product flow caused by SFDR. Since the non-constraints are the vast majority of work resources, future throughput is enhanced. The details of this procedure, outlined in the next section, are of particular interest for this research since they have a direct application on the scheduling of the shop floor.

Synchronized Manufacturing. Synchronized manufacturing, as defined by TOC, is any systematic way that attempts to move material quickly and smoothly through the various resources of the plant in concert with market demand (Goldratt and Fox, 1986:70).

Those familiar with the harsh realities of scheduling, particularly job shop scheduling, may question being able to successfully implement a synchronized schedule. In a typical manufacturing facility, management is confronted by a multitude of complex interacting variables that must be considered when constructing a schedule. Routings, set-up times, lot sizes, run times, tooling, maintenance, schedule delays, changes in personnel, changes in customer demands, are just a few of the variables that management has address.

TOC has developed a procedure that appears to overcome the barriers to achieving synchronized manufacturing, producing simple, workable, and effective schedules for the most difficult of scheduling environments, the job shop.

Constraint management is the foundation on which TOC generates the "leg on the ground" called drum-buffer-rope (DBR). The essence of this technique is as follows: The production rate of the constraints serves as the "drum beat" for the entire plant. A inventory "buffer" is placed in front of the constraints to protect the throughput of the plant against disruptions. A "rope" is then tied from the constraint to the first operation in the manufacturing process in the plant (referred to as the gating operation). The rate at which the gating operation will be allowed to release materials into production will be dictated by the rate at which the constraint is producing (Goldratt and Fox, 1986:96-102).

Schragenheim and Ronen provide an insight to dynamics of DBR as being an application of the first three steps of the five step process that was explained in the paradigm of TOC (Schragenheim and Ronen, 1989a:12-13). Applying the three steps:

1. Identification: Since the performance of firm, and for that matter the schedule, is controlled by the constraint the first step is to identify the constraint. A straightforward way to indicate the existence of a problem is to calculate the accumulated demand placed on each of the resource centers relative to their capacity. Providing that the data are correct, the constraint should manifest itself

in the form of large quantities of WIP in front of the suspected constraint.

2. Exploitation: In terms of the DBR schedule, this step means a number of things. To gain the maximum productivity, a constraint should never be idle. A capacity constrained resource that is almost a bottleneck should be utilized up to the point that market demand is satisfied. In order to protect the throughput of the constraint from being starved of work, a protective inventory "buffer" is constructed in front of the constraint. It is filled up by the required processing time of the sequenced WIP. Naturally its content changes continually over time as materials are processed. Other "buffers" may need to be constructed after the constraint to prevent WIP that has been processed by the constraint from being delayed to the extent that due dates are missed. Maximum productivity also means that the constraint is being utilized on the most profitable product mix. Where the market is the constraint, efforts should be taken to ensure that at the very minimum all due dates are meet. These efforts would include the construction of a finished goods buffer.

3. Subordination: Since the schedule is focused on the exploitation of the constraint, the efforts of all the other work centers (non-constraints) need to be directed in support of that exploitation. Raw materials required by the

constraint need to be released on time to arrive at the inventory buffers as scheduled. The timely release of raw materials onto the shop floor is achieved by controlling the "gating operation". It is equally important that raw materials are not released prematurely on to the shop floor. Prematurely releasing materials on to the shop floor can have a disastrous effect on product flow. Work centers inevitably find themselves working on jobs that could be postponed, while other jobs that are needed to meet due dates, are left unnoticed waiting in line before the busy work centers. Such scenarios are avoided through applying the principle of subordination.

To appreciate the simplistic effectiveness of DBR, as well as to understand how to build DBR schedules, further elaboration is required. The definition of the components drum, buffer, and rope, can now be better understood in light of the above explanation.

1. Drum: Defined as the exploitation[11] of the constraint of the system. The evocative name emphasizes the fact that the constraint dictates the overall pace of the system (Schragenheim and Ronen, 1989b:3). The drum will include in most cases a detailed schedule, meaning a list of products

[11]The same meaning as step two of the five step process outlined in the paradigm.

and their quantities in priority that are processed by the constraint.

The importance of the drum should not be underestimated since it dictates the schedule for the entire shop floor. The release of all materials onto the shop floor (their timing and quantity) is dictated by the "beat of the drum" (i.e. the production rate of the drum's schedule). The release of raw materials in turn drives the activities of the work centers. The scheduling rule for the non-constraints is simple--work on whatever jobs are in front of you. Non-constraints being idle will be a logical result of the DBR schedule.

2. Buffer: Defined as the amount of protective time against disruptions to the schedule. The protection is expressed in time units, since the parts are planned to reach the protected area some time before they are scheduled to be processed (Schragenheim and Ronen, 1989b:3-4).

Goldratt refers to the causes of disruptions to the schedule as Murphy. There are two types of Murphy - one is statistical variation of the process (examples are breakdowns, absenteeism, fluctuations in setup times); the other is the instant non-availability of non-constraint resources (i.e. the resource is busy with another job). Goldratt suspects intuitively that the dominant of the two for most manufacturing environments is the non-availability of non-constraints (Goldratt, 1990b).

The time buffer must be large enough to protect the throughput of the plant against any reasonable disruption that can be overcome within the predetermined time interval (Goldratt and Fox, 1986:98).

TOC identifies three types of buffers (Schragenheim and Ronen, 1989b:4):

1. The constraint buffer: WIP is expected to wait a certain amount of time in front of a capacity constraint, thus protecting the planned schedule of the constraint. The constraint buffer is the most critical buffer of the three types. Should the buffer be inadequate to protect the throughput of the constraint, the result is an irreversible loss of throughput for the entire firm.

2. The shipping buffer: Finished products are expected to be ready to be shipped a certain time before due date, thus protecting the due dates.

3. Assembly Buffer: WIP which is not processed by a constraint, but needs to be assembled with the constraint WIP, is expected to wait a certain amount of time in front of the assembly before the constraint's WIP arrives. The buffer itself is located prior to any assembly operation which joins constraint parts with non-constraint parts. The reason for this buffer is that the constraint's WIP carries

all the capacity investment, hence it should be protected from delays at the assembly point that could result in missing due dates.

3. Rope: The rope is a mechanism to force all the parts of the system to work up to the pace dictated by the drum yet no more than that pace. The way this mechanism works is to backward schedule from the buffer the release of all materials into the shop floor (Schragenheim and Ronen, 1989b:4).

Constructing the TOC Schedule. DBR provides the guidelines for constructing a TOC schedule for the shop floor. The TOC schedule is vastly different from the traditional scheduling attempts. The most noted difference is its simplicity. Rather than trying to schedule everything, as is traditionally done, TOC builds its schedule around the constraint, with only a very limited number of variables on the shop floor coming into play. The development of the schedule requires four steps:

1. The master production schedule (MPS) is determined. If the market is the constraint for a product then clearly there is no problem to determine the MPS, which is in effect the due dates of that product. The picture is different if there are orders for products whose aggregate load creates a capacity surge on a shop floor resource, to the extent that the shop floor resource becomes a constraint. For the sake

of simplicity these products are referred to in this study as "constraint products". What is clear from this scenario is that the firm will be unable to meet all its due dates without "elevating" the constraint (for example overtime or sub-contracting). If management is committed to the due dates, the MPS is in effect the due dates. On the other hand if there is a question of having to choose between orders given the capacity constraints of the firm, then the firm should give preference to those products that contribute most to the firm's profits. TOC calculates profit contribution very differently from the traditional methods. The details of TOC's method will be reserved for later in this presentation. For the present only the conclusion is presented, which states that preference should be given to those products that have the highest profit margin per constraint unit of processing time.

2. The constraint's schedule is constructed. This schedule consists of product type and quantity in accordance with the MPS (details shortly follow).

3. The buffer time lengths are determined (details follow).

4. The materials release schedule is calculated in accordance to steps two and three.

For the purpose of presenting the mechanics of the schedule in greater detail, a distinction is drawn between the schedule of a "constraint product" and a "non-constraint product."

Scheduling the "constraint product":

It is essential that the constraint resource is properly loaded; meaning that all of its available capacity is effectively utilized to the extent that it satisfies market demand (as reflected in the MPS).

The difficulty for the constraint schedule is in determining the sequence of jobs (i.e. product type and quantity) to be loaded onto the constraint. Basically, common sense is the best guideline. Firstly you should only schedule an amount of material for the constraint that can be sold within a reasonably reliable forecast horizon. Generally the sequence will commence with WIP that has already been released onto the shop floor in front of the constraint to provide enough time for the system to build up a sufficient constraint buffer. As for the remaining work, due dates will normally provide a good first cut to sequencing the jobs.[12] A few additional words should be made

[12]Due dates will provide normally a "reasonable" first cut. However there are exceptions that can complicate the sequence: different lead time from the capacity constraint resources to due dates; one capacity constraint resource feeding another one ; setup considerations on the constraint resource may lead to combining orders for the same product type to reduce capacity waste due to set up changes; where the constraint resource is processing more than one part for the same product, then due date will not be a guide to sequencing for those parts since they have the same due dates (Goldratt and Fox, 1986:110).

about setups. Ideally the sequence should aim at minimizing the number of setups on the constraint, while at the same time not unduly affecting the flow of materials through the system. By this statement it is meant that there is a trade off in system performance by having too small or too large a process batch loaded onto the constraint. By having too small a process batch, the frequency of setups will "eat into" the already limited capacity of the constraint resource. However, what isn't generally recognized, is that by having too large a process batch there is the risk of transforming non-constraint resources downstream from the constraint (i.e. after the constraint in terms of process flow) into constraint resources. The transformation of non-constraints into constraints results from the overall process flow being focused for too long on one product. There can be other work stations downstream from the constraint, that are only activated if there is work to do on products other than the product from the large batch. The resources of these work stations are eventually transformed into constraints as a result of remaining idle for too long.

After the sequence of the jobs has been decided, a time schedule for the constraint is constructed. The available work time for the constraint is known. The time of each job, including setup, is also known. All that is required to construct the constraint's time schedule is to fill the constraint's available capacity with the processing and setup times of the sequenced jobs.

The timely release of materials on to the shop floor is critical to the success of the shop floor schedule. The schedule for the release of materials is a function of the constraint schedule and buffer sizes. Tracing the logic of the release of materials for a single job will illustrate the details of the mechanics of this schedule. The job's commencement time on the constraint is used as a base line. From that base time is subtracted the constraint buffer time. This now provides the ideal time that the WIP for that job should be in place waiting. The entire lead time required to process the WIP from the moment that it is released until reaches the constraint buffer should then be subtracted from ideal arrival time to the constraint buffer. It is this final calculation in time that provides the release of materials schedule for that job. This logic of backward scheduling is repeated for each of the jobs processed by the constraint to provide the entire schedule for the release of materials.

In backwards scheduling to meet due dates, the timing of release of material may need to consider the existence of an assembly buffer. If that should be the case then the same backward scheduling that was applied to the job that went through the constraint is likewise applied to a job that needs to wait in an assembly buffer. Note that the initial base line time for a job from which it is backward scheduled, is in fact the same initial base line time for the job at the constraint that is feeding the same order.

The schedule of the release of materials for the constraint together with that of the assembly buffer constitute the entire release of materials for the shop floor.

No further calculations are required for scheduling constraint products. Note in particular that there is no need to provide detailed schedules for the non-constraint activities, apart from the gating operation. It was pointed out earlier that non-constraints are activated by having work placed in front of them. There is simply no need to have detailed schedules. The DBR logic ensures that whatever is placed in front of them needs to be worked on urgently (but without panic) to support the throughput constraint. Using DBR logic seems to vastly simplify what is traditionally thought to be the "nightmare" of job shop scheduling. Only a very limited number of schedules need to be calculated. What is more, even that limited number of schedules is a derivative of one schedule, namely the constraint schedule. The implication of the DBR logic is that the entire shop floor schedule is driven by the constraint schedule.

The scheduling section above only addresses a constraint product. What scheduling logic and mechanics are used for a non-constraint product? The term non-constraint product refers to the case where the constraint for the shop floor is the market. That is to say, production has no capacity limitations in fulfilling market demand.

In this scenario, the logic of DBR remains exactly the same as the processing of a constraint product. The "drum beat" is market demand. It is equally important to have a buffer in front of that constraint to protect throughput, which is committed sales. A rope needs to be tied to a gating operation to ensure the timely release of materials on to the shop floor for processing. The mechanics of constructing the schedule are similar to logic used in the constraint scenario. Instead of a constraint buffer though, a shipping buffer is constructed. An assembly buffer is not relevant for a non-constraint product. The release of materials schedule is backward scheduled from the shipping buffer and is calculated using the same backward scheduling logic as was applied in the constraint scenario.

Up to this point buffer size has been assumed without explaining how it is determined. The purpose of the time buffer is to protect throughput from the negative effects of

SFDR. The larger the time period the greater the protection.[13] Initially, the length of a time buffer is based more on a "gut reaction" rather than any scientific method (Schragenheim and Ronen, 1989a:20). If one does not feel comfortable with this approach, a more scientific methodology can be used; namely that the buffer size should be more than three times an average lead time to the buffer (Schragenheim and Ronen, 1989a:21).

This approach however is not the end of the "story". TOC provides what seems to be a very useful heuristic for validating what should be the buffer length. The heuristic is based on approximating what TOC refers to as a buffer profile. There is expected to be a difference between the actual and planned contents of the buffer as a result of variance in the process. If there is no difference, hence no variation, then there would be no need for a time buffer and the firm would save on unnecessary inventory. It is the profile of the difference between the planned and the actual WIP in the time buffer that is the key to determining the buffer's size. By differing the size of the time Buffer the Buffer profile also differs.

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[13]This statement is true up to a point. A time buffer that is too long can in fact damage throughput more than it protects it. This phenomenon is elaborated on further in the text.

In order to gain a picture of the profile of the difference between the planned and actual WIP in the time buffer, TOC arbitrarily divides the buffer length into three regions. Using those regions as base lines, the desired profile is as follows (Goldratt and Fox, 1986:122-127): In the first third of the time buffer (i.e. region one), the material that is to be consumed next by the constraint should always be there. In contrast, one would expect to find that most of the material planned for the last third of the buffer is missing. The actual versus planned contents of the middle third of the buffer (i.e. region two) should lie somewhere in between these two extremes. It is this buffer profile that should protect the organization's critical operations from all but the most extreme fluctuations. The size of the time buffer is varied until the above profile is approximated.

It would be naive to think that even with the above buffer profile achieved, that "holes" in region one will not occur and that it will not be necessary to expedite. No matter what length is assigned to the buffer, there is always a probability that the forces of SFDR will be disruptive enough to cause holes in region one that will require management to expedite jobs. The difference with DBR is however, that management need only contend with fighting the occasional fire which is quickly contained.

Without DBR it seems that traditional scheduling results in management continuously fighting fires that are not always controlled and end up consuming the greater part of management's efforts. This leaves very little opportunity for management to exercise its proper role, namely dealing with improvement.

It needs to be recognized that there is a point of negative return in terms of throughput when the buffer length is extended beyond a certain size. The occurrence of diminishing returns can be explained. The increase in buffer size means an earlier release of materials onto the shop floor. In the event of an earlier large release of material, resources will inevitably at times be occupied processing jobs that could be deferred, while other more urgent jobs end up having to wait to the extent that throughput is jeopardized.

The application of the buffer size heuristic need not necessarily wait until DBR is implemented on the shop floor. A simulation could be used of the shop floor employing DBR to determine the effective buffer length.

The basics of implementing a DBR schedule have been presented up to this point. With that there are a number of additional considerations that could further enhance the effectiveness of a DBR schedule.

1. Control points: There is a need to pay attention to jobs that process common parts for two or more products. A control schedule needs to be constructed that will direct the correct number of processed parts to the prioritized product routing.

2. Quality Control: Inherent in synchronized manufacturing is excess capacity except for the constraint. If a defective part is produced upstream of the constraint, the result is that there will be a loss of material. Because of the excess capacity and buffer inventory, there is still time to do another operation to replace the one just scrapped. For the constraint however, since excess capacity does not exist, there should be a quality control inspection <u>just prior to the constraint</u> to ensure that constraint capacity is not wasted by processing defective parts. Furthermore, preventive actions need to be taken downstream from the constraint to prevent wasting any parts that have been invested with constraint capacity. Any defective part that has been processed by the constraint represents lost throughput (Chase and Acquilano, 1989:812).

3. Sequencing procedure for non-constraints: Earlier it was written that part of the simplification of DBR is that there is no need to build schedules for non-constraints since the DBR logic ensures that whatever materials reach a non-constraint resource needs to be processed without delay.

However problems can arise when competing jobs arrive at a non-constraint resource. A sequencing procedure needs to be formulated for the shop floor. Several alternatives can be used, however, there is no single procedure which will always guarantee the best result in terms of protecting throughput. Management will always need to expedite jobs on occasion regardless of what procedure is used.

3. Batch sizing: The impact of batch sizing on the performance of the firm, and particular on the success of the schedule has been discussed in several different contexts during this presentation. Because of the importance of this variable a focused overview is appropriate. The distinction between transfer and process batch has already been mentioned. The advantages of a smaller transfer batch are less WIP, faster product flow, consequently reduced lead time, and inventory investment. The disadvantage of smaller transfer batches, though, is increased material handling. Where the transfer batch is subject to change, management will need to determine the size in accordance with the performance measurements. What is clear that a decision as important as this one, should not be left to the fork lift driver, which unfortunately seems to be the case in many shop floors.

The size of the process batch also involves trade-offs. While a larger process batch saves on setup time, smaller process batches help facilitate product flow through the early activation of work centers that process different product types. In general, larger process batches will be more critical for constraint resources. Non-constraints, by virtue of having excess capacity, will be able to employ smaller process batches to support product flow without inflicting the disadvantages normally associated with such a policy.

Scheduling Controls. The successful implementation of any schedule requires the design and activation of control mechanisms. Control itself can be exercised either internally or externally. By internal it is meant that the workers themselves on the shop floor exercise the necessary self control. External control, on the other hand, requires the involvement of management to initiate and direct corrective action. TOC makes use of both these controls.[14]

Internal control (Goldratt, 1990b; Cox and Blackstone, 1990:12-14; Chase and Aquilano, 1989:816-817): TOC facilitates the exercise of internal controls through local performance measurements, in which what is being measured at the local level is performance to schedule. There are two types of deviation that can adversely effect schedule

[14]The use of the terms internal and external control were not found by this author in any TOC writings. However, the use of these labels are appropriate to clarify what is inferred by TOC.

performance--namely some action was meant to have been done yet it wasn't; some action was not meant to have been done yet it was. The unit of measurement used is dollar days. What this measurement captures is the <u>total amount</u> of damage caused by deviating from the schedule, since it considers both the dollar amount of damage as well as the length of time that the damage was sustained. For each of the types of deviation a different dollar day measurement is applied:

1. Inventory dollar days: It measures actions that should not have happened but did. The measurement is based on the value of the inventory and the time it stays within an area. By applying inventory dollar days as a local performance measurement, any work center or department should be motivated not to release material prematurely into the system inventory that can't be transformed into throughput. It has already been explained in DBR methodology just how critical the timely release of materials onto the shop floor is to have a successful schedule. Timely release includes not releasing too early. Examples of its use include the discouraging of traditional current practices that TOC deems damaging, such as: the high utilization of equipment irrespective of whether or not it is a constraint; purchasing materials on the basis of quantity discounts; using EOQ as the basis of batch sizing.

2. Throughput dollar days: It measures actions that

should have happened but didn't. The measurement is based on the selling price of the product times the number of days that an order is late. The construction and monitoring of the inventory time buffers provides the initial information required to know if a job is late. With this timely information, management can immediately trace back to the source of the problem. Where the result is a missed due date, then the original source of the problem is penalized with throughput dollar days. By applying this performance measurement, local work centers should be motivated to immediately process WIP that has arrived at their work station, which, after all is what a DBR schedule demands. In order for this measurement to be fair, the original schedule itself has to be workable. The assumption is that DBR provides a workable schedule to begin with, otherwise it is not only unfair, but damaging to the firm, to measure performance on what can't be performed.

External control: The TOC definition of control in this context is "having the knowledge of where things are versus where they are supposed to be, and who is responsible for any deviation" (Goldratt and Fox, 1988a:15). The application of this control is no easy matter. In general a simple comparison between the planned and actual state of performance is not practical due to the enormous data collection that is required to be done frequently. Even if it could be collected, it would be too degrading on management to make intelligent conclusions from the lists of deviations collected (Schragenheim and Ronen, 1989b:2).

TOC's solution to what seems to be an effective and simple exercise of external control is buffer management, "a diagnostic tool which is a shop floor control methodology" (Schragenheim and Ronen, 1989b:2). In essence, buffer management operates through monitoring the profile of the time Buffers to discriminate between disruptions to the schedule's performance. Through monitoring the "holes" in the Buffer regions, that represent parts that have not arrived, management is provided with a warning devise to determine the necessity to expedite jobs behind schedule. The size of the hole represents the amount of disruption to the schedule. The position of the hole in the buffer profile represents the length of time remaining until the schedule is damaged. Both those pieces of information are made available through the application of DBR.

In general, holes that occur in region three (i.e. the region most distant from the constraint) will be disregarded. Holes in region two call for locating the missing part. In most cases management will refrain from expediting since there should frequently be some holes in this region if the buffer size is correct. Management should only interfere in those cases where a mistake is revealed that can damage the schedule. Holes in region one are what threaten throughput. Expediting is immediately required for the missing job (Schragenheim and Fox, 1989b:12).

The logic of how buffer management operates seems straightforward enough. The buffer management layout accumulates all the disruptions, delays, and faster than usual operations into one map. The assumption is that parts missing from region one can be expedited in time to protect the schedule. After all those missing parts have been monitored by management since their appearance of a hole in region two and should have been located (Schragenheim and Fox, 1989b:13).

There is nothing inherent to buffer management per se that demands the need for computer technology. The need for a computer is a function of the size and complexity of the data base of the shop floor, which, although interfaces with the principles of buffer management, is a separate issue. Where computer technology can certainly assist is in the presentation of the information used by buffer management. Schragenheim has developed educational simulation packages that portray pictorially information in a buffer management format. The following figures are examples of the buffer profile developed by Schragenheim:

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```
Time in   60| C1 C1 C1-C1 C2 C2 C2 C2-C1-C1
minutes     | C1 C1 C1-C1 C2 C2 C2 C2-C1-C1
          45| C1 C1 C1-C1 C2 C2 C2 C2-C1-C1
            | C1 C1 C1-C1 C2 C2 C2 C2-C1-C1
          30| C1 C1 C1 C1-C1 C2 C2 C2-C1-C1
            | C1 C1 C1 C1-C1 C2 C2 C2-C1-C1
          15| C1 C1 C1 C1-C1 C2 C2 C2 C2-C1
            | C1 C1 C1 C1-C1 C2 C2 C2 C2-C1
            -----------*---------*---------*---
              1  2  3 *4  5  6 *7  8  9 *10
                      *        *        *Time in hours
              Region  *Region  *Region  *
              one     *two     *three   *
                      *        *        *
```

Figure 1. Constraint Buffer Profile (Schragenheim and Ronen, 1989b:9).

In the Constraint Buffer profile the display of a negative sign indicates a missing WIP(i.e. a hole). The labels C1 and C2 indicate the names of the operation that takes place at the constraint. In this case there are two different operations processed by the same constraint resource. The display of the constraint operation indicates the processing time of the WIP at the constraint. The format used by Schragenheim is not meant to reflect a TOC convention and is only a suggestion of a format that could be used.

Units										
16										
14										
12						B				
10						B				
8			-A			B			-A	
6			-A			B			-A	
4			A			B			-A	
2			A			B			-A	
	1	2	3	4	5	6	7	8	9	10

Time in hours (or days)

Figure 2. Shipping Buffer Profile (Schragenheim and Ronen,1989b:10)

In the Shipping Buffer profile, finished parts missing are indicated by a negative sign. An empty space means that no shipments are due. Taking the above figure as an example, eight units of product A are due to be shipped in three hours, but only four have been completed. In the convention that Schragenheim used, the shipping buffer does not have any processing time of its own. Because of this the rows in the shipping buffer layout represents parts and not time. The same is also true for the conventions used in portraying the assembly buffer.

The exercise of external control through buffer management offers a number of advantages:

management can only be implemented if DBR itself has been implemented on the shop floor.

2. The buffer management layout seems to allow management to easily see the impact of any disruption to the schedule in terms of its global ramifications on the firm's performance and not on its local ramifications which, after all, are argued to be not always in tune with the bottom line measurements of the firm.

3. The bottom line is that buffer management appears to provide an effective, relatively simple, "good enough", control solution. It achieves these results by directing management to focus its efforts where it really makes a difference. The remainder of the system, which is typically 90-95%, will run itself providing DBR has been properly instituted. This approach is a recurring theme in TOC.

Organizational Issues (Goldratt and Fox, 1987:1-16). The implementation of the procedures outlined for a manufacturing firm has wide ramifications on the firm's organizational structure. The organizational approach taken by TOC claims to solve one of the problems that has plagued organizational scientists for decades, namely what is the organizational structure that best supports the performance of an organization. The topic is presented through the evaporating clouds technique as was presented by Goldratt and Fox.

The enhancement of an organization's performance should be the objective of an organizational structure. A major problem that is encountered by all large organizations is span of control. As the numbers of the organization grow how does management successfully control it? An answer which dates back as far as the Bible is the use of a hierarchial pyramid structure. At the same time that management seeks a strong span of control, however, management also seeks a clear transfer of directives from the top down, as well as an undistorted comprehensible flow of information from the bottom up. It is here that a conflict of demands arises. The use of a hierarchial chain of command is achieved through intermediate links that introduce distortions in the two way flow of information. There is perceived to be an inherent conflict in the pre-requisites. The prerequisite to a strong span of control is the extensive use of the pyramid structure. On the other hand, the prerequisite to avoiding distortions in the informational flow is to suppress the use of the pyramid structure.

How can this conflict be resolved? Making use of the evaporating clouds technique we can "evaporate" the conflict through breaking one of the key assumptions that have led to this perceived conflict. A keystone assumption is that intermediate management distorts evaluations and informational flow is to suppress the use of the pyramid structure.

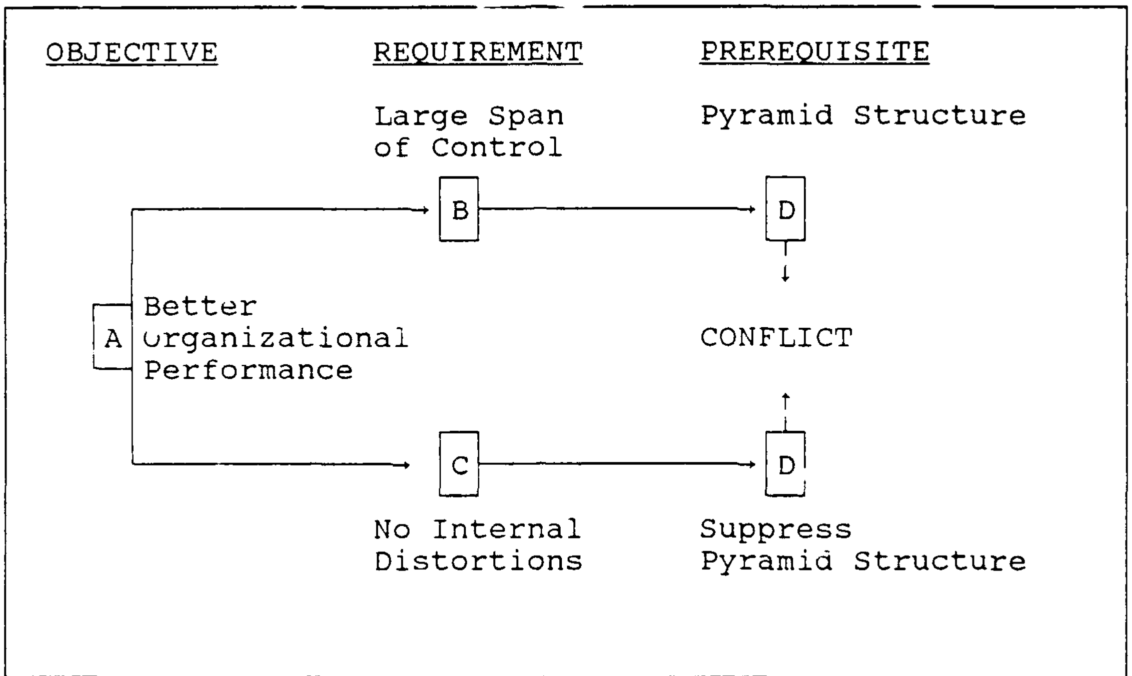

Figure 3. Evaporating Clouds presentation of the problem (Goldratt and Fox, 1987:3)

How can this conflict be resolved? Making use of the evaporating clouds technique we can "evaporate" the conflict through breaking one of the key assumptions that have led to this perceived conflict. A keystone assumption is that intermediate management distorts evaluations and interpretations because of their local rather than global points of view. However is that always true? TOC argues that it is true given the traditional performance measurements and cost accounting approach used in most firms. However, the developed procedures directed toward continuing improvement of the performance of the manufacturing firm. Just as DBR is the manifestation of the first three steps of the five-step process, the drive for continuing improvement is the manifestation of the the last two steps, namely elevation and the need to repeat the process after the constraint is broken.

In any system, including the shop floor, there are a limited number of variables whose improvement results in a significant improvement for the performance of the system as a whole. TOC's constraint orientation guides management to the limited number of variables whose improvement results in a global improvement. The improvements will either be on the constraint(s) or on non-constraint "trouble makers" whose improvement will allow the reduction of buffer size.

Expanding on improving non-constraint trouble makers, the key to identifying the source of the problem is through buffer management. A trouble maker is any cause of frequent holes in region two of a buffer (Schragenheim and Ronen, 1989b:15). The appearance of holes allows management to trace back the source of disruption(s), either a work center or vendor. Most likely the disruptive source is the work center or vendor that the part is sitting in front of awaiting processing. Through employing the logic of the local performance measurements, management is able to quantify the extent of the disruption caused by this source. Through quantifying the problem, a list of troublemakers according to priority is drawn up (Goldratt and Fox, 1986:128-130).

If in addition to holes in region two, holes frequently appear in region one, the buffer size should be increased. If this action does not improve performance than it is likely that there is an interactive constraint in the system (Schragenheim and Ronen, 1989b:15). TOC has recently developed an approach for dealing with interactive constraints. For now, it is adequate to take the approach that in the event of interactive constraints management will be forced to break one of the constraints. Until that occurs, expediting will be the short term answer.

It is not always easy to find the source of the disruption. Even though there is meant to be a high correlation between missing parts being in front of a work center and that work center being the source of disruption, this approach is far from foolproof. TOC provides additional insight through a methodology known as VAT analysis. According to TOC, nearly every process flow of a manufacturing firm can be categorized under one of the structures V, A, or T , or as a combination of the three categories. Each of these categories demonstrates certain general characteristics that help narrow down the investigation for trouble makers, and, for that matter, constraints.

Cox and Blackstone provide the following summary of VAT analysis (Cox and Blackstone, 1990:15-17):

1. V-plants consist of product structure networks where product divergence dominates. A primary problem in a V - plant is one of misallocation of WIP materials at a divergent point to the wrong finished product.

2. A-plants contain product structure networks where part convergence dominates. A primary problem of A-plants is the misallocation of work center time or capacity to the wrong part. All parts have to be at an assembly area for product assembly to occur. The misallocation of time to producing one part at any one center can disrupt the entire assembly schedule for a product.

3. T-plants exist where a large number of finished goods are assembled from common assemblies, parts and raw materials. A primary problem with T-plants is the misallocation of material at the final assembly stages of manufacturing.

The identification and "treatment" of non-constraint "trouble makers" leads to the reduction of time buffers, which means less inventory in the system . This in turn provides an additional competitive advantage (*vis a via* the earlier presentation of the advantages of lower inventory) that results in greater demand for increased throughput.

Since throughput is controlled by the constraint, management should examine all the possibilities of "squeezing" the full capacity from the constraint before incurring additional expenses through the purchase of more capacity. In *The Race* a list of quick, relatively inexpensive steps are mentioned. The constraint should always be manned, even during rest periods and change of shifts. Steps should be taken that so that the constraint does not work on defective parts. Operations after the constraint need to process constraint parts very carefully because every scrapped part represents lost throughput for the firm (Goldratt and Fox, 1986:136). Where feasible the manufacturing process on the constraint parts should be reviewed to reduce as much as possible the constraint processing time per part. Only after all the available capacity of the constraint has been feasibly exhausted, should the constraint be "elevated" by way of purchasing additional capacity.

With the additional capacity on the constraint obtained, throughput will increase to the point that a new constraint may emerge. Not only does a new constraint have to be dealt with, but management will also need to reexamine the issue of non-constraint trouble makers. The increase in productivity will reduce the excess capacity in the plant, decreasing the time available to recover from disruption. There will a pull towards increased buffers which in turn will need to be countered with ongoing improvement metric directed towards the non-constraint trouble makers. To continue the momentum of improvement, the firm needs to take the fifth step, namely to avoid inertia and to regroup its forces of change to address the new set of problems that have arisen. If the firm can successfully put itself into the loop of the five steps, it begins a journey on what TOC calls the "productivity flywheel". By this term it is meant that the momentum of improvement sets into motion forces that drive further improvement that in turn drive the improvement process to be repeated at a faster rate. An upward cyclical pattern of continual improvement is set (Goldratt and Fox, 1986:138).

A final point on the issue of the inertia to change. It would appear that policy constraints are what so often facilitate the inertia of resistance change. At the time that a policy was made it made good sense. Since that time the realities of the organization may have changed, but the policies have not always been changed accordingly. The larger the organization the larger the problem of having the control over the updating and checking for relevance of policies. According to TOC most of the systems of today limited mainly by policy constraints (Goldratt, 1990a:14).

The risk of inertia to change should not be underestimated, and it this risk that makes the ability to take the fifth step so difficult. The task of continual improvement is perhaps the most challenging task in the implementation of TOC.

Implementation

In Goldratt's most recently published book, *The Theory of Constraints*, the issue of implementing TOC was extensively addressed based on his personal experiences in implementing TOC in companies. Among the points raised is the need to have the commitment of the entire organization in order to assure the successful adoption of TOC by the organization. The first step is to convince top management. With top management's backing, a formal consensus is obtained from the organization as a whole. After this commitment is obtained, educational workshops are delivered to the key personnel of every department. The required level of education depends on the individual's function in the organization. Even though this across-the-board method of implementation may seem slow, Goldratt is convinced that it is necessary to significantly reduce the risk of failure. The greatest barrier to implementation is the natural emotional resistance by the organization's members where TOC is perceived as a threat to their stability. An across-the-board approach is aimed at placating that emotional resistance and eventually in redirecting that emotion to one of enthusiasm through the Socratic approach (Goldratt, 1990a:97-104).

The use of pilot studies is traditionally thought of as an acceptable way of "sowing the seeds" of a new management approach in an organization, particularly large organizations. The logic behind this approach is that by visibly demonstrating the success of a department or plant, then this new approach will be more readily accepted by the rest of the organization. Goldratt dismisses this approach. "Pilots, even though successful locally, are not helpful at all in moving an entire organization" (Goldratt, 1990a:97). The success of a pilot, according to Goldratt, will run then risk of alienating others in the organization. Those outside of the pilot will emotionally perceive recognition of the pilot's success as a criticism of their competency, even though logically this is not the case.

The use of TOC consultants is also addressed. The Institute encourages organizations to develop "internal Jonahs" as soon as possible; meaning people who are skilled in TOC and who are part of the organization. To begin with, no one knows the organization like the people inside it. Further more, the dynamic environment of the firm requires that TOC is continually adapted to the firms needs. This requirement of continuity precludes the use of outside TOC consultants as the driving force behind the implementation of TOC. That doesn't say that there is no place for the outside consultant. Goldratt recognizes that the greatest contribution of the outside consultant is in his detachment from the organization and as such is less likely to be caught up in the inertia of that organization and its rooted assumptions (Goldratt, 1990a:89).

The implementation of TOC comes down to the issues of dealing with the psychology of the organization and of the individual. Earlier in the paradigm it was discussed that the vast majority of operations management literature stays clear of this issue, even though it is intuitive that no solution involving people can be achieved without addressing the psychological issues. In the final analysis, however, it will be the internal Jonahs that will have to grapple with the specific problems of how best to implement TOC for their organization. Creative solutions will need to be constantly prepared. The techniques of Effect-Cause-Effect, Evaporating Clouds, and the Socratic method help provide a methodology. However, it will be up to the organization itself, with the help of these tools and a good "dosage" of common sense, to come up with specific solutions.

An example of this need to be innovative when addressing the psychological issues of implementation, is in dealing with the problems associated with the tolerances that engineers specify. Often the tolerances specified are an "overkill'. If there is a need to relax those specifications so as to facilitate better performance on the shop floor (e.g. lowering constraint processing time), there will often be strong resistance from the engineering department, since any relaxation of the specifications will be perceived as initial faulty judgement by the engineer. A solution to this problem is for the engineer to initially provide two tolerances. One tolerance is what the engineer would prefer to achieve if it doesn't cause any problems with performance on the shop floor. The other tolerance is what is the absolute minimum that can be accepted. This solution addresses the psychological issues by providing for a change of tolerances with no inference of misjudgment on the part of the engineer (Goldratt, 1990b).

The Break from Traditional Management

A conclusion that can be reached after the presentation of the paradigm and procedures that have evolved from the paradigm, is that TOC presents a break from traditional management. This break manifests itself in a variety of a management areas.

A Global Versus Local Perspective. Even though much traditional management talks about the need for a global perspective of decision making, it would appear that, in reality, this ability is seldom achieved. TOC on the other hand, through its performance measurements and constraint management orientation, has seemed to succeed in instituting the ability to provide management with a system's view of the impact of their actions.

Cox and Blackstone (1990:2-3) offer a number of reasons for the failure of traditional management to overcome the hurdle of a limited local perspective:

1. The specialization of labor has led to a functional emphasis and one-dimensional analysis in developing and managing a business.

2. The growing complexity of the business environment further strengthens the barriers separating functions and departments and cuts the communication between them.

3. The inability of management information systems to synthesize data into relevant information.

4. The traditional performance measurements focus on the local impact of an action. This point is elaborated on in the discussion of cost orientation.

The Cost World Versus the Throughput World. TOC can be described as being throughput oriented; meaning that the thrust of the TOC philosophy is towards promoting throughput while being mindful of costs. Traditional management, however, is described by TOC as cost-oriented; meaning that management focuses primarily on reducing costs relative to throughput. The difference between the cost world and the throughput world should not be underestimated. Quoting the Institute's journal:

> There is apparently a world of difference in almost all management actions if the most important measurement is no longer "cost", but throughput. The change from the "cost world" to the "throughput world" is grossly underestimated. Actions that are must in the "cost world" are regarded as totally devastating in when judged through the prism of the "throughput world". (Goldratt and Fox, 1990:14)

It would appear that most U.S. companies rely on the cost concept in the attempt to build a bridge between local actions and bottom line measurements. In the eyes of TOC the cost concept is not only inadequate, but at times it actually takes the company further away from its goal.

Manifestations of the cost world that damage a company can be classified into at least three categories: local efficiencies; evaluating the cost of inventory; and product costing. To understand just how devastating the cost world can be, each of these categories are addressed individually.

One of the expressions of local efficiencies is local performance measurements. The assumption behind the use of local performance criteria is that if all organizations resources are being utilized efficiently, then the overall organization success is maximized (Fry and Cox, 1989:52). However it can be demonstrated that many of the traditional local efficiency criteria have the reverse effect.

Adopting Fry and Cox approach, local performance measurements can be presented in terms the individual worker, the department, the plant, and finally corporate functions (Fry and Cox, 1989:55):

1. The negative effects of worker time standards:

a. The worker compromises on the inspection of quality during his process. This in turn requires a later inspection which leads to scrap, extra expense related to rework, and the waste of the constraint's capacity.

b. The promotion of individual incentive systems that inevitable result in discrimination of segments of the organization which in turn leads to demoralization of workers.

c. Excess WIP is entered into the system to reduce idle time. The problems resulting from the premature introduction of WIP into the system has already addressed. In short, it leads to a number of production evils (unavailability of resources to process higher priority jobs, increased carrying costs, the reduction of cash flow).

d. The use of long production runs which goes hand in hand with infrequent setup changes. According to the logic of cost accounting, such a policy reduces the cost per unit by spreading the setup costs over a larger number of units. However the "true" cost to the system is quite different. The labor costs, both direct and indirect are given and can be regarded as sunk costs in the short-term. Thus the number of setups does not change the real cost outlayed by the firm. However process batch sizes and the frequency of setups have already been shown to have a major impact on the throughput of the firm. A larger process batch is not always advantageous, particularly on non-constraints where it can lead to the disruption of process flow and the transformation of non-constraint resources into constraints. Even on the constraint resource, too large a process batch can have the same negative effects.

e. Standards promote changing the priorities of jobs to create favorable variances. In simple terms, a worker may have a choice between two jobs and the performance measurements make no distinction between the two. Job "A" has higher priority then job "B", however job "A" often turns out to be more time-consuming than job "B". It is clear what the preference of the worker will be.

2. The negative effects of departmental efficiencies:

a. Departmental managers further encourage the workers to strive for individual efficiencies which results in the further exacerbation of the negative results outlined above.

b. Barriers to teamwork are erected between departments due to the perception of departmental competition. However departmental teamwork is essential to company success. The most obvious area in which team work is required is in dealing with the plant's constraint.

c. The area of improvement and quality is particularly hampered since it is to be expected that most departmental heads would not be willing to agree that there is a problem in their department.

3. The negative effects of plant utilization:

a. Striving for high utilizations further encourages the premature release of WIP into the plant in an attempt to gain the high utilization of work centers.[15]

b. The practice promotes building finished goods inventory even though no sales are anticipated.

c. It also promotes delays in operator training, preventive maintenance, and performance of corrective maintenance. The performance of these actions would be on the account of plant utilization.

4. The negative effects of functional performance measurements:

a. Marketing performance measurements based on total sales ignores the negative effects that can accrue from unnecessary additional inventory investment or additional expenses attributed to expediting and overtime.

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[15]As a side note, according to TOC this phenomena of early release for the sake of plant utilization is what has added to the distortion of the use of MRP so that today it is labeled a push system. The original logic of MRP was in fact to stop the push of materials into the plant, only releasing material when it is needed. The premature pushing of materials on to the shop floor resulted from cost procedures of keeping everybody busy, hence altering the master schedule accordingly (Goldratt and Fox, 1990:30-31).

b. Purchasing based on the ordering costs ignoring the host of problems introduced with the release of prematurely timed large batches, compromised quality, the disruption and possible severing of a long-term vendor relationship. Even where purchasing is based on EOQ, the scope of considerations is far too limited. EOQ batch sizes ignore the impact of process batch sizing on performance.

As an alternative to the traditional performance measurements, TOC offers its set of local performance measurements that are expressed in inventory dollar days and throughput dollar days. It would seem from the earlier presentation that TOC's performance measurements have been able to measure the true impact of a local action on the bottom line measurements of the firm.

In addition to traditional performance measurements there are other expressions of local efficiencies that can "hurt" a company:

1. Cutting operating expense is often justified under the "battle cry" of efficiencies. Unfortunately, what isn't always known to management, are the full repercussions of those cuts on the performance of the company. By failing to have a clear picture of the dependency relationship between resources and where the constraints are, traditional management can often set off a chain reaction through cost cuts that impair performance. The constraint's processing

capability could be reduced, which clearly reduces throughput; or, by "cutting" into excess capacity (i.e. non-constraints), these resources are transformed into constraints since they no longer have the flexibility to respond in time to processing demands of the dynamic environment.

2. It would seem that traditional investment decisions between alternatives (e.g. purchasing new machinery) focus far more on the savings that can result, without proper weight being given to the impact of different alternatives on throughput. A company can often limit its growth opportunities by only considering part of the relevant data required for a sound decision (Goldratt and Fox, 1986:24-26).

3. Improvements in performance require that management has a clear picture of the firm's process flow to know where and how to focus its improvement efforts. The traditional view of management that views the firm's resources as an assemblage of independent cost centers, prevents management from being able to be effective in focusing improvement efforts. In contrast, TOC's application of buffer management seems to provide the solution to this problem. Both the constraint and non-constraint trouble makers are clearly identified.

4. Part of the logic of cost accounting is to measure the cost of a product by dividing the number of items processed by a resource into the cost of the resource. Following through with this logic can lead management to deciding on processing a job through the least "cost" machine rather than a more "expensive" machine with no consideration of how heavily loaded ether machine is. For example, the cost accounting logic would actually oppose a decision to off load a job to a more "expensive" machine which which is not being utilized. According to traditional management such a decision is efficiently utilizing the firm's resources. TOC challenges this logic. The true cost to the firm is in wasted throughput (in not having off loaded the job to the more "expensive" machine), and not the costs which have been out laid in the past and are regarded by TOC as sunk costs.

5. The desire for a balanced plant, in which excess capacity is equated with wasted capacity, is often found in production management literature and management board rooms. What seems to be ignored by these bodies are the negative effects of SFDR on process flow. According to TOC, reality prevents the attainment of a balanced plant by the simple reasoning that a balanced plant would quickly become dysfunctional and cease to exist. However the desire for a balanced plant, in which excess capacity is trimmed has in

itself a negative enough effect on a firm's performance. What TOC strives for is balancing the flow of a product rather than balancing capacity. When the flow is balanced then capacity by definition will be unbalanced as a result of the need for built in excess capacity on non-constraints.

What can be concluded from the alternative presented by TOC to the traditional cost approach to efficiencies is, that being effective is not always synonymous with being efficient.

The treatment of inventory is another manifestation of the cost approach that TOC challenges. The cost accounting methodology includes in the calculation of inventory worth an assessment of all "value added", meaning the value of all labor and other operating expenses that are invested into the inventory up to that point in time. Since profit is revenue from sales minus all expenses, all expenses related to WIP and finished goods inventory that is not sold in the present period, should not be included in the present period's profit calculation. According to traditional cost accounting, all these assessed expenses are transferred to future profit calculations in which it is assumed the inventory is sold. TOC opposes this approach to evaluating inventory, claiming that it leads to a distortion on the period of a company's performance, creating what it calls "inventory profits". The cost accounting approach will overestimate the profits of those periods in which excess WIP and finished goods inventory was produced by providing unwittingly a "get away" vehicle for transporting many of the expenses (i.e. value added) from the present period over to a future period. An absurd situation can be created in which a plant manager will be encouraged to have as much finished inventory and WIP that the plant's capacity can produce by the end of a financial period. By doing so the profit picture of the plant's present period is improved since many of the plant's expenses will not be taken into account. Conversely, the plant manager who tries to decrease the production of unsold inventory and WIP will be penalized by being unable to mitigate many of the present period's operating expenses. As a result, there now exists confusion over whether or not inventory is an asset or a liability (Goldratt and Fox, 1988a:6-13).

TOC avoids the whole issue of how to allocate expenses to what period, by not recognizing the convention of value-added. The reader is reminded that TOC's definition of Inventory only includes those expenses outlayed for the specific purchase of raw materials. All the operating expenses of the firm are considered expenses for the period that they were incurred, regardless of what was sold or unsold. This approach clearly discourages the build up of unsold inventory and WIP and Inventory is clearly considered a liability.

Product costing is the final manifestation of the cost approach. One of the applications of product costing is in determining the most profitable product mix for the firm in order to obtain maximum output given the available resources and market demand . An example that is commonly used in TOC presentations is what is known as the PQ demonstration (Fox, 1989:43-48):

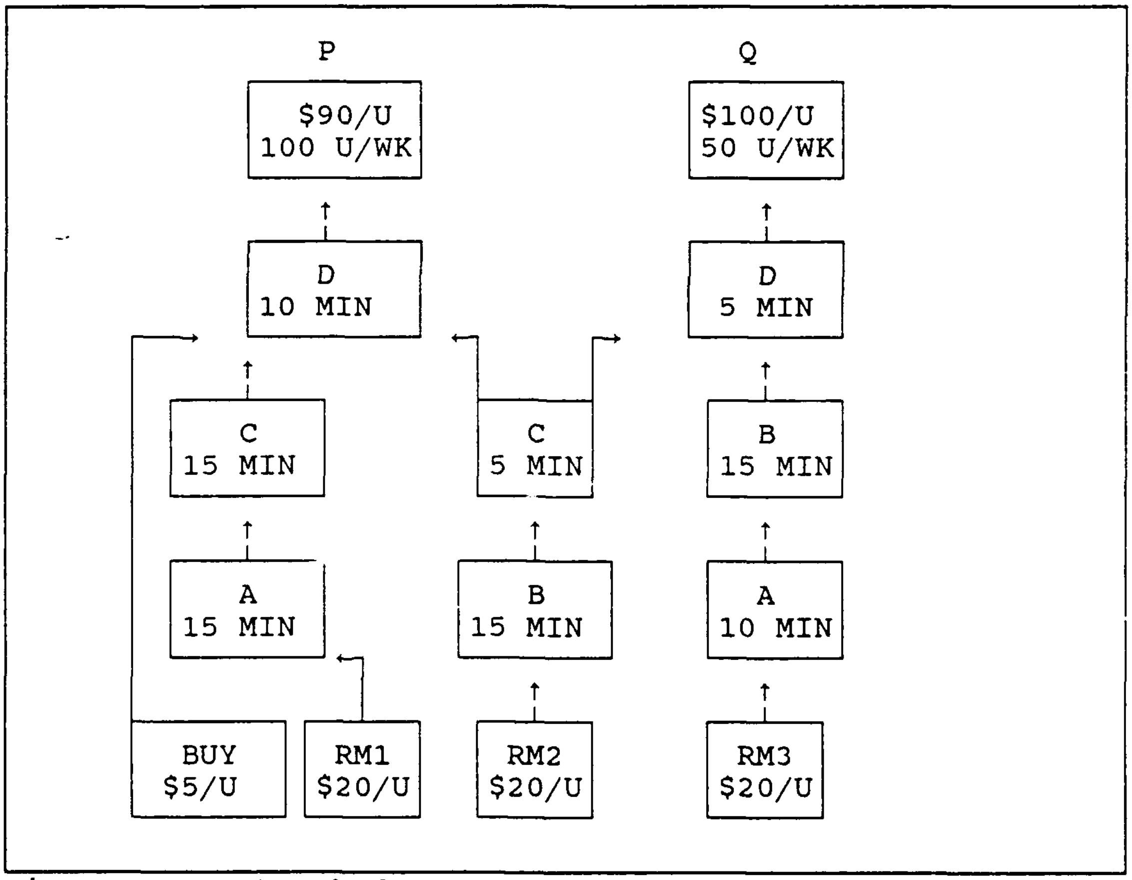

Figure 4. Network for PQ Example

In a plant two products are manufactured. Product P sells for $90 per unit with a weekly market demand of 100 units. In order to make that product an assembly is required. Resource D does the assembly work which takes 10 minutes per part. The assembly operation involves putting together a purchased part that costs $5 as well as putting together two manufactured parts. Each of those manufactured parts needs to go through a process. One of the part's raw materials RM1 costs $20 per unit and is processed first through department A for 15 minutes, followed by department C for 10 minutes. The other manufactured part's raw material RM2 costs $20 per unit and is processed firstly through department B for 15 minutes, followed by department C for 5 minutes. The assembler D puts the two manufactured parts together with the purchased part to produce a final product P. A similar process is used to manufacture product Q. The details of that process can be followed from the figure that represents the production network of this plant. Note that there is only one available unit resource in each of the departments A, B, C, and D. Each unit resource can only process one part at a time. The available working time for each unit is 2400 minutes a week--a 40 hour week. The operating expenses of the plant are $6000 per week.

The question that is asked is what is the maximum performance that can be obtained from this network (i.e.

maximum net profit), and how is it obtained (i.e. optimal product mix)? By doing a calculation of the required work load on each of the resources A, B, C, and D, to manufacture the entire market demand for products P and Q, it can be concluded that the available capacity of 2400 minutes per week for each resource is insufficient for the load on resource B. Since not all the units of both products can be manufactured in the available time, it is necessary to decide on an optimal product mix.

The logical approach is to give priority to that product that offers the highest profit to the firm. The conventional approach to calculating highest profit is to firstly subtract the cost of raw materials from the selling price of each of the products. The contribution of product P is $45. The contribution of product Q is $60. What needs to be examined next to complete the analysis is labor. 55 minutes of labor are required to make one unit of product P. For product Q only 50 minutes are required to produce one unit. It would seem clear from this analysis that product Q is preferred since it takes less time to produce and offers a higher contribution. Given this conclusion priority will be given to product Q and with whatever capacity is left over, the plant will produce as much as possible of product P. The product mix is not that difficult to calculate. It is already known that the only resource that does not have enough capacity for both products is resource B. All 50 units of product Q are manufactured (i.e. total market potential). With the remaining capacity of resource B it is possible to manufacture 60 units of product P (note that market potential is 100). The net "profit" that results from this product mix is in fact a loss of $300. The calculation is elaborated on in the figure.

Product	P	Q
Selling Price	$90.00	$100.00
Raw Material Cost	$40.00	$ 40.00
Contribution (SP-RM)	$45.00	$ 60.00
Direct Labor Time/Prd.	55 MIN	50 MIN
$/Direct Labor Minute	$ .82	$ 1.20

Product Q is preferable

The net profit per week from this plant:

Product	P	Q	
Market Potential	100	50	
Product Mix	60	50	
Contribution (SP-RM)/Unit	45	60	
Min of Res. B/Prd.	15	30	
Units of Res. B used	900	1500	= 2400
Revenues	2700	3000	= 5700
Operating Expenses			=(6000)
Net Profit/Week			= (300)

Figure 5. The Conventional Approach to PQ

The method TOC employs to determine the optimal product mix differs from the conventional approach. Maximum output is determined by the system's constraint, which in this plant is resource B. Rather than calculate each product's dollar contribution per direct labor minute, the accurate profit potential of a <u>constraint product</u> is measured by its <u>dollar contribution per constraint processing minute</u>. The constraint processing time for product P is considerably less than the time for product Q. Even though product Q provides a greater profit margin than P (selling price minus raw materials),and it takes less processing time overall than P, the overall profit contribution of Q is limited compared to P because of the long processing time required on the constraint. By processing first the entire market demand for P and using the remaining capacity of resource B to process Q, the firm optimizes its product mix, hence performance. The details are found in the accompanying figure.

To those readers who have had a managerial cost accounting background, such a result seems to be counter-intuitive. The problem with the cost accounting approach to product costing is in its assumptions. One of the erroneous assumption in conventional product costing is in assuming that all the resources have infinite capacity. In the overall profit contribution of a product, no consideration is given to the limited capacity of the constraint's impact on throughput.

Product	P	Q
Selling Price	$90.00	$100.00
Raw Material Cost	$40.00	$ 40.00
Contribution (SP-RM)	$45.00	$ 60.00
Direct Labor Time/Prd.	55 MIN	50 MIN
$/Constraint Minute	$ .82	$ 1.20

Product P is preferable

The net profit per week from this plant:

Product	P	Q	
Market Potential	100	50	
Product Mix	100	30	
Contribution (SP-RM)/Unit	45	60	
Min of Res. B/Prd.	15	30	
Units of Res. B used	1500	900	= 2400
Revenues	4500	1800	= 6300
Operating Expenses			=(6000)
Net Profit/Week			= 300

Figure 6. The TOC Approach to the P Q Example

Since throughput is controlled by the constraint, TOC's approach approach is to calculate the cost based on the constraint's processing time. A product's bottom line contribution to profit is generated by its profit margin in relation to the constraint's processing time of that product.

Traditional cost accounting product costing is further distorted by the allocation of fixed costs. Direct labor hours are often used as a base for cost allocation of fixed and indirect costs between products. Such a method can lead to a further distortion of product costs, particularly as direct labor costs become increasingly less significant in modern industries as the result of automation and computerization. This in turn further exacerbates incorrect judgments on product mix. There are attempts today to shift the allocation base from direct labor hours to something more significant and less erodible such as maintenance and or machine hours. However even these very complicated attempts fail to accurately capture the full impact of different product cost. What TOC has done is to evaporate the problem by challenging the assumption that a company needs to know individual product costs to optimize performance. What TOC claims is necessary for a decision is not the product cost but rather the bottom line contribution of the sale of a specific product sold at a price dictated by the market (Goldratt and Fox, 1988a:17-18).

Using TOC's method of a product's bottom line profit contribution, seems to require far less time, effort, and money than the conventional method. All that is required for this method are expenses of items "brought in" to the firm (normally only raw materials), the expected selling price, and the processing time per unit type at the constraint (Fox, 1989:46).

Given the fact that the decision making of most companies is formally based on managerial cost accounting procedures and many companies on the whole seem to perform well, some readers may be skeptical about just how ineffective these procedures are. According to Goldratt, what saves management is their intuition so that when it is important managers disregard the "logic" of the cost procedures and act on instead on their survival instincts. The occurrence of the "hockey stick" phenomenon is clear evidence of this process.[16] At the beginning of the period, cost accounting efficiency measurements are being used that drive the actions on the shop floor. As the period progresses it becomes clearer that the bottom line measurements stated in terms such as dollars of output shipped, are in danger of not being reached. There is a mad rush to meet due dates in which basically efficiencies are ignored. When the pressures decrease the shop floor again returns to the cost accounting measurements and so the cycle repeats (Chase and Aquilano, 1989:793). What TOC tries to do is to refine and focus the instinctive common sense practices of management that allow the firm to survive in spite of the damaging effect of the cost accounting procedures.

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[16]The "hockey stick" phenomenon means rushing to meet due dates at the end of a performance period. It's called a hockey stick because because of its shape when graphed: the time period's performance starts off as, and continues along a relatively flat bottom, yet, towards the end of the period there is a rapid rise in performance so as to meet due dates.

Compare and Contrast TOC to JIT and TQM

The management philosophies of Just-in-time (JIT) and Total Quality Management (TQM) are perceived as having departed from many of the principles of the traditional body of knowledge, as is similar to TOC. According to Goldratt, these three philosophies do more than complement one another; together they produce a powerful synergy of change (Goldratt, 1990a:117). In order to investigate this assertion, the similarities and differences between TOC and these philosophies needs to be explored.

Comparisons. According to Goldratt (1990a:117-122), the emphasis of both JIT and TQM is on throughput as being the avenue for long-term improvement as opposed to the traditional cost orientation. Throughput is largely affected indirectly through the efforts reduce inventory.

JIT is well known for its drive to decrease inventory by releasing to the shop floor only that amount of inventory required to satisfy market demand. Such an effort requires a concerted attack on the underlying reasons for the buildup of inventory buffers. The underlying reason for buffers is statistical fluctuation and dependent resources (SFDR). JIT's attack on SFDR is reflected in several ways: in its efforts to reduce setup time; in performing preventive maintenance; in the use of U cells where one worker is moving with the processed part from one work center to another (reduces the number of dependent resources); streamlining the process flow to reduce the number of dependent resources.

TQM also attacks the underlying reason for inventory buffers through focusing on reducing statistical fluctuations (variability) by way of statistical process control.

Contrast. What differentiates both JIT and TQM from TOC, according to Goldratt, is their lack of focus, which can be traced back to an inability to translate the impact of a local improvement on global performance Goldratt, 1990a:122). The manner in which JIT has compensated for this lack of focus is to allow for a very gradual process of implementation. Inventory levels are slowly reduced to provide time to identify and to remove the "rocks" that emerge. Even the increase in sales is only allowed at a controlled pace to avoid throwing the production operations out of equilibrium (Chase and Aquilano, 1989:792).

TOC appears to have overcome these limitations, and to have taken the strengths of JIT and TQM one step further by focusing the application of their techniques effectively according to a global impact.

Evaluation of TOC

Most of the material written on TOC has come from sources associated with either the previous OPT organization or the

Goldratt Institute. It could be argued that such sources lack objectivity. However not all published articles were associated with the Institute.

Outside TOC Sources. In 1986, APIC's published a special feature on what was then optimized production technology (OPT). Even though TOC has evolved considerably since the period of OPT, many of the comments written still merit consideration. What is particularly noteworthy is that even at this earlier stage of Dr. Goldratt's theory, all the practitioners who contributed to this review were in agreement that what was then OPT has contributed significantly to the complex world of scheduling. The differences that were expressed among the authors was on the extent to which OPT provided an all encompassing solution to the scheduling problem. The following is a summary of their evaluations:

Melton (1986:14) expressed reservations concerning the extent of OPT's capabilities. Even though Melton acknowledged many of the advantages OPT has over traditional materials scheduling methods by incorporating a bottleneck strategy, he contended that the traditional systems convey benefits that TOC fail to incorporate. For example, JIT encompasses a total productivity approach that reaches beyond the scheduling of TOC. Quality control, feedback, and decision making are finely intertwined under JIT.

Melton concluded by suggesting that TOC is best suited to a dynamic job shop environment where the bottleneck phenomenon is problematic. This is not the case in a repetitive environment or process industry (Melton, 1986:20).

A different conclusion was reached by Lundrigan and Plenert who fully endorsed OPT concepts as being the next generation in scheduling. Lundrigan wrote that OPT "integrates the best of MRP and JIT, combines them, and uses the power of the computer to elevate production and inventory control to a new level" (Lundrigan, 1986:11). According to these authors, the main problem with MRP is in its unrealistic assumption that resources have infinite capacity. Similarly, JIT fails to focus on the critical resources of the plant. OPT found solutions to these problems. At the same time OPT continued to utilize the strengths of these two traditional approaches: the data base system of MRP, and the improvement of flow and elimination of waste in JIT (Lundrigan, 1986:2).

The same conclusions are reached by Plenert through a case study conducted at California State University in which the three systems, MRP, JIT, and OPT, were compared.

The remaining evaluation in this review was that of Swann. Swann took a "middle of the road" approach towards OPT. According to Swann it is incorrect to choose between MRP and TOC. Both processes complement one another with each having its own strengths. The correct approach is to use both systems in scheduling. MRP should be used in planning material requirements, and TOC should be activated in determining realistic shop schedules (Swann, 1986:35-36).

Nearly all the authors raise the same problems associated with using OPT on the shop floor. It can be argued that most of the same problems raised then are equally valid today in TOC. The following common problems were raised:

1. OPT, as in the case of MRP, requires extensive data maintenance. Note however that there is one major difference in data maintenance that distinguishes both OPT, and the newly released software package "Disaster," from MRP. It is a difference that none of the authors of this review, except for Plenert, were alerted to; namely, that the data accuracy needs to be mainly focused on the constraint activities. On the non-constraints there can be a greater tolerance of data inaccuracies. The implication of TOC's approach is to greatly alleviate the data requirements.

2. New computer skills have to be learned in the company. A note though on current developments should be added here. Even though the newly released software package "Disaster" does require the learning of a new computer

package, the program appears to be very user-friendly and as such the amount of learning required is minimal.

3. Finally, a high level of discipline is demanded on the shop floor as a result of the tight scheduling. Even though none of the authors of this review address this specifically, what is implied by their comments is that the successful implementation of the then OPT and today's Disaster requires that the organization first undergo a cultural re-education based on the TOC throughput approach. Without this re-education no amount of software will help.

Author's evaluation. After reviewing much of the material written on TOC as well as experimenting with the scheduling procedures, it appears that TOC has made a significant contribution to management philosophy, and more specifically to the complex world of job shop scheduling.

The evolvement of simple, effective solutions is a manifestation of TOC's contribution. The synchronous manufacturing procedures, such as DBR and buffer management, provide the manufacturing organization with simple heuristics which help solve enormously complex scheduling problems. This achievement is a major breakthrough in scheduling theory.

It should not come as a surprise that Goldratt's formal education is in physics. The essence of physics is simplification. Physicists attempt to subsume existing theories into a design theory, to find a root cause.

TOC seems to be one of the few management theories that has developed procedures that have achieved a <u>system's approach</u>. While many theories emphasize the importance of having a system's approach, very few provide "tools" that bridge the impact of a local action on the global perspective of the organization.

According to Cox and Blackstone, the academic world of business research has failed to provide the necessary answers, and more fundamentally questions, to an integrated systems approach to economic realities. The majority of the effort has been at the tools and techniques level that provide solutions for achieving local optimums. (Cox and Blackstone, 1990:1)

The thoughtware of TOC provides in itself the opportunity for making improvements, without the need for any investment in support software.

<u>Software</u> is in the process of being marketed by the Goldratt Institute, known as *Disaster*, for those organizations that have already been initiated into the thoughtware of TOC and desire to enhance their improvement effort with the aid of the software. In addition to enhancing the improvement effort, the advantages of this software appear to be: its user friendliness; its

microcomputer application; its ability to work with large data bases; its price relative to existing scheduling software packages.

Concluding TOC

There are those who would criticize TOC, and particularly Goldratt, for making statements based on intuition and what Goldratt calls common sense, without necessarily being supported by all scientific rigor demanded by academia. While it would be preferable that all the TOC claims were subject to scientific rigor, it is questionable whether the developers of TOC should have delayed publishing their claims, and possibly dissipated their energies, to satisfy all the stringency that is demanded by academia. TOC is first and foremost a practical approach to system's problem solving. It appears that occasionally elements of the academic community of the business world become obsessed with the methodology of its science and loose sight of their goal, namely to solve real-world problems. TOC has clearly addressed the pressing issues with solutions that work, without waiting to strictly prove every detail before proceeding. TOC provides a framework for effectively managing organizations. TOC should provide a "jolt" to those in the academic community who have failed to address the real issues that burden management and in particular the management of manufacturing organizations.

V. Simulating the Depot

A simulation experiment was performed on the IAF's armament depot's process flow. This experiment was designed to investigate the applicability and merits of TOC to the depot's scheduling environment. In the course of determining TOC's applicability, a simulation experiment was used to compare traditional scheduling strategies to TOC's scheduling procedures. The chapter is divided into the following sections: a description of the system; details of different simulated scenarios; results and their statistical validation; analysis of the findings.

Describing the System

The first step in any simulation is to define the system being simulated, i.e. its boundaries and contents. The system under study is the scheduling network of the depot. However, as explained in the methodology section, the definition of a system is relative. How much of the environment that is outside of the depot yet impacts its performance should be included? Should all the different types of depot jobs be included? What is the suitable time frame that reflects depot performance? What level of activity of a resource center should be depicted? Unfortunately, there do not appear to be any definitive answers to any of these questions. The formal guideline is that the purpose of the study dictates the scope of the system (Pritzker, 1986:4-5). The purpose of this study is to investigate the applicability of TOC to the scheduling environment of the depot through simulating different scheduling strategies. The system needs to be detailed to a level of complexity that:

1. Is sufficient to warrant the need for scheduling procedures on the shop floor.

2. Is capable of distinguishing between different scheduling strategies.

Input variables. A simplified replica of the depot was simulated. Four different types of weapon systems were included. Each of the weapon system types (WST) arrives at the depot for major periodic maintenance. The time period being simulated is 360 working days. The depot is expected to fulfill the following preassigned requirements: WST1 - 56, WST2 - 54, WST3 - 40, WST4 - 34. No specific due dates have been set within the 360 day period, however ideally weapon systems that are taken out of the field for maintenance will spend the least possible amount of time in the depot.

The shop floor of the depot is comprised of the four functional workshops (FWS) and one common service department (CSD). Each functional workshop is charged with the specialized maintenance tasks of one of the WSTs. That is to say FWS1 has the specialized tasks for WST1, FWS2 for WST2, FWS3 for WST3, and FWS4 for WST4. The CSD, on the other hand, performs common maintenance tasks for all weapon systems that enter the depot regardless of type. These tasks include welding, sheet metal, painting. The term "common" is used to denote that the CSD's services are commonly shared regardless of the WST or FWS.

When a WST enters the depot it is routed to its respective FWS. At the FWS a preliminary inspection is performed to determine maintenance requirements. After the preliminary inspection, a maintenance team from the FWS commences its work. At the same time as the FWS's maintenance team commences its work, parts are sent from the FWS to the CSD for treatment. At the completion of both the FWS and CSD's maintenance actions, the weapon system's parts are reassembled. Weapon system's parts are reassembled according to tail number and are not interchangeable among weapon systems of the same type. After the weapon system is reassembled it exits the depot in a combat-ready state. Figure 7 depicts the product flow of the weapon systems through the depot.

Each FWS as well as the CSD are comprised of separate manpower "pools" that are independent of one another. The numbers of these manpower pools are as follows: FWS1 - 26; FWS2 - 26; FWS3 - 28; FWS4 - 34; CSD - 8. When a weapon

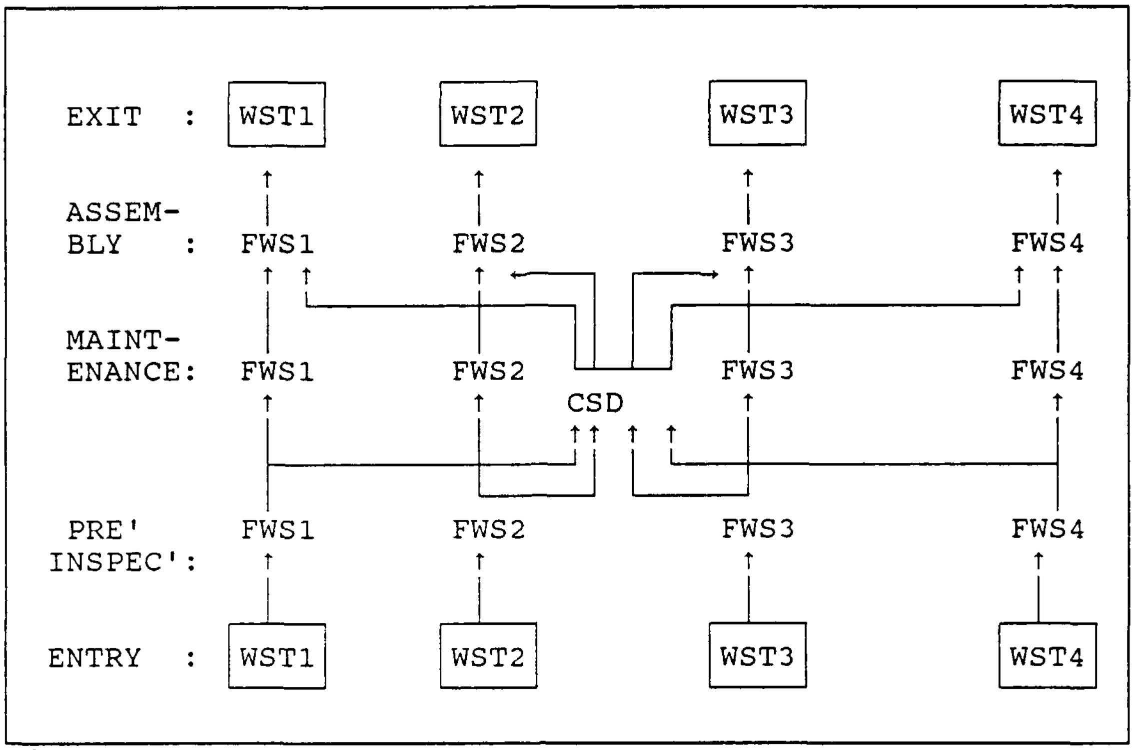

Figure 7. The Process Flow of Weapon Systems through the Armaments depot.

system enters the depot, a maintenance activity can only begin if a predetermined number of soldiers are available to carry out the maintenance action. The absence of one soldier or more from a maintenance team prevents the commencement of any work on the particular maintenance task required. In addition to the manpower requirements, a preassigned distribution time is used for each of the maintenance actions of a WST. An exponential distribution was used for all the maintenance actions.[17] The following table outlines both the manpower requirements and distribution times of the maintenance actions of the different WSTs.

Table 1

MANPOWER REQUIREMENTS AND DISTRIBUTION TIMES FOR MAINTENANCE ACTIONS

WST	TASK	WORK SHOP	TEAM SIZE	DISTRIBUTION TIME*
1	PREL' INSPEC'	FWS1	2	f(2)
1	SPEC' MAINT'	FWS1	4	f(34)
1	COMMON MAINT'	CSD	2	f(10)
2	PREL' INSPEC'	FWS2	2	f(2)
2	SPEC' MAINT'	FWS2	4	f(34)
2	COMMON MAINT'	CSD	2	f(7)
3	PREL' INSPEC'	FWS3	2	f(3)
3	SPEC' MAINT'	FWS3	5	f(37)
3	COMMON MAINT'	CSD	2	f(15)
4	PREL' INSPEC'	FWS4	3	f(3)
4	SPEC' MAINT'	FWS4	10	f(27)
4	COMMON MAINT'	CSD	2	f(15)

* Exponential distribution function (μ)

For security reasons the names of weapon systems as well as detailed data pertaining to their maintenance has been

[17]The exponential distribution is commonly recognized as being representative of most manufacturing activities (Chase and Aquilano, 1989:128).

deliberately avoided. In spite of that, attention has been paid to using simulated data that gives an approximation of the scale of activities for WSTs that enter the depot.

Performance measurements. To determine the success of a simulated schedule for the depot, it is necessary to define performance measurements. In accordance with the logic of TOC, performance measurements need to be determined in accordance with the goal oi the organization. For the moment it will be assumed that the goal of the depot is to contribute to the defense of the State of Israel.[18] The performance measurements used in the simulation are a logical outgrowth of supporting that goal and are consistence with TOC guidelines; namely improving throughput relative to decreasing inventory and operating expense.

Defining throughput for a military depot environment is not so straightforward. There is no market in the traditional sense nor are there "dollar" sales to calculate profit. However, certain parallels can be drawn from the commercial manufacturing environment, which, together with the orientation of the TOC paradigm, provide insight into constructing appropriate performance measurements. As far as the depot is concerned the market demand is dictated by IAF HQ and defined in terms of the requirements placed on

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[18]The question of what constitutes the goal for the depot will be entered into more detail in the discussion following this chapter.

the depot, i.e. performing the necessary maintenance on a defined number and type of weapon systems within a given period of time.[19]

The throughput of the depot needs to indicate a measurement of satisfying this "market" demand. That measurement should ideally be expressed in a uniform scale that has an equal weight regardless of the WST. In the commercial environment money is the uniform scale that cuts across product types. In order to gain an overall picture of the throughput performance of the plant, management is interested in having a dollar figure of total sales rather than being presented with a table of the number of each product type sold. Similarly, for the depot, management would not want to be presented with a table of the number of each weapon system type that has passed through the depot. What is used in the IAF depots to indicate total throughput is the total number of standard hours invested by the depot. For every weapon system or repairable that arrives at the depot for maintenance, a standard has been established that reflects the number of process hours the depot invests in performing the maintenance tasks on that weapon system. The

[19]The use of the word "dictated" is not meant to be misconstrued as meaning that the depot has no input into the decision of the requirements placed upon it. The periodic work programs evolve as a result of iterations between HQ and the depot. In the final analysis however it is HQ that has the responsibility and authority on determining the depot's work load.

standard is based on a mean of processing hours from past history.

Even though total standard processing hours provide a uniform measurement of throughput, some qualifications need to be made. The depot needs to ensure that at least some portion of each of the requirements of the different weapon systems is fulfilled. It may be possible to achieve a higher total number of standard processing hours by focusing the depots efforts on a number of WSTs at the expense of not performing any maintenance on other WSTs. In the military environment, such a strategy could be fatal. At least a certain minimum of each of the requirements has to be fulfilled before completely fulfilling the requirements of any one WST. In this sense the military depot environment is very different from the commercial environment. As long as a weapon system is deemed as playing a role in the defense of the country it is essential that a minimum level of maintenance is always achieved. The depot can manipulate to a certain extent its "product mix" to obtain higher total standard hours. However it has far more constraints on the manipulation of that "product mix" than does the commercial environment. By adding this qualification management no longer has a totally uniform quantitative measurement of throughput. In addition to total standard processing hours, management needs to insure that no one WST is ignored. What constitutes "too ignored" is a difficult question to answer. This research did not succeed in finding a quantitative answer, apart from the more obvious extremes of the depot not doing any maintenance on a particular weapon system.

Another limitation to using total standard hours is that the depot should not exceed the limit of the requirement for any WST. Here a parallel can be drawn to the commercial environment. In the commercial world a certain product may be deemed as being a "star"--the most profitable products. However there is no point in manufacturing any more of this product than demanded by the market. In fact, by producing an excess of this product the company incurs additional costs that erode profit. In the military environment, the "cost" of performing excess maintenance for a WST is possibly even more damaging than in the commercial setting. Whenever a weapon system is brought in for periodic maintenance it means that there is one less weapon system in a combat ready state to defend the country. The military has very little choice in the case of a "legitimate" requirement to pull a weapon system out the defense line to perform periodic maintenance. However, if sucn a requirement does not exist and the depot proceeds to bring in a weapon system, then it is clear that the defense posture of the courtry is being unnecessarily damaged.

The length of this discussion concerning what constitutes throughput is, indicative of the problematic nature of attempting to quantify performance of the military environment. The lengthy definition that has been applied for the simulation is very similar to the IAF's view of its depot's throughput.

The concept of using inventory as a performance measurement needs to be expanded. A weapon system that has been taken out its combat ready posture is regarded as inventory. It is in the interest of defense to minimize such an occurrence to only when it is necessary. Furthermore, when a weapon system does enter the depot, it is also in the interest of defense to minimize the period that such weapon system remains in the depot. In terms of the depot's performance, both of the above elements of inventory are reflected in:

1. The number of weapon system in the depot at any given time.

2. The length of time a weapon system remains in the depot until it completes its maintenance.

Operating expense for the depot can be defined the same as the TOC definition of operating expense for a commercial manufacturing plant. For the purposes of this simulation, operating expenses will be assumed to be constant and as such will not play a part in determining the relative merits of different scheduling strategies.

Decision rules. The success of a schedule, in terms of the performance measurements used, depends on the manipulation of the relevant decision rules of the simulation. Decision rules were manipulated to compare traditional strategies with TOC strategies.

1. A gating operation was used to release weapon systems into the depot. In the traditional case the gating operation for each WST was dependent on the buffer size and processing rate of the WST's respective FWS. In applying TOC, the gating operation was dependent on the buffer size and processing rate of the depot's constraint (i.e. the application of DBR).

2. Weapon systems would compete for processing if they were waiting in queue before the CSD. The traditional approach was to have a priority listing of the weapon systems waiting in queue according to the rule of first in first out (FIFO). The TOC approach was to have a priority list of the weapon systems according to the WST's contribution to throughput.

3. The buffer size of the constraint was changed to determine its impact on the schedules performance.

Steady state. At the commencement of the simulation all of the depot's work centers were empty and idle. In order to reach steady state it is necessary for the simulation to run sufficiently long enough so that the probability mechanism of the variability in simulation response is no longer affected by the starting conditions (Pritzker, 1986:43). Given the parameters of the simulation data, the simulated period of 360 days is more than adequate to reflect steady state as well as to reduce to an insignificant level any bias introduced into the collected statistics as a result of the initial conditions.

A Description of the Simulated Scenarios

In the course of investigating the applicability of TOC as well as its merits, three different simulation scenarios were analyzed.

Scenario One: Traditional Job Scheduling. The traditional approach used in the simulation is based on how the depot schedules its jobs at present. After the requirements have been determined, the depot focuses its attention on the efficiencies of the individual FWSs. Weapon systems enter the depot according to the processing rate of the specialized maintenance tasks performed in the individual FWSs. A small queue is developed of weapon systems waiting to be serviced by its respective FWS. These weapon systems in queue have completed their preliminary inspection and are waiting to commence their specialized maintenance. The development of the queue is necessary to insure an uninterrupted flow of weapon systems being processed by the FWS's respective specialized maintenance teams. The size of the queue is the same number of specialized maintenance teams that can work simultaneously in the FWS. For example, in FWS1 the maximum number of specialized teams working concurrently is six.[20] Translating this logic in terms of a decision rule means that a gating operation is applied for each WST. A weapon system will only be brought into the depot if a space has become available in a predetermined queue in front of the FWS's specialized maintenance task. Since the specialized maintenance task of each WST is processed by its respective FWS, a separate gating operation is applied for each of the WSTs. The traditional approach fails to acknowledge the existence of an internal constraint on the shop floor.

A caveat to this approach whereby traditional management itself will typically intervene, is in the event that the depot becomes "clogged" with weapon systems. The expected response of management is not to allow any further entry of weapon systems into the depot until the depot is able to show signs of clearing the "clog". To model management's response one of the decision rules that is applied in the traditional simulated environment is that in the event that a queue of more than 100 weapon systems develops before a work center, then no more weapon systems of the same type

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[20]The total manpower of FWS1 is 26. The number of soldiers required for a specialized maintenance team is 4. Four divided into twenty six produces 6 teams.

that are in that queue, can enter the depot until that queue is reduced below 100.

The maintenance requirements placed on the depot provide an upper limit of the number of weapon systems of a particular type that are allowed into the depot. Even if a FWS is idle, depot management recognizes the damage caused to defense by prematurely taking weapon systems out of a combat posture to supply work to a FWS.

In the traditional schedule, no priority is assigned *a priori* to any particular weapon system or WST. Weapon systems that are waiting in queue are prioritized according to the rule of FIFO.

All of the above considerations have been incorporated into the traditional simulated schedule modelled in SLAM II. Refer to Appendix A, program 1 for the SLAM II program of the depot's traditional job scheduling network.

Scenario Two: A TOC Approach. The TOC approach is oriented around processing speed of the constraint in the system. The first step in applying TOC is to identify the constraint. A capacity load profile, as described in the TOC chapter, identifies the CSD as being the bottleneck in the system. The CSD is loaded 142 percent under the present maintenance requirements. In contrast all the FWSs have excess capacity. Refer to Appendix B for details of the calculation of the capacity load profile.

The second and third steps of TOC, namely to exploit and subordinate, are achieved through the application of DBR. Applying DBR, weapon systems only enter the depot according to the processing rate and buffer size of the constraint, which is in this case the CSD. A gating operation controls the entry of weapon systems according to the "drum beat" of the CSD. It is important to note that the CSD is the only work center common to all the WSTs. In terms of the simulation, DBR is applied by installing a control mechanism that routinely checks the queue size of weapon system waiting before the CSD for service. The preassigned queue size is the required constraint buffer required in DBR. Weapon systems are released into the depot in the event that the constraint buffer is less than the preassigned queue size. Once the buffer is full, the gating operation prevents further entry of weapon systems until the buffer requires replenishing.

Throughput is protected by maintaining an adequate constraint buffer. A queue of waiting weapon systems ensures an uninterrupted flow of weapon systems since there is a time lag between the release of a weapon system into the depot and its arrival at the CSD. The time lag is also subjected to a degree of uncertainty as reflected in the exponential distributions of the preliminary inspections at the FWSs.

A sufficiently early release of weapon systems also prevents the non-constrained resources from being transformed into constraints resulting from being starved for work. A further advantage of the earlier release of weapon systems is the development of an assembly buffer after the specialized maintenance actions of the FWSs.

The application of TOC for this network is also reflected in the priority list of the WSTs. In the chapter on TOC, the concept of dollars per constraint unit of processing time was explained. The most profitable product mix for a firm is determined by the application of this concept. Similarly, in the depot environment this concept can be applied What is modified is the use of standard processing hours in the place of profit dollars. The earlier discussion in this chapter on performance measurements has already justified the use of standard processing hours in the place "profit dollars". Since all the required data is available, one can proceed to calculate standard processing hours per constraint unit of processing time. Based on this calculation the order of priority of the WSTs from top to bottom is: WST2, WST4, WST1, WST3. Refer to Appendix C for details of the calculation.

In the scheduling network of the depot, different WSTs are going to compete for common resources. The most obvious place of competition is for the constraint services, namely the CSD. In applying TOC, weapon systems that are competing for CSD services, are released to the CSD according to the pre determined priority of WST. The FIFO rule only applies where two or more waiting weapon systems are of the same WST.

Weapon systems also compete against one another at the gating operation of the depot. However, care needs to be taken in applying the priority rule at the gating operation. On one hand, the depot needs to ensure that a "bias" is given to those WSTs with a higher priority. Since by definition, the constraint is unable to process all the all weapon systems, priority should be given to the most "profitable" weapon systems. On the other hand, overall damage to the depot's performance would be caused if the gating operation were to only allow a WST to enter the depot providing that the requirements have been fulfilled for a WST of higher priority. The reasons for this damage are twofold:

1. It is not enough to judge throughput only on standard processing hours. Even though there is an order of priority amongst the WSTs, a certain minimum of all the requirements needs to be achieved before fulfilling the complete requirements of any single WST. This point was elaborated on in the earlier discussion in this chapter on performance measurements.

2. A number of non constraints, namely FWSs, would be transformed into constraints as a result of having been "starved" for work for too long. The overall result would be to drastically decrease the total throughput hours of the depot.

A decision rule was designed into the simulation to ensure that a priority "bias" is introduced at the gating operation without harming the overall throughput performance. A higher probability of a weapon system entering the depot has been assigned to those weapon systems that have been assigned a higher priority according to their WST. Those WSTs that are of a lower priority also have a probability of entering the depot, however the probability assigned is less. The ratio of probability between the WSTs is an approximation of their relative priority. What this procedure ensures is that all of the WSTs have a probability of entering the depot and arriving at the constraint buffer. At the same time, those WSTs that have a higher priority, will succeed in introducing a relative higher percentage of weapon systems by virtue of the higher probability assigned to them.

A further decision rule that is applied in the TOC approach is not to permit the entry of a weapon system to the depot if the maintenance requirement of its WST has been fulfilled. This same decision rule was also applied for the traditional schedule and its justification has been expounded upon. Refer to Appendix A, program 2 for the SLAM II program of the TOC schedule for the depot.

Scenario Three: Buffer Sizing. In the TOC approach it was assumed that an appropriate buffer size was used. This section describes the logic behind arriving at an appropriate buffer size. As explained in chapter IV, the purpose of a buffer is to protect throughput from the negative effects resulting from SFDR. At the same time the buffer length should only be as long as is required to protect throughput. Any additional buffer length is damaging the depot's goal by prematurely introducing weapon systems into the depot, which in turn means a reduction in Israel's combat readiness. In the earlier TOC chapter it was explained in detail the mechanics of constructing and monitoring a buffer profile to determine buffer length. The use of this methodology is beyond the scope of this experiment. In spite of this lack of "sophistication," an appropriate buffer length can be determined through trial and error and using common sense after being familiar with the depot network. The term "appropriate" means in this context "good enough". Even though this approach does not ensure an optimal answer it should provide a workable and effective solution.

Results and their Statistical Validation

This section presents the results of the simulation runs and their statistical validation. For each of the simulation runs the following observations were recorded: the quantity of each weapon system type (WST) that completed its maintenance; the average makespan[21] in days for all those weapon systems of the same WST; the number of weapon systems still being processed by the depot at the completion of the simulation. The results mirror the performance measurements outlined earlier in this chapter.

The quantity of each WST that completes maintenance provides the researcher with a quantitative value of throughput. Each quantity is multiplied by its standard processing hours, after which each of these sums are aggregated to produce a sum total of standard processing hours for the depot. For example, the following number of weapon systems completed maintenance in the work span of 360 days: WST1--29, WST2--53, WST3--25, WST4--33. Each of these quantities are then multiplied by their respective standard of processing hours. For example, the standard of processing hours for WST1 is 1280 hours. Hence the sum total of standard processing hours for WST1 is 29 times

[21]Makespan measures the amount of time that passes from the beginning until the end of a production action on an item. In the depot scenario the amount of time measured in days is from when a weapon system enters the depot until it completes its maintenance action and exits the depot.

1280, which produces 37120 hours. This methodology is applied to each of the WSTs. An aggregate of the sum total of 228192 standard processing hours of the depot is calculated by summing each the WSTs total standard processing hours.

Both the makespan and total inventory left in the system are a measurement of inventory. The logic behind these values as an inventory measurement has already been discussed, and ideally the depot would want to reduce these values to a minimum. The makespan value is based on an average of only those weapon systems that have completed maintenance and does not include weapon systems which are still in the system at the completion of the simulation run.

Statistical validation was performed through constructing a 95% symmetrical confidence interval around each of the averages of the observations from multiple simulation runs. Each value obtained from a single simulation run constitutes a single observation. The statistical value of that single observation is limited and should not be used in itself to provide any statistical significance. However, by collecting a large enough sample of observations for each of the values of interest through multiple simulation runs, a confidence interval can be constructed around each parameter. That confidence interval in turn provides the researcher with a statistically significant result. It needs to be clarified the parameter of interest is the true population mean from which the observations of our sample are drawn. The sample provides only a statistic, which in this case is a sample mean, around which the confidence interval is built.

A number of conditions need to be satisfied to construct a statistically sound confidence interval:

1. Each of the observation values in the sample are statistically independent.

2. The statistic used, which in this case is the sample average, has at least an approximately normal distribution.

3. The sample's standard deviation can be used in place of the population's standard deviation providing that the sample size is large enough (Devore, 1987:259-260).

All of the above conditions were satisfied. A random generator was used in each of the simulations for input variable distributions. The random generator was reinitialized after each of the simulation runs thereby ensuring that the results from each run were independent. A sample size of thirty was used for each of the simulation scenarios (i.e. thirty simulation runs for each scenario). By virtue of the Central Limit Theorem such a sample size ensures that the variable statistic (i.e. the sample average) is distributed at least approximately normal. The sample size is also large enough to allow the use of the sample standard deviation in place of the population's standard deviation.

Table 2 is a summary of the statistical results of each of the three simulation scenarios. Each of the results displays a 95% confidence interval constructed after a thirty run sample for each scenario. Appendix D details the observation values from all of the simulation runs.

Interpreting the Results

The performance measurements T, I, and O.E., provide the basis of comparison between the different simulated scenarios.

The Traditional Schedule Verses the TOC Schedule. In the case of the TOC schedule a buffer size of four weapon systems was used. The TOC schedule in terms of the performance measurements of both throughput and inventory displayed a definite advantage over the traditional schedule.

The most striking difference was in inventory. It is detailed in Table 2 that under the traditional schedule the amount of inventory left in the system has a CI of between 190 and 183 weapon systems. Compare this result with a TOC schedule in which there was a CI of only between 22 and 17 weapon systems. Given this result it should be no surprise that the makespan of completed WSTs in the traditional schedule ranged from two to four times longer than the TOC

Table 2

SUMMARY OF SIMULATION RESULTS

SCENARIO ONE: TRADITIONAL SCHEDULE

PARAM' OF INTEREST	SAMPLE AVERAGE	% REQUIRE-MENT	SAMPLE SD	95% CI
QTY WST1	40	71%	5.55	(42,38)
QTY WST2	38	70%	6.84	(40.4,35.6)
QTY WST3	29.6	74%	4.91	(31.3,27.8)
QTY WST4	23	68%	3.93	(24.4,21.6)
TOTAL HRS	207021	N/R	18347	(213586,200455)
MK'SPAN WST1	129	N/R	17.7	(135,122)
MK'SPAN WST2	125	N/R	15.7	(131,120)
MK'SPAN WST3	128	N/R	15.6	(133,122)
MK'SPAN WST4	129	N/R	16.6	(135,123)
INVENTORY	187	N/R	10.3	(190,183)

SCENARIO TWO: TOC SCHEDULE--CONSTRAINT BUFFER SIZE 4

PARAM' OF INTEREST	SAMPLE AVERAGE	% REQUIRE-MENT	SAMPLE SD	95% CI
QTY WST1	25.8	46%	4.41	(27.4,24.3)
QTY WST2	52.7	98%	1.79	(53.3,52.1)
QTY WST3	19.2	48%	3.62	(20.5,17.9)
QTY WST4	30.3	89%	2.59	(31.2,29.4)
TOTAL HRS	206899	N/R	15967	(212613,201186)
MK'SPAN WST1	42.2	N/R	6.71	(44.6,39.8)
MK'SPAN WST2	45.8	N/R	11.3	(49.8,41.7)
MK'SPAN WST3	78.3	N/R	10.4	(82,74.5)
MK'SPAN WST4	45.9	N/R	9.2	(49.2,42.6)
INVENTORY	19.2	N/R	7.58	(21.9,16.5)

SCENARIO THREE: TOC SCHEDULE--CONSTRAINT BUFFER SIZE 15

PARAM' OF INTEREST	SAMPLE AVERAGE	% REQUIRE-MENT	SAMPLE SD	95% CI
QTY WST1	30.7	55%	4.98	(32.5,29)
QTY WST2	52.8	98%	1.84	(53.4,52.1)
QTY WST3	13.7	34%	5.46	(15.7,11.7)
QTY WST4	32.4	95%	2.13	(33.2,31.7)
TOTAL HRS	208744	N/R	18069	(215207,202281)
MK'SPAN WST1	65.1	N/R	10.5	(68.8,61.3)
MK'SPAN WST2	72.4	N/R	23.2	(80.7,64.1)

schedule's result. The impact of the difference of these figures on the combat readiness level of the different WSTs should not be underestimated.

The TOC schedule achieved a quicker "turn a round" as well as the introduction of fewer weapon systems into the depot at any one time, when compared to the traditional schedule. In TOC, the gating operation of the depot is based on the constraint's rate of process. A weapon system is only released into the system if a space has become available in the constraint buffer. The traditional schedule on the other hand released weapon systems into the depot according to the FWSs processing rates, without considering the constraint in the system. The result of this decision was the premature release of weapon systems into the depot with a bottleneck effect at the constraint.

In terms of throughput, the TOC schedule was able to emphasize those WSTs that were assigned a higher priority. It is recalled that the order of priority among the WSTs, from high to low was, WST2, WST4, WST1, and WST3. The TOC schedule not only achieved this order of priority but in addition ensured that a "reasonable" minimum was achieved of the lower priority WSTs. In the traditional schedule there was no priority of WSTs.

It should be pointed out that there was no discernable difference in terms of total standard processing hours ween the two programs. The confidence intervals of total processing hours are very similar in both schedules. This result may at first appear to be in contradiction to the logic of the TOC schedule having achieved a priority of output amongst the WSTs. The fact that this priority was achieved should have produced an advantage in terms of total standard processing hours based on the logic of standard processing hours per constraint unit of processing time. However, it needs to be remembered that the simulation reflects a stochastic environment in which the maintenance times of different tasks are exponentially distributed. The ratio of standard processing hours per constraint processing unit of time, is based on a mean values. Further more, differences in the constraint ratio between most of the WSTs was not great to begin with. The ratio of standard processing hours per constraint processing unit of time, is based on a mean values. Over time it can be expected that the TOC schedule would favor a higher total standard hours as compared to the traditional schedule.

Buffer Sizing. The constraint buffer used in the TOC schedule should only be as a large as required to protect the depot's throughput from the negative effects of SFDR. Several different buffer sizes were simulated.

The summary result's table, scenario two, indicates that throughput was protected with a relatively small buffer size of four weapon systems. An indication of throughput being protected is to calculate the constraint's processing time relative to its available capacity. A close approximation of the constraint processing time is to total the multiplication of each of the completed weapon systems by its standard constraint processing hours.[22] The result of this calculation is that the constraint is utilizing close to a 100% of its available capacity to process weapon systems.

Since throughput is already protected with a relatively small buffer size of four weapon systems, any increase in buffer size will only result in the unnecessary release of additional weapon systems into the depot. This negative result is reflected in the performance measurements obtained from using a TOC schedule with a buffer size of fifteen (see scenario 3 in the summary table of simulation results). The only notable difference in comparing the results of a TOC schedule buffer size fifteen with a buffer size of four is in performance measurements of inventory. A buffer size of fifteen doubled the number of weapon systems in the depot at the end of the simulation as compared to a buffer size of

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[22]The reason that this calculation is only a close approximation and not an exact figure is that the actual constraint processing times in the simulation runs are based on an exponential distribution. The standard processing times used in the calculation are the means of those distributions.

four. Similarly the makespan of the WSTs increased considerably with the larger buffer size.

VI. Conclusions and Recommendation

This chapter provides a final discussion on the topic of the thesis, based on the earlier chapter on TOC and the simulation experiment. The chapter is divided up into the following sections: the significance of TOC to the depot environment; the experiment's validity; reservations on TOC; recommendations; and concluding statement.

The Significance of TOC to the Depot Environment

In the earlier chapter on TOC an intermediate conclusion was reached that TOC seems to have potential for making a major contribution to the manufacturing commercial setting. TOC appears to offer simple, workable, solutions to improved performance. The procedures that it has developed for job shop scheduling can be regarded as revolutionary in terms of their simplicity and effectiveness. Apart from TOC sources, independent sources have reported the success of TOC in a number of U.S. firms (Melton, 1986:13). Logically it can be argued that if a parallel exists between the commercial setting and the depot scheduling environment, then TOC has the same if not similar merits in the depot setting.

Comparisons. A number of comparisons can be drawn between the commercial manufacturing and the depot environment:

1. The network of the depot shop floor answers the criteria of a "job shop". As defined earlier job shop is characterized by multiple work centers processing a variety of different jobs arriving at work centers in an intermittent fashion (Chase and Aquilano, 1985:588). This operational definition characterizes the depot shop floor. Multiple work centers are found in the various FWSs, CSD, quality inspection department, receiving and shipping dock, engineering design department, and other specialized functions. The fact that the depot's "product" is maintenance and upgrading of weapon systems and their components, does not detract from the nature of a "job shop" setting. Given that the depot is a "job shop" network, the same problems of job synchronization are faced by the depot as in the commercial setting. The TOC procedure of DBR is similarly applicable as a workable, simple, and effective solution for achieving a synchronized solution. The simulation experiment validated the application and merits of DBR within the depot setting. The experiment also demonstrates that the similarities between the commercial and depot "job shop" network are so strong that there was no need to adapt the DBR procedure to the depot.

2. Use of buffer management is the logical derivative of DBR. Once DBR has been institutionalized there should be no difficulty for depot management to use buffer management as

an external control device in the same manner as in the commercial setting. Buffer management permits management to focus its efforts in: effectively expediting jobs when needed; determining the size of the buffer; improving the production process. The experiment only encompassed the aspect of buffer sizing. The limitations of the simulation do not imply that buffer management could not be applied to the depot. Logically there is no barrier to its application and merits of this external control device as applied in the commercial setting. The application of buffer management can be achieved in the depot without having to develop any supporting software. The thoughtware of TOC appears to be in itself powerful enough to provide advantages.

Differences. The following differences exist between the commercial and depot environment:

1. Defining the goal: Clearly the goal of the depot is not to make money now and in the future. The major problem with defining a goal in the military environment is its abstract nature. For example the goal could be to contribute to the defense of the nation. How does one measure the organization's goal? In the commercial setting there is the clear advantage of being able to measure their goal via net profit, ROI, and cash flow. The problem of measuring the organization's goal can be mitigated though if

suitable performance measurements can be defined at the local level of the organization that capture the global impact on the organization. In the IAF's organization the local level represents the depot shop floor.

2. Defining local performance measurements: The definitions of throughput, inventory, and operating expense need to be reexamined for the depot environment. A detailed discussion of the definition of these measurements has already been elaborated on in the section on performance measurements in the previous chapter. The intent of this discussion is to draw conclusions related to performance measures. It is recalled that the main problem in developing measures for the depot was in finding a suitable definition of throughput and inventory. By relying on the logic of the universal definitions as outlined in the TOC paradigm, it was possible to arrive at definitions of local measurements that provide a bridge between the actions on the shop floor and the attainment of the organization's goal. The problem that remained for these definitions was the lack of a standard unit of measurement regardless of the weapon systems that are being maintained. In the commercial setting the standard unit is money. The obvious advantage of using a standard measurement is in the ease of the information passed on to management. Even though throughput for the depot was partially defined in terms of a

standard utility measurement such as standard processing hours, this measurement only provided a partial picture of throughput. As for inventory, no standard unit of measurement was defined.

3. The lack of a standard unit of measurement for throughput and inventory, prevents the application of the equivalent of the internal control devices of "inventory dollar days" and "throughput dollar days".

Conclusion on Application. The question that needs to be answered is what are the implications of the above similarities and differences on the application and merits of TOC? The similarities between the depot and the commercial manufacturing are strong enough to effectively apply the core scheduling procedures of TOC, namely DBR and buffer management. However, TOC should not be applied without the use of adequate performance measurements. Adequate performance measurements have been developed for the depot. The definitions developed, while being logically sound, are "clumsy". Until an appropriate standard measurement is developed, depot management is prevented from fully utilizing TOC's thoughtware.

The Experiment's Validity

Since the simulation model is a key measurement instrument of the research, it is important to discuss both its internal and external validity.

One of the question raised for internal validity is whether or not the simulation model is a predictor of the real world process? Even though the simulation is a simplified version of the armaments depot, the logic used in building the network is an accurate predictor of the process flow. The simulation's inter relationship between the CSD and the FWSs, as well as the process flow of a weapon system through the depot reflects the main elements of the process flow in the armaments depot.

A further question raised for internal validity is whether or not the performance measurements used in the simulation reflect what is meant by good or bad performance by the depot. The topic of local performance measurements, namely throughput and inventory, have been discussed at length. The logic behind the definitions used has been defended.

The issue of external validity examines whether or not the results from the simulation of the armaments depot can be generalized across the other depots. The process flow described in the simulation is common to all the depots. The structure and work flow of all the depots is centered around their FWSs. Each of the FWSs is assigned the direct responsibility of a specific weapon system. In each depot there is the equivalent of a CSD that performs common services for all the FWSs. The traditional way of scheduling that was simulated in the depot is typical of all the depots. In the current situation, the scheduling of the depots is focused on the processing rate of the FWSs rather than focusing on the constraint in the system.

Criticism

It has been clearly stated above that TOC has advantages over the traditional approach in the achievement of a synchronized schedule. Having stated that, there are some reservations on TOC.

The Goal. The major criticism is in the definition of the goal. What seems to be inferred from the TOC writings is that the organization's attainment of its goal results in continual growth. TOC's discussion of the "productivity flywheel" clearly reflects this inference (Goldratt and Fox, 1986:134-140). While growth can constitute a viable intermediate means to an end, continual growth in the long run would result in the downfall of an organization. History is full of examples of organizations that cease to function after passing a threshold of size. Control of the organization no longer becomes feasible.

Perhaps a more realistic and meaningful goal can be defined for all organizations by taking a different approach. Instead of the first step of the paradigm being to define our goal, it may be more appropriate to first ask "what is our system?". Only after we have defined the scope and contents of our system does it become clearer to define the system's goal. The cybernetician Stafford Beer possibly provides insight into answering the question of what should be an organization's goal, regardless of the type of organization. According to Beer the goal of all living systems should be stability (Beer, 1966:99). Living systems do not live in a vacuum. In order to survive, a system needs to foster the "ecology" in which it lives. What constitutes stability depends on the system in question. Growth of a manufacturing firm, up to a certain point and during certain time phases may engender stability. Defining the parameters that constitute stability, may provide a more meaningful and realistic goal. The IAF's goal of contributing to the defense of the State can be argued as a parameter that constitutes stability for the organization as well as higher recursions of the system that encompasses the Jewish nation as a whole.

The cybernetics approach to defining the goal seems to complement the TOC paradigm and does not appear to compromise the procedures that have been developed. In fact, it can be argued, that this redefinition enhances TOC through putting more meaning into TOC's demand for continual improvement. Continual improvement is the key to stability and should not be misunderstood as being synonymous with continual growth. Given the dynamic and turbulent nature of any living system's environments, the only way any system can maintain stability is through constant improvement. Stability will require growth up to a certain point, but even more importantly it requires adapting to changes in the environment. Adaption is enabled through constantly improving. Certainly the military environment in the Middle East is subject to increasingly turbulent and competitive forces. The IDF needs to constantly improve its performance to maintain stability for Israel and ensure the survival of the State.

Reliance on Intuition. The development of new procedures would not appear to be such an easy undertaking. Goldratt claims though, that the development of new procedures can be achieved by being skilled in the thinking process of the TOC paradigm together with one's intuition (Goldratt, 1990a:81). It appears that many of the procedures that Goldratt and his associates have developed for the commercial manufacturing environment have a spark of creativity to them. The adaption of existing procedures to a specific environment seems to be a more realistic achievement for an internal Jonah, rather than the creation of totally new procedures.

Recommendations

The following are recommendations for further research that can build on this thesis effort:

1. There is a need to develop a standard unit of measurement for the performance measurements of throughput and inventory in the military. The lack of such a unit of measurement hinders the full utilization of the TOC thoughtware in the depot scheduling environment.

2. Possibly the greatest challenge for TOC in the military environment is the development of TOC procedures in the operational side of the military. If the contribution of TOC to the manufacturing scheduling environment is any indication of its possible contribution to the performance of the operational side of the military, then the ramification to defense would be far reaching.

Concluding Statement

The above discussion of this chapter points to the conclusion that TOC offers significant advantages over the traditional scheduling approach to the depot's scheduling environment.

At the same time, TOC does not claim to have the ultimate answers to improving the performance of a system, and more specifically to providing the ultimate schedule for a shop floor. Goldratt is the first to remind his audience that they are dealing with a management science and as a science validity is more the concern rather than truth. That is why TOC emphasizes the thinking process of the paradigm (Goldratt, 1990a:125). The continual improvement of the depot requires an understanding of the thinking process behind the procedures rather than merely applying the procedures.

The application of TOC to the IAF depots can be compared to the process of teaching someone to grow food. There are two alternatives. One path is to teach someone to grow food in a specific climate. Normally results can be achieved in a relatively short period of time. The other path, that takes far longer, is to educate a person so that he can determine how to grow food no matter what the climate (Avraham Y. Goldratt Institute, 1990:4). Given the climate changes that today's military organizations face, the latter approach is preferable. TOC appears to be a feasible framework for survival in today's turbulent climate.

Appendix A: Slam II Programs for Simulating Depot

Program 1: Traditional Depot Schedule

```
GEN,LEWIS,TOC EX1 MAINTENANCE DEPOT,5/12/1990,30,,,,,,78;
LIMITS,33,8,250;
EQUIVALENCE/ATRIB(1),WSTYPE/
            ATRIB(2),STHOURS/
            ATRIB(3),CSD_HOURS/
            ATRIB(4),CONSTRAINT_HOURS_RATIO/
            ATRIB(5),ARRIVAL_TIME/
            ATRIB(6),TAIL_#/
            ATRIB(7),DISMANTLING_WSTYPE/
            ATRIB(8),MANPOWER_CSD/;
INTLC,XX(1)=1;
SEEDS,9375295(1)/YES;
;        *****************************************
;THE PURPOSE OF THIS NETWORK IS TO DEMONSTRATE THE
;CURRENT SCHEDULING USED IN THE IAF DEPOTS.  THE
;MILITARY  ENVIRONMENT USED IS A SIMPLIFIED VERSION OF THE
;IAF ARMAMENTS DEPOT.
;          ***************************************
 NETWORK;
        RESOURCE/MENWS1(26),9,13;
        RESOURCE/MENWS2(26),10,19;
        RESOURCE/MENWS3(28),11,24;
        RESOURCE/MENWS4(34),12,29;
        RESOURCE/MENCSD(8),15;
        GATE/GAT1,OPEN,1;
        GATE/GAT2,OPEN,3;
        GATE/GAT3,OPEN,5;
        GATE/GAT4,OPEN,7;
;
;  **** ARRIVAL OF WEAPON SYSTEM TYPE 1 ****
;
        CREATE,2,0,5,,;
        ASSIGN,WSTYPE=1,
               STHOURS=1280,
               CSD_HOURS=160,
               CONSTRAINT_HOURS_RATIO=8,
               TAIL_#=XX(1),
               XX(1)=XX(1)+1,
               DISMANTLING_WSTYPE=1,
               MANPOWER_CSD=2;
        AWAIT(1/1),GAT1,BALK(PST1);
        ACTIVITY,,,SHP1;
;
;  **** ARRIVAL OF WEAPON SYSTEM TYPE 2 ****
;
```

```
        CREATE,2,0,5,,;
        ASSIGN,WSTYPE=2,
               STHOURS=1232,
               CSD_HOURS=112,
               CONSTRAINT_HOURS_RATIO=11,
               TAIL_#=XX(1),
               XX(1)=XX(1)+1,
               DISMANTLING_WSTYPE=1,
               MANPOWER_CSD=2;
        AWAIT(3/1),GAT2,BALK(PST2);
        ACTIVITY,,,SHP2;
;
;   **** ARRIVAL OF WEAPON SYSTEM TYPE 3 ****
;
        CREATE,2,0,5,,;
        ASSIGN,WSTYPE=3,
               STHOURS=1768,
               CSD_HOURS=240,
               CONSTRAINT_HOURS_RATIO=7.37,
               TAIL_#=XX(1),
               XX(1)=XX(1)+1,
               DISMANTLING_WSTYPE=1,
               MANPOWER_CSD=2;
        AWAIT(5/1),GAT3,BALK(PST3);
        ACTIVITY,,,SHP3;
;
;   **** ARRIVAL OF WEAPON SYSTEM TYPE 4 ****
;
        CREATE,2,0,5,,;
        ASSIGN,WSTYPE=4,
               STHOURS=2472,
               CSD_HOURS=240,
               CONSTRAINT_HOURS_RATIO=10.3,
               TAIL_#=XX(1),
               XX(1)=XX(1)+1,
               DISMANTLING_WSTYPE=1,
               MANPOWER_CSD=2;
        AWAIT(7/1),GAT4,BALK(PST4);
        ACTIVITY,,,SHP4;
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 1 ****
;
SHP1    AWAIT(9),MENWS1/2;
        ACTIVITY/2,EXPON(2);
;
; **** THIS ACTIVITY NODE ACCOUNTS FOR THE PRELIMINARY
;INSPECTION AT THE WORKSHOP OF THE INCOMING WEAPON SYSTEM
;TYPE 1 AS WELL AS THE DISMANTLING OF PARTS FOR THE C.S.D'S.
;THIS PROCESS HAS AN EXPONENTIAL DISTRIBUTION WITH A MEAN OF
```

```
;TWO DAYS.  THE AWAIT NODE INDICATES THAT TWO MEN HAVE TO BE
;AVAILABLE IN ORDER TO WORK ON THE PROCESS. ****
;
         FREE,MENWS1/2;
;
; **** FOLLOWING THE COMPLETION OF THIS INITIAL ACTIVITY AT
;THE WORKSHOP, THE TWO MEN ARE MADE AVAILABLE TO WORK ON
;OTHER ASSIGNMENTS.  ****
;
SPT1     UNBATCH,7,2;
         ACTIVITY,,,CSDQ;
         ACTIVITY,,,ZFT1;
ZFT1     AWAIT(13),MENWS1/4;
         ACTIVITY/6,EXPON(34);
         FREE,MENWS1/4;
         ACTIVITY,,,Q14;
CSD1     GOON,1;
         ACTIVITY/7,EXPON(10);
         FREE,MENCSD/2;
Q17      QUEUE(17),,,,M1PAR;
Q14      QUEUE(14),,,,M1PAR;
M1PAR    MATCH,6,Q14/Q18,Q17;
Q18      QUEUE(18);
         ACTIVITY;
         COLCT,INT(5),TIS_WS1;
         ACTIVITY,,,SHMSH;
;
; **** THE TERM "SHMSH" IS HEBREW FOR COMBAT READINESS.
;HENCE WHEN THE WEAPON SYSTEM HAS COMPLETED ITS MAINTENANCE
;IT EXITS THE SYSTEM FROM THE TERMINATE NODE THEREBY
;INDICATING THAT IT HAS BEEN RESTORED TO COMBAT
;READINESS. ****
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 2 ****
;
SHP2     AWAIT(10),MENWS2/2;
         ACTIVITY/3,EXPON(2);
         FREE,MENWS2/2;
SPT2     UNBATCH,7,2;
         ACTIVITY,,,CSDQ;
         ACTIVITY,,,ZFT2;
ZFT2     AWAIT(19),MENWS2/4;
         ACTIVITY/8,EXPON(34);
         FREE,MENWS2/4;
         ACTIVITY,,,Q20;
CSD2     GOON,1;
         ACTIVITY/9,EXPON(7);
         FREE,MENCSD/2;
Q22      QUEUE(22),,,,M2PAR;
Q20      QUEUE(20),,,,M2PAR;
```

```
M2PAR   MATCH,6,Q20/Q23,Q22;
Q23     QUEUE(23);
        ACTIVITY;
        COLCT,INT(5),TIS_WS2;
        ACTIVITY,,,SHMSH;
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 3 ****
;
SHP3    AWAIT(11),MENWS3/2;
        ACTIVITY/4,EXPON(3);
        FREE,MENWS3/2;
SPT3    UNBATCH,7,2;
        ACTIVITY,,,CSDQ;
        ACTIVITY,,,ZFT3;
ZFT3    AWAIT(24),MENWS3/5;
        ACTIVITY/10,EXPON(37);
        FREE,MENWS3/5;
        ACTIVITY,,,Q25;
CSD3    GOON,1;
        ACTIVITY/11,EXPON(15);
        FREE,MENCSD/2;
Q27     QUEUE(27),,,,M3PAR;
Q25     QUEUE(25),,,,M3PAR;
M3PAR   MATCH,6,Q25/Q28,Q27;
Q28     QUEUE(28);
        ACTIVITY;
        COLCT,INT(5),TIS_WS3;
        ACTIVITY,,,SHMSH;
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 4 ****
;
SHP4    AWAIT(12),MENWS4/3;
        ACTIVITY/5,EXPON(3);
        FREE,MENWS4/3;
SPT4    UNBATCH,7,2;
        ACTIVITY,,,CSDQ;
        ACTIVITY,,,ZFT4;
ZFT4    AWAIT(29),MENWS4/10;
        ACTIVITY/12,EXPON(27);
        FREE,MENWS4/10;
        ACTIVITY,,,Q30;
CSD4    GOON,1;
        ACTIVITY/13,EXPON(15);
        FREE,MENCSD/2;
Q32     QUEUE(32),,,,M4PAR;
Q30     QUEUE(30),,,,M4PAR;
M4PAR   MATCH,6,Q30/Q33,Q32;
Q33     QUEUE(33);
        ACTIVITY;
        COLCT,INT(5),TIS_WS4;
```

```
        ACTIVITY,,,SHMSH;
;
; **** CONSTRAINT BUFFER ****
;
CSDQ    AWAIT(15),MENCSD/MANPOWER_CSD;;
        ACTIVITY/14,0;
SNCSD   GOON,1;
        ACTIVITY,,WSTYPE.EQ.1,CSD1;
        ACTIVITY,,WSTYPE.EQ.2,CSD2;
        ACTIVITY,,WSTYPE.EQ.3,CSD3;
        ACTIVITY,,,CSD4;
;
; **** EXIT COMBAT READY WEAPON SYSTEM ****
;
SHMSH   TERM;
; **** CONTROLLING PROCEEDURE FOR OPENING AND CLOSING THE
;       GATE OF WEAPON SYSTEM TYPE 1. ****
;
        CREATE,,0.001;
        ACTIVITY,,,RPE1;
RPE1    GOON,1;
        ACT,0.001,NNQ(13).GE.6 .OR. NNQ(15).GE.100,CLS1;
        ACTIVITY,0.001,,RPE1;
CLS1    CLOSE,GAT1,1;
        ACT,0.001,NNQ(13).LE.5 .AND. NNQ(15).LE.99,OPN1;
        ACTIVITY,0.001,,CLS1;
OPN1    OPEN,GAT1,1;
        ACTIVITY,0.001,,RPE1;
;
; **** CONTROLLING PROCEEDURE FOR OPENING AND CLOSING THE
;       GATE OF WEAPON SYSTEM TYPE 2. ****
;
        CREATE,,0.001;
        ACTIVITY,,,RPE2;
RPE2    GOON,1;
        ACT,0.001,NNQ(19).GE.6 .OR. NNQ(15).GE.100,CLS2;
        ACTIVITY,0.001,,RPE2;
CLS2    CLOSE,GAT2,1;
        ACT,0.001,NNQ(19).LE.5 .AND. NNQ(15).LE.99,OPN2;
        ACTIVITY,0.001,,CLS2;
OPN2    OPEN,GAT2,1;
        ACTIVITY,0.001,,RPE2;
;
; **** CONTROLLING PROCEEDURE FOR OPENING AND CLOSING THE
;       GATE OF WEAPON SYSTEM TYPE 3. ****
;
        CREATE,,0.001;
        ACTIVITY,,,RPE3;
RPE3    GOON,1;
```

```
        ACT,0.001,NNQ(24).GE.5 .OR. NNQ(15).GE.100,CLS3;
        ACTIVITY,0.001,,RPE3;
CLS3    CLOSE,GAT3,1;
        ACT,0.001,NNQ(24).LE.4 .AND. NNQ(15).LE.99,OPN3;
        ACTIVITY,0.001,,CLS3;
OPN3    OPEN,GAT3,1;
        ACTIVITY,0.001,,RPE3;
;
; **** CONTROLLING PROCEEDURE FOR OPENING AND CLOSING THE
;      GATE OF WEAPON SYSTEM TYPE 4. ****
;
        CREATE,,0.001;
        ACTIVITY,,,RPE4;
RPE4    GOON,1;
        ACT,0.001,NNQ(29).GE.3 .OR. NNQ(15).GE.100,CLS4;
        ACTIVITY,0.001,,RPE4;
CLS4    CLOSE,GAT4,1;
        ACT,0.001,NNQ(29).LE.2 .AND. NNQ(15).LE.99,OPN4;
        ACTIVITY,0.001,,CLS4;
OPN4    OPEN,GAT4,1;
        ACTIVITY,0.001,,RPE4;
;
PST1    TERM;
PST2    TERM;
PST3    TERM;
PST4    TERM;
        END;
;
INIT,0,360;
FIN;
```

Program 2: TOC Schedule

```
GEN,LEWIS,TOC EX1 MAINTENANCE DEPOT,5/12/1990,30,,,,,,78;
LIMITS,33,8,250;
EQUIVALENCE/ATRIB(1),WSTYPE/
            ATRIB(2),STHOURS/
            ATRIB(3),CSD_HOURS/
            ATRIB(4),CONSTRAINT_HOURS_RATIO/
            ATRIB(5),ARRIVAL_TIME/
            ATRIB(6),TAIL_#/
            ATRIB(7),DISMANTLING_WSTYPE/
            ATRIB(8),MANPOWER_CSD/;
INTLC,XX(1)=1;
SEEDS,9375295(1)/YES;
PRIORITY/15,HVF(4);
;       ******************************************
;THE PURPOSE OF THIS NETWORK IS TO DEMONSTRATE THE
```

```
;APPLICABILTY OF THE TOC TO A MILITARY ENVRONMENT.  THE
;MILITARY  ENVIRONMENT USED IS A SIMPLIFIED VERSION OF THE
;IAF ARMAMENTS DEPOT.
;           ****************************************
 NETWORK;
        RESOURCE/DEMWS1(56),1;
        RESOURCE/DEMWS2(54),3;
        RESOURCE/DEMWS3(40),5;
        RESOURCE/DEMWS4(34),7;
;
; **** RESOURCES TERMED "DEMWS*" ARE USED FOR CONTROLLING
;THE ENTRANCE OF A WEAPON SYSTEM INTO THE MAINTENANCE SYSTEM
;DEPENDING ON THE OUTDTANDING FULLFILLMENT OF MARKET DEMAND.
;THE  NUMBER OF "RESOURCES" LEFT IN THE SYSTEM INDICATES THE
;OUTSTANDING FULLFILLMENT OF MARKET DEMAND.  IF THE NUMBER
;IS POSITVE THEN A WEAPON SYSTEM WILL BE PERMITED TO ENTER
;THE SYSTEM THROUGH THE "RESOURCES" "AWAIT" NODE. ****
;
        RESOURCE/MENWS1(26),9,13;
        RESOURCE/MENWS2(26),10,19;
        RESOURCE/MENWS3(28),11,24;
        RESOURCE/MENWS4(34),12,29;
        RESOURCE/MENCSD(8),15;
        GATE/GAT1,OPEN,2;
;
;  **** ARRIVAL OF WEAPON SYSTEM TYPE 1 ****
;
        CREATE,1.5,0,5,,;
        ASSIGN,WSTYPE=1,
               STHOURS=1280,
               CSD_HOURS=160,
               CONSTRAINT_HOURS_RATIO=8,
               TAIL_#=XX(1),
               XX(1)=XX(1)+1,
               DISMANTLING_WSTYPE=1,
               MANPOWER_CSD=2;
        ACTIVITY,,,GAT1;
DEM1    AWAIT(1/1),DEMWS1/1,BALK(MKT1);
        ACTIVITY,,,SHP1;
;
; **** THE FIRST CONDITION TO BEING RELEASED ONTO THE SHOP
;FLOOR IS THAT THERE EXISTS A MARKET DEMAND.  IF SO THE ITEM
;ENTERS A QUEUE. ****
;
;  **** ARRIVAL OF WEAPON SYSTEM TYPE 2 ****
;
        CREATE,.5,0,5,,;
        ASSIGN,WSTYPE=2,
               STHOURS=1232,
               CSD_HOURS=112,
```

```
                CONSTRAINT_HOURS_RATIO=11,
                TAIL_#=XX(1),
                XX(1)=XX(1)+1,
                DISMANTLING_WSTYPE=1,
                MANPOWER_CSD=2;
        ACTIVITY,,,GAT1;
DEM2    AWAIT(3/1),DEMWS2/1,BALK(MKT2);
        ACTIVITY,,,SHP2;
;
;   **** ARRIVAL OF WEAPON SYSTEM TYPE 3 ****
;
        CREATE,2,0,5,,;
        ASSIGN,WSTYPE=3,
                STHOURS=1768,
                CSD_HOUPS=240,
                CONSTRAINT_HOURS_RATIO=7.37,
                TAIL_#=XX(1),
                XX(1)=XX(1)+1,
                DISMANTLING_WSTYPE=1,
                MANPOWER_CSD=2;
        ACTIVITY,,,GAT1;
DEM3    AWAIT(5/1),DEMWS3/1,BALK(MKT3);
        ACTIVITY,,,SHP3;
;
;   **** ARRIVAL OF WEAPON SYSTEM TYPE 4 ****
;
        CREATE,1,0,5,,;
        ASSIGN,WSTYPE=4,
                STHOURS=2472,
                CSD_HOURS=240,
                CONSTRAINT_HOURS_RATIO=10.3,
                TAIL_#=XX(1),
                XX(1)=XX(1)+1,
                DISMANTLING_WSTYPE=1,
                MANPOWER_CSD=2;
        ACTIVITY,,,GAT1;
DEM4    AWAIT(7/1),DEMWS4/1,BALK(MKT4);
        ACTIVITY,,,SHP4;
;
; **** A "GATE" TO THE DEPOT IS EITHER OPEN OR CLOSED TO
;ALLOWING WEAPON SYSTEMS INTO THE DEPOT.  THE GATE BEING
;OPEN IS A NECESSARY CONDITION FOR ALLOWING A WEAPON SYSTEM
;TO ENTER THE DEPOT.  ****
;
GAT1   AWAIT(2/1),GAT1,BALK(PST1);
       ACTIVITY;
       GOON,1;
       ACTIVITY,,WSTYPE.EQ.1,DEM1;
       ACTIVITY,,WSTYPE.EQ.2,DEM2;
       ACTIVITY,,WSTYPE.EQ.3,DEM3;
```

```
        ACTIVITY,,,DEM4;
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 1 ****
;
SHP1     AWAIT(9),MENWS1/2;
         ACTIVITY/2,EXPON(2);
;
; **** THIS ACTIVITY NODE ACCOUNTS FOR THE PRELIMINARY
;INSPECTION AT THE WORKSHOP OF THE INCOMING WEAPON SYSTEM
;TYPE 1 AS WELL AS THE DISMANTLING OF PARTS FOR THE C.S.D'S.
;THIS PROCESS HAS AN EXPONENTIAL DISTRIBUTION WITH A MEAN OF
;TWO DAYS.  THE AWAIT NODE INDICATES THAT TWO MEN HAVE TO BE
;AVAILABLE IN ORDER TO WORK ON THE PROCESS. ****
;
          FREE,MENWS1/2;
;
; **** FOLLOWING THE COMPLETION OF THIS INITIAL ACTIVITY AT
;THE WORKSHOP, THE TWO MEN ARE MADE AVAILABLE TO WORK ON
;OTHER ASSIGNMENTS.  ****
;
SPT1     UNBATCH,7,2;
         ACTIVITY,,,CSDQ;
         ACTIVITY,,,ZFT1;
ZFT1     AWAIT(13),MENWS1/4;
         ACTIVITY/6,EXPON(34);
         FREE,MENWS1/4;
         ACTIVITY,,,Q14;
CSD1     GOON,1;
         ACTIVITY/7,EXPON(10);
         FREE,MENCSD/2;
Q17      QUEUE(17),,,,M1PAR;
Q14      QUEUE(14),,,,M1PAR;
M1PAR    MATCH,6,Q14/Q18,Q17;
Q18      QUEUE(18);
         ACTIVITY;
         COLCT,INT(5),TIS_WS1;
         ACTIVITY,,,SHMSH;
;
; **** THE TERM "SHMSH" IS HEBREW FOR COMBAT READINESS.
;HENCE WHEN THE WEAPON SYSTEM HAS COMPLETED ITS MAINTENANCE
;IT EXITS THE SYSTEM FROM THE TERMINATE NODE THEREBY
;INDICATING THAT IT HAS BEEN RESTORED TO COMBAT
;READINESS. ****
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 2 ****
;
SHP2     AWAIT(10),MENWS2/2;
         ACTIVITY/3,EXPON(2);
         FREE,MENWS2/2;
SPT2     UNBATCH,7,2;
```

```
         ACTIVITY,,,CSDQ;
         ACTIVITY,,,ZFT2;
ZFT2     AWAIT(19),MENWS2/4;
         ACTIVITY/8,EXPON(34);
         FREE,MENWS2/4;
         ACTIVITY,,,Q20;
CSD2     GOON,1;
         ACTIVITY/9,EXPON(7);
         FREE,MENCSD/2;
Q22      QUEUE(22),,,,M2PAR;
Q20      QUEUE(20),,,,M2PAR;
M2PAR    MATCH,6,Q20/Q23,Q22;
Q23      QUEUE(23);
         ACTIVITY;
         COLCT,INT(5),TIS_WS2;
         ACTIVITY,,,SHMSH;
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 3 ****
;
SHP3     AWAIT(11),MENWS3/2;
         ACTIVITY/4,EXPON(3);
         FREE,MENWS3/2;
SPT3     UNBATCH,7,2;
         ACTIVITY,,,CSDQ;
         ACTIVITY,,,ZFT3;
ZFT3     AWAIT(24),MENWS3/5;
         ACTIVITY/10,EXPON(37);
         FREE,MENWS3/5;
         ACTIVITY,,,Q25;
CSD3     GOON,1;
         ACTIVITY/11,EXPON(15);
         FREE,MENCSD/2;
Q27      QUEUE(27),,,,M3PAR;
Q25      QUEUE(25),,,,M3PAR;
M3PAR    MATCH,6,Q25/Q28,Q27;
Q28      QUEUE(28);
         ACTIVITY;
         COLCT,INT(5),TIS_WS3;
         ACTIVITY,,,SHMSH;
;
; **** COMMENCEMENT OF MAINTENANCE ON WSTYPE 4 ****
;
SHP4     AWAIT(12),MENWS4/3;
         ACTIVITY/5,EXPON(3);
         FREE,MENWS4/3;
SPT4     UNBATCH,7,2;
         ACTIVITY,,,CSDQ;
         ACTIVITY,,,ZFT4;
ZFT4     AWAIT(29),MENWS4/10;
         ACTIVITY/12,EXPON(27);
```

```
        FREE,MENWS4/10;
        ACTIVITY,,,Q30;
CSD4    GOON,1;
        ACTIVITY/13,EXPON(15);
        FREE,MENCSD/2;
Q32     QUEUE(32),,,,M4PAR;
Q30     QUEUE(30),,,,M4PAR;
M4PAR   MATCH,6,Q30/Q33,Q32;
Q33     QUEUE(33);
        ACTIVITY;
        COLCT,INT(5),TIS_WS4;
        ACTIVITY,,,SHMSH;
;
; **** CONSTRAINT BUFFER ****
;
CSDQ    AWAIT(15),MENCSD/MANPOWER_CSD;;
        ACTIVITY/14,0; ;
SNCSD   GOON,1;
        ACTIVITY,,WSTYPE.EQ.1,CSD1;
        ACTIVITY,,WSTYPE.EQ.2,CSD2;
        ACTIVITY,,WSTYPE.EQ.3,CSD3;
        ACTIVITY,,,CSD4;
;
; **** EXIT COMBAT READY WEAPON SYSTEM ****
;
SHMSH   TERM;
; **** CONTROLLING PROCEEDURE FOR OPENING AND CLOSING THE
;       GATE. ****
;
        CREATE,,0.001;
        ACTIVITY,,,RPE1;
RPE1    GOON,1;
        ACTIVITY,0.001,NNQ(15).GE.4,CLS1;
        ACTIVITY,0.001,,RPE1;
CLS1    CLOSE,GAT1,1;
        ACTIVITY,0.1,NNQ(15).LE.3,OPN1;
        ACTIVITY,0.1,,CLS1;
OPN1    OPEN,GAT1;
        ACTIVITY,0.1,,RPE1;
;
PST1    TERM;
MKT1    TERM;
MKT2    TERM;
MKT3    TERM;
MKT4    TERM;
        END;
;
INIT,0,360;
FIN;
```

Appendix B: Calculation of Capacity Load Profile

1. Potential yearly working capacity of one soldier:

   360 days x 8 hrs per day = 2,880 hrs

2. Capacity load profile for FWS1:

   a. Standard processing hrs for one WST1 in FWS1:
      Preliminary inspection:
      2 men x 2 days x 8 hrs = 32 hrs
      Maintenance action:
      4 men x 34 days x 8 hrs = 1,088 hrs
      Total processing hrs:
      32 hrs + 1,088 hrs = 1,120 hrs

   b. Yearly demand for WST1 in standard processing hrs:
      56 WST1 x 1,120 hrs = 62,720 hrs

   c. Potential yearly working capacity of FWS1:
      26 men x 2,880 hrs = 74,880 hrs

   d. Capacity load profile calculation:
      62,720 hrs / 74,880 hrs = 83.76 %

3. Capacity load profile for FWS2:

   a. Standard processing hrs for one WST2 in FWS2:
      Preliminary inspection:
      2 men x 2 days x 8 hrs = 32 hrs
      Maintenance action:
      4 men x 34 days x 8 hrs = 1,088 hrs
      Total processing hrs:
      32 hrs + 1,088 hrs = 1,120 hrs

   b. Yearly demand for WST2 in standard processing hrs:
      54 WST2 x 1,120 hrs = 60,480 hrs

   c. Potential yearly working capacity of FWS2:
      26 men x 2,880 hrs = 74,880 hrs

   d. Capacity load profile calculation:
      60,480 hrs / 74,880 hrs = 80.86 %

4. Capacity load profile for FWS3:

   a. Standard processing hrs for one WST3 in FWS3:
      Preliminary inspection:
      2 men x 3 days x 8 hrs = 48 hrs

AD-A231 278 INVESTIGATING THE APPLICATION OF THE THEORY OF CONSTRAINTS TO THE SCHEDUL..(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF SYST.. L S TRIGGER 3/3

UNCLASSIFIED DEC 90 AFIT/GLM/LSM/90D-61 XF-AFIT F/G 5/1 NL

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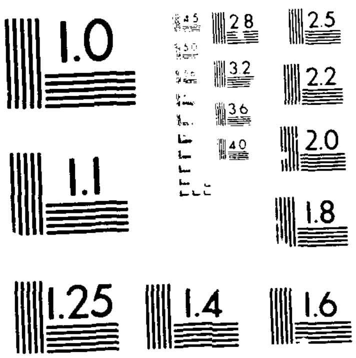

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Maintenance action:
5 men x 37 days x 8 hrs = 1,480 hrs
Total processing hrs:
48 hrs + 1,480 hrs = 1,528 hrs

b. Yearly demand for WST3 in standard processing hrs:
40 WST3 x 1,528 hrs = 61,120 hrs

c. Potential yearly working capacity of FWS3:
28 men x 2,880 hrs = 80,640 hrs

d. Capacity load profile calculation:
61,120 hrs / 80,640 hrs = 75.79 %

5. Capacity load profile for FWS4:

a. Standard processing hrs for one WST4 in FWS4:
Preliminary inspection:
3 men x 3 days x 8 hrs = 72 hrs
Maintenance action:
10 men x 27 days x 8 hrs = 2,160 hrs
Total processing hrs:
72 hrs + 2,160 hrs = 2,232 hrs

b. Yearly demand for WST4 in standard processing hrs:
34 WST4 x 2,232 hrs = 75,888 hrs

c. Potential yearly working capacity of FWS4:
34 men x 2,880 hrs = 97,920 hrs

d. Capacity load profile calculation:
75,888 hrs / 97,920 hrs = 77.5 %

6. Capacity load profile for CSD:

a. Yearly demand for WST1 in standard processing hrs:
56 WST1 x 2men x 10days x 8hrs = 8,960 hrs

b. Yearly demand for WST2 in standard processing hrs:
54 WST2 x 2men x 7days x 8hrs = 6,048 hrs

c. Yearly demand for WST3 in standard processing hrs:
40 WST3 x 2men x 15days x 8hrs = 9,600 hrs

d. Yearly demand for WST4 in standard processing hrs:
34 WST4 x 2men x 15days x 8hrs = 8,160 hrs

e. Total yearly demand in standard processing hrs:
8,960hrs + 6,048hrs + 9,600hrs + 8,160 hrs = 32,768

f. Potential yearly working capacity of CSD:
8 men x 2,880 hrs = 23,040 hrs

g. Capacity load profile calculation:
32,768 hrs / 23,040 hrs = 142 %

Appendix C: Standard Processing Hours per Constraint Unit of Time

1. Constraint ratio for WST1:
   Standard processing hrs for WST1 = 1280 hrs
   Constraint processing hrs for WST1 = 160 hrs
   1280 hrs / 160 hrs = 8 hrs

2. Constraint ratio for WST2:
   Standard processing hrs for WST2 = 1232 hrs
   Constraint processing hrs for WST2 = 112 hrs
   1232 hrs / 112 hrs = 11 hrs

3. Constraint ratio for WST3:
   Standard processing hrs for WST3 = 1768 hrs
   Constraint processing hrs for WST3 = 240 hrs
   1768 hrs / 240 hrs = 7.37 hrs

4. Constraint ratio for WST4:
   Standard processing hrs for WST4 = 2472 hrs
   Constraint processing hrs for WST4 = 240 hrs
   2472 hrs / 240 hrs = 10.3 hrs

Appendix D: Observations from Simulation Runs

TOC SCHEDULE: BUFFER SIZE FOUR

RUN	QTY-WST 1	2	3	4	TOTAL HOURS	MAKESPAN-WST 1	2	3	4	INV
1	29	53	25	33	228192	45	54	63	50	25
2	23	51	18	30	198256	62	41	87	43	12
3	31	54	24	34	232688	35	40	59	37	29
4	32	54	18	34	223360	39	34	77	53	17
5	31	54	22	29	216792	36	45	73	49	21
6	28	46	15	30	193192	44	65	87	44	25
7	20	52	15	31	192816	45	57	87	43	13
8	23	54	18	32	206896	44	39	75	44	46
9	19	52	15	26	179176	34	36	96	52	23
10	23	54	14	31	197352	45	56	102	42	11
11	31	54	25	32	229512	33	41	71	79	30
12	20	51	20	32	202896	47	77	77	40	16
13	22	53	17	31	200144	47	42	78	37	15
14	23	54	21	31	209728	34	41	73	45	9
15	29	54	21	33	222352	50	44	76	48	20
16	29	52	18	30	207168	29	46	75	42	13
17	33	51	21	31	218832	37	53	79	63	13
18	29	53	24	29	216536	42	52	70	47	18
19	23	54	18	28	197008	38	36	75	46	18
20	21	51	14	28	183680	39	40	77	45	15
21	25	54	22	32	216528	38	38	76	37	12
22	24	50	17	27	189120	45	38	90	51	25
23	19	54	17	29	192592	45	40	72	54	20
24	24	53	16	29	195992	43	33	89	48	16
25	21	54	17	24	182792	45	65	89	37	25
26	30	54	24	33	228936	37	42	70	44	14
27	26	53	16	32	205968	51	45	91	36	13
28	28	54	18	27	200936	46	34	84	32	20
29	27	52	21	27	202496	45	64	71	50	22
30	32	52	26	34	235040	46	35	59	39	19
AVG	25.8	52.7	19.2	30.3	206899.2	42.2	45.8	78.3	45.9	19.2
SD	4.41	1.79	3.62	2.59	15967.03	6.71	11.3	10.4	9.2	7.58
CIU	27.4	53.3	20.5	31.2	212612.9	44.6	49.8	82	49.2	21.9
CIL	24.3	52.1	17.9	29.4	201185.5	39.8	41.7	74.5	42.6	16.5

TOC SCHEDULE: BUFFER SIZE FIFTEEN

RUN	QTY-WST 1	2	3	4	TOTAL HOURS	MAKESPAN-WST 1	2	3	4	INV
1	24	53	8	31	186792	68	37	266	50	36
2	25	48	15	34	201704	85	122	193	51	55
3	43	54	26	34	251584	57	47	133	84	39
4	33	54	15	34	219336	54	51	172	51	32
5	27	53	12	32	200176	61	74	241	51	35
6	29	53	12	34	207680	65	71	253	52	33
7	28	53	11	34	204632	74	53	209	53	63
8	33	53	13	34	214568	63	78	217	48	37
9	28	53	12	34	206400	56	106	216	48	28
10	33	53	16	34	219872	60	75	204	51	39
11	40	53	24	34	242976	47	101	156	54	41
12	32	53	15	34	216824	61	92	221	44	36
13	29	52	7	28	182776	75	90	270	64	49
14	28	54	15	33	210464	72	67	200	56	36
15	33	54	19	29	214048	60	86	191	110	41
16	33	53	16	34	219872	60	74	197	75	48
17	32	54	12	33	210280	64	113	240	42	32
18	31	54	21	34	227384	63	44	173	54	43
19	33	54	16	33	218632	52	39	189	69	34
20	40	52	22	27	220904	43	105	178	82	38
21	25	54	4	29	177288	86	56	246	62	34
22	32	52	13	34	212056	60	66	225	45	41
23	25	50	14	32	197456	72	83	203	43	39
24	35	53	16	33	219960	69	74	175	82	34
25	37	54	17	31	220576	58	77	199	65	34
26	28	54	9	30	192440	67	42	262	88	35
27	26	54	8	32	193056	76	64	249	54	45
28	29	53	11	34	205912	78	61	211	63	30
29	27	53	9	34	199816	67	45	25	48	35
30	24	46	3	30	166856	79	78	316	54	48
AVG	30.7	52.8	13.7	32.4	208744	65.1	72.4	208	59.8	39
SD	4.98	1.84	5.46	2.13	18059.91	10.5	23.2	52.5	16.3	7.73
CIU	32.5	53.4	15.7	33.2	215206.7	68.8	80.7	226	65.6	41.8
CIL	29	52.1	11.7	31.7	202281.3	61.3	64.1	189	53.9	36.2

TRADITIONAL SCHEDULE

RUN	QTY-WST 1	2	3	4	TOTAL HOURS	MAKESPAN-WST 1	2	3	4	INV
1	37	37	24	29	207064	135	132	135	125	191
2	45	35	32	17	199320	155	148	154	156	187
3	47	60	34	20	243632	113	111	109	107	187
4	46	37	29	24	215064	125	120	126	134	193
5	44	34	35	18	204584	122	127	120	133	186
6	38	42	37	22	220184	122	120	122	122	187
7	51	43	32	23	231688	116	116	122	113	159
8	37	37	37	22	212744	142	136	135	130	188
9	43	44	31	21	215968	89	111	109	132	[illegible]
10	30	30	18	31	183816	142	131	141	147	193
11	42	31	28	26	205728	161	140	139	150	189
12	31	36	36	25	209480	117	120	134	129	187
13	35	34	28	16	175744	128	117	121	97	195
14	44	43	33	26	231912	104	92	114	107	191
15	41	43	31	29	231952	118	104	122	104	173
16	38	39	30	22	204112	100	102	104	107	184
17	38	31	17	19	163856	156	154	160	156	199
18	46	29	27	18	186840	141	143	133	[illegible]	187
19	31	35	28	29	203992	148	133	141	143	202
20	38	46	29	21	208496	111	119	102	122	190
21	35	39	30	25	207688	141	133	129	125	189
22	44	31	32	27	217832	118	108	119	136	193
23	44	32	31	23	207408	121	123	121	116	186
24	33	39	32	24	206192	132	127	140	134	186
25	39	36	25	22	192856	119	113	106	113	195
26	36	31	25	20	177912	144	144	142	144	191
27	39	35	28	23	199400	146	146	150	146	185
28	48	36	24	21	200136	138	134	124	138	185
29	35	48	34	19	211016	138	147	149	146	151
30	44	47	30	27	234008	117	113	114	117	186
AVG	40	38	29.6	23	207020.8	129	125	128	129	187
SD	5.55	6.84	4.91	3.93	18347.2	17.7	15.7	15.6	16.6	10.3
CIU	42	40.4	31.3	24.4	213586.3	135	131	133	135	190
CIL	38	35.6	27.8	21.6	200455.3	122	120	122	123	183

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Vita

Major Lewis S. Trigger was born in Brisbane, Australia in 1955. After completing undergraduate studies in History and Law at the University of Queensland, he emigrated to Israel at the age of 21. On completing graduate studies in Business Administration at the Hebrew University of Jerusalem, he enlisted in the Israeli Air Force in 1981. He completed officer's course in 1982. Major Trigger has had several assignments related to logistic's planning both at the field and HQ level. He was sent to the School of Systems and Logistics, Air Force Institute of Technology, in May 1989. He is married and has two children.

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13. ABSTRACT *(Maximum 200 words)*
This research investigated the application and merits of the Theory of Constraints (TOC) to the scheduling environment of the Israeli Air Force's (IAF) maintenance depots. TOC was extensively reviewed including an elaboration of the TOC paradigm and the scheduling procedures developed for a commercial manufacturing setting. Background information was also presented on the IAF depots and traditional scheduling rules. An experiment was designed and conducted that simulated a simplified version of the process flow of the armaments depot. The simulation compared the performance of the depot using a schedule based on TOC as opposed to the traditional depot schedule. The results of the simulation clearly favored the TOC schedule in terms of lower inventory and makespan. The experiment did not conclusively show any difference in standard throughput hours as a result of the TOC schedule. These results were statistically validated. It was concluded that the core scheduling procedures of TOC, specifically the concept of drum-buffer-rope and buffer management were applicable to the depot environment and provided advantages over the traditional depot schedule. Difficulties were found in defining a uniform measurement for throughput and inventory for the depot environment. (25)

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