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Value enhancement in a dynamic environment—a constraint management expert system for the oil refinery industry

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This paper analyses a case study of a dynamic expert system which was developed according to the theory of constraints (TOC) approach, and implemented at the Ashdod refinery of Oil Refineries Ltd in Israel, as part of an overall improvement process based on the focused management philosophy. The unique feature of the system is its ability to cope with dynamic bottlenecks typical of the continuous process industry, as well as frequent shifts from an external market constraint to internal capacity constraints. The paper examines the development and implementation stages, describes the expert system along with the new process control, and evaluates its impact. The system creates a dynamic, effective and immediate link between the production planning and the operation control, which enables the oil refinery to maximize its profits. During the first two years of its use, the system generated over $3 million of estimated benefits. Finally, we suggest practical implications to assist organizations in developing and utilizing similar applications, emphasizing knowledge gathering and maintenances, which are the major challenges facing expert systems projects.

Keywords: Theory of constraints (TOC); Focused management; Expert system; Oil refineries

1. Introduction

Continuous process industries, such as oil refining, are apparently prime candidates for a theory of constraints (TOC) implementation, since they are capital intensive and their throughput is usually constrained by their refining capacity (Goldratt and Cox 1986). However, most of the TOC manufacturing implementations are in assembly industries, job shops and batch production industries (Mabin and Balderstone 2000, Gupta 2003), while reports on continuous process TOC applications, such as that by Schragenheim *et al.* (1994), are rare. The oil refining production process is complex and although it is continuous, and therefore never stops, there exist bottlenecks that block the system from producing more throughput; some of them are planned in advance, while others occur due to malfunctions, variations in crude oil quality, and so forth. Linear programming (LP)

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may facilitate the production planning, but its ability to support the operation control are limited. The situation became even more complicated during the years 2001–2002 when there was a sharp drop in the global demand for oil products, and some refineries had excess capacity which caused a decrease in refinery margins. The operators had to change their practices abruptly; instead of trying to maximize production, they had to adhere to the plan. Even knowledgeable experts would find it difficult to perform in an optimal manner in this dynamic and complex environment, for reasons of human bounded rationality (Simon 1957). An expert system may help organizations to relieve the bounded rationality constraint (Gurbaxani and Whang 1991) as, unlike human operators, it immediately adjusts to changes in the production environment and can provide the operators with guidance which will improve their performance. Nevertheless, there are just a few articles on expert system applications in oil refineries, and they mainly deal with the technical characteristics of the system (e.g. Qian *et al.* 2005) and not with its managerial aspects.

This paper describes a case study of a dynamic expert system which was developed according to the TOC approach, and implemented at the Ashdod refinery of Oil Refineries Ltd. in Israel, as part of an overall improvement process based on the focused management philosophy. The unique feature of the system is its ability to cope with dynamic bottlenecks typical of the continuous process industry, as well as frequent shifts from an external market constraint to internal capacity constraints.

The contributions of this paper are three-fold:

First, it demonstrates that TOC concepts can be successfully applied in a dynamic, production environment using an expert system.

Second, it shows how to use TOC in the specific environment of the continous flow shop floor. Thus, the paper is an application that combines expert system practice with TOC.

Third, it demonstrates the contribution of focused management practices to working together with TOC. TOC, powerful as it is, is not sufficient for complex implementations, and needs the support of other managerial philosophies and techniques.

Section 2 presents the focused management philosophy, explains the opportunities and challenges of expert systems, and reviews the relevant literature. Section 3 depicts the Ashdod oil refinery, its production process and its dynamic constraints. In section 4 the expert system development process which followed the TOC focusing steps is described. Section 5 portrays the expert system and the new improved process control. Section 6 describes the implementation and its impact, and ends with an epilogue which reflects the state of affairs three years later. The last two sections discuss the implications of the case study in order to assist organizations in developing and utilizing similar applications, and conclude the article.

2. Theoretical background

2.1 *The focused management philosophy*

The focused management philosophy is aimed at increasing the value of organizations. It has been successfully implemented in dozens of industrial, high-tech and service organizations worldwide (Ronen *et al.* 2006). Focused management combines innovative managerial approaches such as those listed below:

- The theory of constraints (TOC) was developed by Goldratt (Goldratt and Cox 1986, Goldratt 1994). TOC claims that the attention of management should be focused on the few constraints which prevent the organization from achieving its goal. We will elaborate on TOC later.
- Just in time (JIT) philosophy originated in Japan (Schonberger 1986). It can be summarized in three main principles: prepare just the required items, at the exact time and according to the specifications; use appropriate, clever small lots; eliminate waste and non-value-adding activities.
- The complete kit concept asserts that work on an assignment should begin only when all the items required for its completion are available at hand. Applying this concept results in shorter lead times, better quality, increased throughput and cost savings (Ronen 1992, Leshno and Ronen 2001).
- The global decision-making methodology (GDM) is a simple practical method for organizational decision-making. It supports decisions on issues like pricing, make or buy, capital investments, product mix and more (Geri and Ronen 2005).

In this article, we will concentrate mainly on TOC, which is gaining increasing acceptance among practitioners as well as academics (Rahman 1998, Gupta 2003), and its application, providing thousands of organizations worldwide with significant performance improvements, such as increased throughput, reduced inventory levels and shorter lead time (Mabin and Balderstone 2000, Ronen 2005). While reports of successful TOC implementation are mainly from manufacturing organizations, especially aerospace, apparel, automotive, electronics, furniture, semiconductor, steel and heavy engineering (Mabin and Balderstone 2003), TOC has also been implemented in diverse non-manufacturing industries, including financial institutions (Smith 2004), enterprise software (Ioannou and Papadoyiannis 2004), health services (Ronen *et al.* 2006) and also in the public sector (Shoemaker and Reid 2005). Schragenheim *et al.* (1994) apply TOC in the process flow industry and adjust the drum-buffer-rope methodology to the needs of this environment. Nevertheless, there are hardly any academic reports on continuous process TOC applications.

Goldratt (1991) initially defined the five focusing steps of TOC to maximizing the performance of a system (see steps 3–7 below). Ronen and Spector (1992) enhanced the process by adding two preliminary steps (see steps 1–2 below). These two steps are particularly important regarding sub-systems or in situations of dynamic constraints, as demonstrated in the following case study. Thus, the seven focusing steps are (Ronen *et al.* 2001):

1. Define the system's goal.
2. Determine global performance measures.
3. Identify the system's constraints.
4. Decide how to exploit the system's constraint.
5. Subordinate the system to the constraint.
6. Elevate the system's constraint.
7. If, in the previous steps, a constraint has been broken, go back to step 3. Do not let inertia become the system's constraint.

Although the principles of the seven focusing steps seem straightforward and practical, their implementation requires a significant effort, since it fundamentally transforms all the organizational processes. Hence, it is crucial for top management to lead the change. The seven focusing steps are further demonstrated in the case study.

The distinction between a resource constraint and a market constraint is especially important in the context of this study:

A resource constraint, or a bottleneck, is any resource whose capacity is equal to or less than the demand placed upon it (Goldratt and Cox 1986). It is termed an internal constraint because it is under the organization's control.

A market constraint is a situation in which the system is able to supply all the demand for its products or services under normal operating capacity. A market constraint is classified as an external constraint, since it is not under the organization's immediate control.

Organizations, such as the oil refinery described in the following sections, which operate in a dynamic environment, face major challenges in applying TOC, since even their global performance measures change as they move from a resource constraint to a market constraint situation.

2.2 *Expert systems opportunities and challenges*

This section explains the essence of expert systems, their potential benefits and the main difficulties in their development, implementation and continuing operation. It provides the necessary theoretical background for analysing the reasons why the expert system described in this paper was successful, which is noteworthy in light of the slow diffusion of such systems. Expert systems are knowledge intensive computer programs which emulate expert problem solving skills in a bounded domain of expertise. They are set out to capture and assist or automate complex non-algorithmic decisions (Sviokla 1990). Expert systems usually consist of three main components (Metaxiotis and Psarras 2003):

1. A *knowledge base*—that contains the knowledge needed for solving a specific problem. The knowledge can be previously installed or acquired by means of self-learning systems. The most commonly used technique for representing the knowledge is by 'if-then' rules.
2. An *inference engine*—that provides the reasoning mechanism. It handles the content of the knowledge base and determines the order in which inferences are made.
3. A *user interface*—which is used for interactive communication with the user, to get information regarding the situation and to display the system's recommendations. Some systems provide explanations on the way they reached their results. Sometimes, the user interface may be used for updating the knowledge base and maintaining the system.

Jayaraman and Srivastava (1996) present an overview of expert systems and examine their application in production and operations management. Expert systems were among the earliest types of artificial intelligence which achieved widespread commercial feasibility (Gill 1995). In the early and mid-1980s, there were successful systems, such as Digital's XCON which produced over $15 million benefits in five years (Sviokla 1990). However, the diffusion of expert systems has been much slower than originally anticipated (Ein-Dor 1999) and the main challenges are to acquire the knowledge and to maintain it.

Successful expert systems usually focus on a narrow domain of knowledge and are custom-made to support specific decisions. This means that the required knowledge must be gathered from the experts who currently perform these tasks. One of the critical success factors of an expert system development project is the willingness of the experts to collaborate and provide their knowledge (Benavides and Prado 2002). Even if they are willing to share their knowledge, still the problems are complex and the decisions are unstructured. If one strives for the optimal solution, the system may never be completed. Hence, the system designers should seek satisfactory solutions, i.e. satisfying (Simon 1957) rather than optimizing. Another difficulty arises when there are several experts involved and each one of them recommends a different course of action; then a consensus must be reached.

After an expert system has been successfully implemented, the knowledge base must be updated. Human experts will always want to add new knowledge, or modify the existing heuristics as new situations occur. Also, while maintaining the knowledge base, one must ensure the consistency of the rules and avoid situations such as contradiction, redundancy or circulation (Qian *et al.* 2005). Although expert systems are technically complex, a study of expert systems which were discarded during the six-year period from 1987 to 1992 (Gill 1995), revealed that in most cases the abandonment was not attributable to failure to meet technical performance or economic objectives. The most significant factors for expert systems disuse appeared to be managerial issues such as lack of system acceptance by users, inability to retain developers, or problems in transitioning from development to maintenance.

Nevertheless, if an expert system is so hard to build, implement and maintain, is it worth the effort? The following case study demonstrates how one company overcame the obstacles and reaped considerable benefits from its expert system.

3. The case study setting

3.1 *Oil Refineries Ltd*

Oil Refineries Ltd (ORL) is an Israeli company owned jointly by the state of Israel (74%) and the Israel Corporation Ltd (26%). ORL's revenues amounted to $3.9 billion in 2004 and it is among the ten largest Israeli industrial companies. ORL provides most of Israel's petroleum needs and exports around 20% of its throughput. The company owns and operates two oil refineries, one in Haifa and the other in Ashdod. During 1999, ORL initiated a company-wide accelerated improvement process which was based on the focused management philosophy. The process resulted in increased throughput which was enabled by releasing bottlenecks, shortening lead times, implementing more efficient maintenance procedures and more.

In light of these achievements, ORL's management decided to carry out another improvement effort that was aimed at the production planning and process control, which is very complicated, but is of great importance to ORL's profitability and value creation potential. It was decided to start with the Ashdod refinery since its

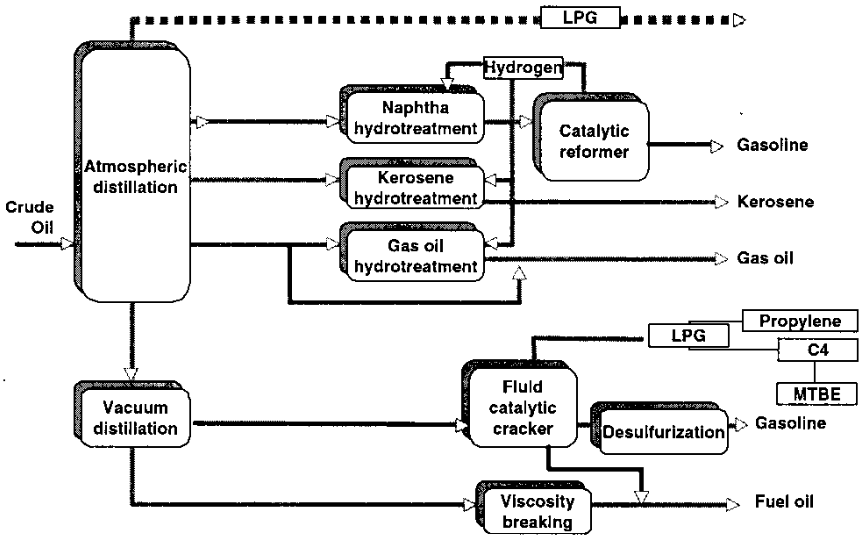

Figure 1. The Ashdod oil refining process.

production layout was less complex than the Haifa refinery's, it had independent planning capabilities, and its management team was willing to go along with the project.

3.2 *The Ashdod refinery and its production process*

The Ashdod Oil Refinery (AOR) was established in 1973 as a primary oil refining plant. Over the years, the production facilities were extended and improved, and a fluid catalytic cracker that was built at the beginning of the 1990s significantly increased the refinery throughput.

AOR produces a wide range of refined products, including liquefied petroleum gas (LPG), gasoline and naphtha, kerosene, gas oil and fuel oil. The refining process is illustrated in figure 1.

The refining process is continuous, so AOR operates three shifts around the clock, 365 days a year. The production facilities are controlled by a central computer, and are monitored by control room operators (also called boardmen or control panel operators, hereafter operators) who sit together in a central control room. The shift supervisor, who also sits in the control room, manages current operations with the help of chief operators and field operators in charge of specific facilities. Each area has an assigned field engineer, who among other things determines the performance measures which are used by the operators. Proper information sharing and communications among all the people involved in controlling the refining process are crucial for effective operations.

3.3 *The dynamic constraints of the Ashdod oil refinery*

Basically, since the refining process is continuous, the quantity of feed (i.e. crude oil) that goes into the distillation unit is the main factor determining throughput. The operator is responsible for controlling feed rate, and decides whether to keep it steady, increase or reduce it. The binding constraint that limits AOR's throughput varies over time, and it is either one of several potential resource constraints or a market constraint, both of which are discussed further below. The optimal operation mode depends on the constraint type. Thus, the operator has first to identify correctly the current constraint, which sometimes may change from shift to shift, and even a few times during a shift. Second, the operator has to decide on the best course of action. After changing one of the operation parameters, one has to wait until the system stabilizes, and repeat the process of constraint identification, operation adjustment, and so on.

As AOR operates in a dynamic constraints environment, it is exposed to several potential constraints.

In a refinery, the presence of a bottleneck (i.e. a resource constraint) leads to reduced feed rate, and therefore decreases throughput.

AOR's resource constraints are mainly influenced by the following factors:

- The installed production capacity.
- The actual equipment performance, which varies and does not always conform to planned capacity.
- Feed type and quality.
- Environmental conditions such as temperature and humidity.

Any installation may become a bottleneck at a certain point of time due to the above-mentioned factors. Therefore, the number of potential bottlenecks is a function of the number of the installations (the main installations are detailed in figure 1). Each of these installations is complex and consists of many units that may cause a constraint.

In the refinery environment, a market constraint means the process is running at a reduced feed rate due to lack of demand. Hence, on these occasions, the aim of the operators is to adjust the feed rate to the lower demand, as close as possible to the production plan, while simultaneously assuring proper functioning of the refinery facilities, which have to run continuously non-stop.

4. The expert system development process

AOR management established a steering team headed by the refinery manager, whose aim was to find an effective way to manage constraints in the production process and by doing so, improve profitability. The secondary objective was to foster the new organizational and managerial culture which was being implemented in AOR at the same time.

The team applied the focused management philosophy, and followed the seven focusing steps, as detailed in the following subsections.

4.1 *Defining the system's goal*

The Ashdod refinery mission is to refine crude oil and secondary feedstock efficiently in a safe and environmentally responsible manner and to reliably supply quality fuels and chemical products that match its customers' needs. By acting so, AOR will achieve its goal, which is maximizing shareholder value by increasing company profits now and in the future.

4.2 *Determining global performance measures*

In order to achieve the goal, AOR had to use two separate objective functions: one for internal resource constraint situations and the other for times of a market constraint.

When there is a resource constraint, the target is to achieve maximal throughput, and the global performance measure will be the system's throughput. Thus, the relevant objective function is to maximize the 'bottleneck throughput'. According to TOC principles, the weakest link determines the strength of the system (Goldratt and Cox 1986). The operators are required to increase feed rate, subject to the capacity constraint, and attempt to increase bottleneck throughput by changing the operation mode of one or more units.

During market constraint periods, the objective is to produce the planned throughput as efficiently as possible. Hence, the operators are required to adhere to the production plan, and the appropriate global performance measure is the deviation from the production plan, which should be minimized. Secondary performance measures should address efficiency issues such as energy consumption.

4.3 *Identifying the system's constraints*

In order to identify and treat potential bottleneck sources, each plant was thoroughly analysed, and the resulting initial potential constraints list contained about a hundred items. Some of these were 'dummy' constraints (i.e. a very inexpensive resource that prevents the system from achieving more throughput) (Ronen and Spector 1992), such as old equipment that was prone to malfunction, and was cheap and easy to replace. The 'dummy' constraints were taken care of and removed at minimal cost.

For instance, the addition of heat exchangers relieved the constraint, and at the same time improved energy efficiency.

The potential constraints screening process resulted in operational improvements and the establishment of organized work procedures. These were executed during the preliminary stage of the expert system development. Consequently, the potential constraints list was down to about 20 items, and it considerably simplified and eased the expert system development.

4.4 *Exploiting the system's constraint*

For about three weeks, the work of the operators and the shift supervisors was observed, in order to find ways to improve the process control. All the operators contributed from their own experience and knowledge regarding process control issues, such as using the measures displayed on the control panel as indicators of specific problems, issuing appropriate directions to field operators and so on.

At this stage, the following conclusions were reached:

- There are different solutions to the same problem, depending on the operator who makes the decision.
- Some problems crop up infrequently and not all the operators have the experience required for dealing with them successfully.
- All operators use the same method to identify the constraints according to the measures appearing on the control screens, but they interpret the indications differently and do not always reveal the real constraint.
- The constraints are constantly changing, and sometimes during an eight hour shift there is more than one actual constraint. Therefore, the procedure of determining 'the' constraint at the end of the shift and reporting just this datum while ignoring the other constraints does not reflect an accurate picture of the events which occurred during the shift.

These conclusions led to the decision to develop an expert system which would encompass the knowledge and expertise of all the operators and promote the use of the best practice. The new system was expected to establish and assimilate a uniform structured process control, to bridge knowledge gaps, and to enable better handling of dynamic constraints on a real time basis.

4.5 *Subordination of the system to the constraint*

The next step was to define processes for actual constraint identification and elevation according to the principles outlined above. The team constructed a list of phenomena indicating the existence of a constraint. It included all the control panel signals that may require operator intervention, and was based on the control room observations. The constraint which is most likely to cause the phenomenon was specified. For example, when the temperature at the tower head rises and does not stabilize, the constraint is 'overloaded tower head'. A flowchart was developed for each phenomenon, which detailed all the necessary checks required for a certain identification of the constraint. Once the constraint was identified, the flowchart specified ways to alleviate it and to increase feed rate. Maintaining current feed rate, or reducing it, was used as the last resort for relieving a constraint. Additional analyses were carried out in order to find more ways to improve throughput, such as using feed characteristics to predict an expected bottleneck, and their consequences were included in the expert system design process.

4.6 *Elevating the constraint*

The computing team chose Lotus Notes® software for automating the flowcharts and managing the related knowledge. The expert system was to be installed on the personal computers at the control room, initially in parallel in the control system, and after the learning phase, it was planned to try to integrate the systems. Each decision point in the flowchart was phrased as a yes/no question. Operators were authorized to take actions for locating bottlenecks and relieving them, within their responsibility areas. The expert system enabled them to view historical data regarding previous shifts' activities, sorted by date, phenomenon or constraint.

The system was also planned to be used by engineers and managers at the production division to supervise the control room activities. They would not be allowed to perform actions, but they would be able to improve or correct the diagnosing questions and the instructions. The expert system would provide them with various statistical reports as well.

4.7 *Returning to step 3 and avoiding inertia*

The initial expert system was examined by knowledgeable employees, who were perceived by AOR management as having a global perspective. When the steering team and the evaluators were discussing the feedback together, they arrived at the conclusion that separate flowcharts for each constraint were not good enough, since operators might ignore some of the control screens, or would have to follow multiple screens simultaneously. Hence, they decided to construct a single flowchart for each area, which would cover the whole process from beginning to end. Since each operator would have to follow a single flowchart, the process control would become effective, simpler and less prone to human errors.

5. The expert system and the new process control

A shift supervisor, who was also an experienced system analyst, helped to construct a single integrated flowchart for each one of the three main production areas. The flowcharts were designed under the TOC approach and followed the seven focusing steps. One of these flowcharts is illustrated in figure 2. It contains 16 main questions (represented by diamonds in figure 2). In order to answer them the operator has to inspect certain measurements, such as the temperatures of specific heat exchangers and their flow rate (see questions 2 and 4 in figure 2). If the operator can answer all of the 16 questions positively, it means that there is no capacity constraint, and feed rate can be increased (unless, according to the production plan, there is a market constraint). Once the feed rate is increased, the operator is required to start all over again from the beginning and answer all the questions. If all the answers are still positive, the feed rate is increased further, and the process goes on until one question is answered negatively.

Such a negative response indicates a constraint, and the operator is referred to a more detailed secondary flowchart, which also consists of yes/no questions. The referral is represented by a rectangle in figure 2, e.g. if the temperatures of the heat exchangers located after the desalters are abnormal (question 4), then the operator should follow heat exchangers operating procedure. This series of tests guides the operator in performing the required operation adjustments or corrective actions. If the operator answers all the questions of the specific secondary flowchart positively, it means that the correct problem was not identified, and the process control continues according to the main flowchart.

The flowcharts were designed to provide feedback on any significant changes in measurements. Therefore, the operator is required to recheck any parameters that may be influenced by the performed adjustments. If the measurements still indicate

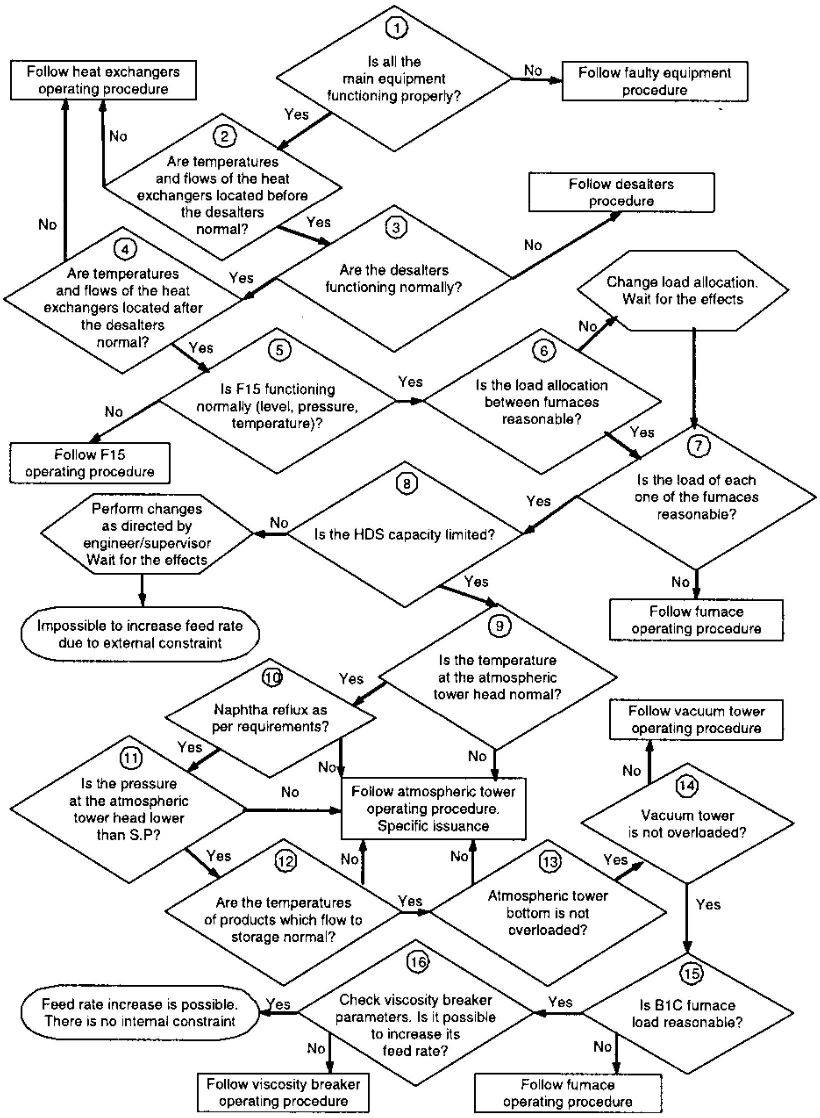

Figure 2. The Ashdod refinery feed rate process control.

that it is impossible to increase feed rate, a message appears on the screen, and specifies the constraint and its cause.

At the outset of the expert system development process, managers remarked that since the system would not enable them to perform the constraint identification process, as the operator does, their ability to control and improve the process was quite limited. Hence, a parallel simulation system was installed, which enables all users to simulate activities performed by an operator during all the processes. The simulation system reports serve as a basis for process improvement suggestions, as well as for training.

6. Implementation and operation

6.1 *The implementation phase*

The constraint management expert system was installed on the personal computers of all the intended users. They received training on how to operate the system, and especially on the best ways to use it for achieving the relevant objectives (see section 4.2). During the initial implementation stage, AOR management made sure that the expert system would be operated at least twice during each shift, and that the shift supervisor would provide feedback regarding both operators' performance and system performance. The system included special screens for recording the feedback in a structured manner, and it generated summary reports that were used for its evaluation and improvement.

The implementation process lasted about six months. At the beginning it required the leadership of AOR management and the close supervision of the steering team and the system designers. However, within three months, the leadership and responsibility for the implementation process were transferred to the production division management. At first, the operators had mixed feelings regarding the expert system: on one hand, they were concerned about the increased control over their performance and the need to change work habits which they had been using for years. On the other hand, they were glad of their job enrichment, their knowledge enhancement, and the opportunity to share their own knowledge with others.

The feedback from users led to changes and improvements to the system. For instance, Lotus Notes®, the initial software chosen for the expert system, was replaced by Microsoft® Access which was widely used at AOR, and it enabled introducing more improvements, better connectivity with other applications, and much greater convenience in using and managing the information.

The broad and ambiguous definition of the project purpose, as well as the way it was carried out and its long duration, all of which may be attributed to its innovativeness, required full commitment of the team leaders. Meetings were convened and members were invited as necessary. Minutes of all meetings were taken, which specified decisions, assignments, responsibility, and due date. All of these measures were essential for the successful completion of the project.

6.2 *The expert system impact*

In June 2001, it was decided to operate the constraint management expert system, even though it was clear that it was not yet complete. The team estimated that the maturity level of the system was sufficient for achieving valuable results. Moreover, the experience gained from its initial operation was expected to contribute to improving its final version. Indeed, during 2002 the system was modified and upgraded in light of the accumulated experience.

Figure 3 compares the work process of the operator before and after the constraint management expert system implementation. The main difference is in the activities during the shift, which became more structured, organized and most important, much cleverer. Hence, the quality of control was improved, and it led AOR closer to its objectives.

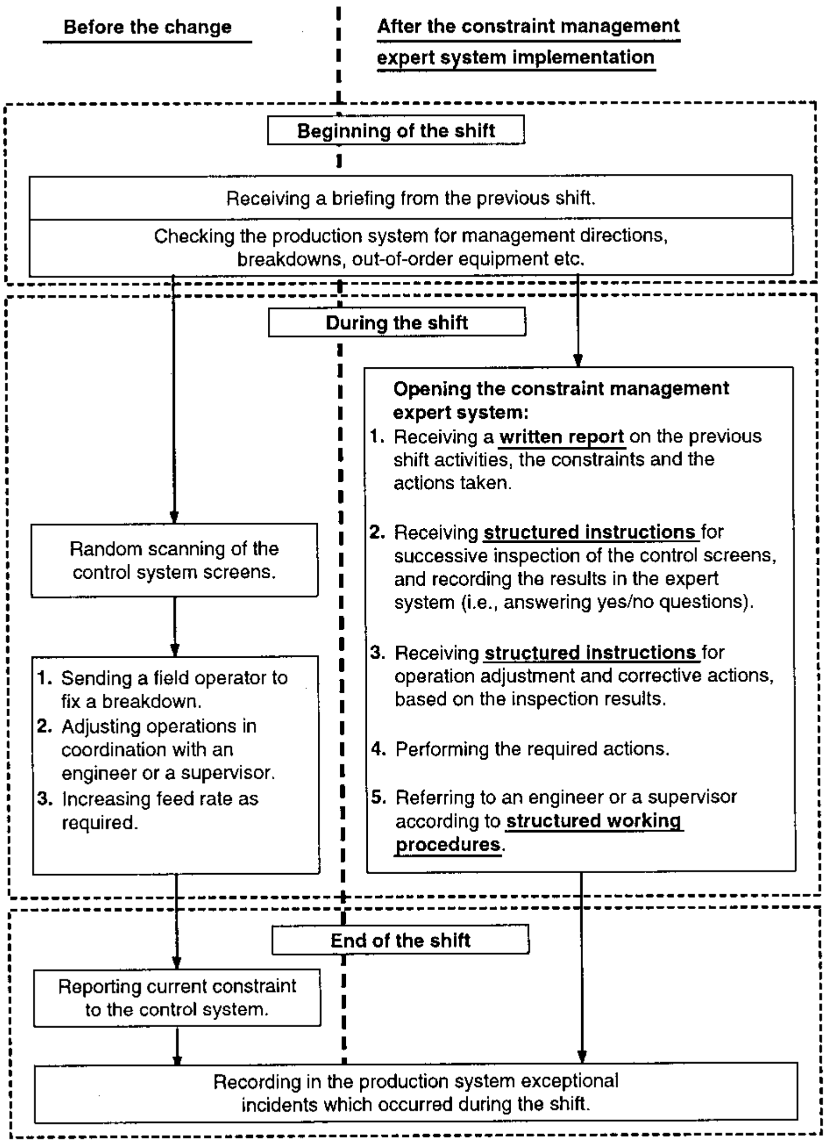

Figure 3. The control room operator work process.

During the first two years of the expert system operation, the market constraint prevailed. There were virtually no resource constraints and the refining profit margins were very low, so the objective was to produce the required throughput as efficiently as possible. Adherence to the production plan was the most important performance measure, which was quantified in terms of deviations from the production plan and measured in two dimensions: throughput quantity deviation and throughput mix deviation. A comparison of daily standard deviation of throughput quantity before and after the system implementation showed that the deviations were significantly reduced, which resulted in a more efficient production process. The throughput mix deviation was considerably decreased as well, which caused increased refining margins. This is especially notable in light of the worldwide reduction in refining margins during that period. Altogether, AOR management estimated that the quantitative benefits of the expert system during the first two years were about \$3 million.

The system improved both the production process control and the performance of the people in charge of it. At the process level, the expert system's main contributions are that it identifies the current constraint in real time and enables fast adaptation of the production process accordingly. Further, it improved managerial control by replacing customs with structured procedures and by timely updates of the relevant managers on issues that require their action.

6.3 *Epilogue: three years later*

The oil and refinery industries have been facing tremendous changes and volatilities during the last decade. These include sharp fluctuations of supply and demand and the resulting price changes, along with new stringent environmental regulations on product and process effluent and discharge. AOR followed the last step of TOC which emphasizes the iterative nature of constraints identification and handling. In order to meet these additional constraints, AOR developed new modules of the expert system, which control the environmental parameters and keep them within the allowed limits. Apart from AOR's commitment to obey the law and preserve the environment, nowadays there is a huge economic benefit in working according to the regulations and not violating them.

Looking for more profitability and efficiency, AOR implemented new advanced optimization control systems in its fluid catalytic cracker (FCC) unit and the crude oil unit. These new control systems are programmed to automatically meet an optimal objective function according to a set of constraints and operational parameters such as product quality, plant limitations, environmental restrictions, etc. The expert system was adjusted to the changes in the process control. Instead of checking the process and the equipment functionality, the operator is now required to check the constraint's relevancy and the objective function and through them to monitor the process.

These examples demonstrate the flexibility of an expert system that fits AOR's operating philosophy and culture and that brought AOR to achieve very high international operating standards. In-spite of the tightening of product specifications and environmental quality regulations, during the years 2004–2005 AOR achieved record levels of throughput and utilization, as indicated by comparative international performance measures. Figure 4 shows the impact of the process control

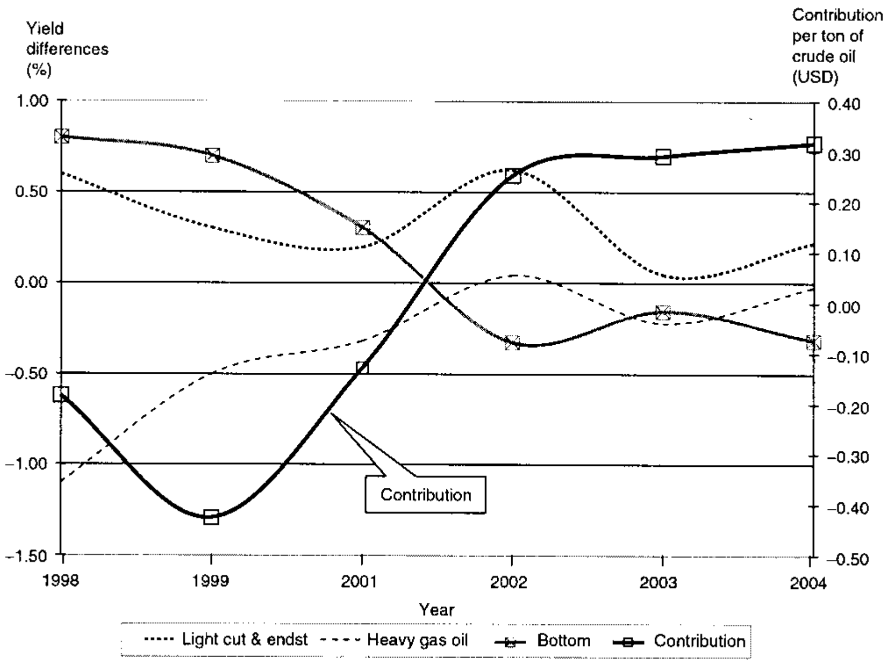

Figure 4. The impact of the process control improvements on AOR's throughput.

improvements on AOR's throughput. The expert system was implemented during the years 2001–2002, and it enabled AOR to reduce the difference between planned and actual yields of the components of its product mix. Ideally, the three lines, which represent the different types of products (Light Cuts and Ends, Heavy Gas Oil, Bottom), should approach the zero line. Approaching the zero line yields the optimal contribution of AOR. We can see that along the years there is a significant conversion to the zero line of the three products, dramatically affecting the contribution per tonne. The improvement process reached its potential in 2004, when efforts were directed at stabilizing the process. As the production process became more stable and safer, it contributed not only to the profit but also to the environment and the safety of the employees and the community.

7. Discussion and practical implications

The constraint management expert system creates a dynamic, effective and immediate link between the production planning and the operation control, which enables the Ashdod oil refinery to maximize its throughput. Nevertheless, the expert system is just a tool. The crucial issue is the implementation of the focused management philosophy. We shall discuss first the improved process control from a focused management perspective, and then point out some practical lessons for expert system development and utilization.

7.1 *Focused management in a dynamic environment*

This section discusses the crucial role of the focused management general implementation, which preceded the development of the expert system, and was essential for its success. Process control is undoubtedly one of the most important factors influencing the oil refineries' throughput. Yet it is complex, especially due to the dynamic environment of ORL. The focused management implementation process started with simple tools, such as the complete kit concept (Ronen 1992), quality management (Deming 1986) and the Pareto rule focusing methodology (Livne and Ronen 1990, Ronen *et al.* 2006), which are easy to implement and provide significant benefits almost immediately. Only then, after the effectiveness of the focused management philosophy was demonstrated and its insights were understood by everyone, did they start to analyse process control by the TOC approach. Although the postponement in relieving a major constraint may seem in contrast to TOC principles, these initial improvements were crucial to the success of the constraint management expert system. Actually, these improvements made it feasible from the organizational perspective, and changing the organizational atmosphere to a 'throughput world' attitude (Goldratt 1991, Geri and Ronen 2005) was the turning point. The preliminary analysis of the refining process identified many constraints, and some of them were relieved by simple inexpensive solutions. This eased the analysis of the process control while at the same time it also created awareness of the potential for improvement.

We should bear in mind that expert systems are just tools, depending on the people that operate them. It takes knowledgeable people and appropriate organizational climate and leadership to succeed in such a complex implementation.

The theoretical conclusion emanating from this discussion is that an isolated application of TOC, or an expert system, or both, is not sufficient, and such applications, which require a major change in the way of thinking, should be integrated in an overall focused management implementation effort.

7.2 *Practical lessons for expert system implementation*

The main practical contribution of the implementation described in this paper is that it overcomes the typical barriers which cause many expert system failures. In light of the challenges and risks involved in expert system implementation described in section 2.2, we raised the question whether the effort is worthwhile. This case study as well as various other successful expert system applications (Sviokla 1990), shows the potential of such systems to increase value. However, it is important to analyse the critical success factors of AOR's expert system and see how they surmounted the challenges.

The most significant actions during the development stage were the knowledge gathering approach and the decision to create a single flowchart for each major process. The knowledge captured in this system was based on the accumulated expertise of all the people who would have to use it later. The system designers spent considerable time and effort observing the actual process control and analysing the relevant data. This was an important factor which contributed to the high quality of the system's knowledge base. The users' confidence in the rules, and their being part of the group that created them, increased their motivation to use the system and follow its recommendations. It was not a 'black box', based on rules created in some other oil refineries, some of which may not be applicable to AOR. Also, the knowledge base rules were not created by just a few experts sitting in a remote laboratory and trying to figure out all the possibilities and the best theoretical rules.

The decision to create a single flowchart which the operator would have to follow was also a critical success factor. The initial design actually allowed each one of the operators to decide on their own process control in an unstructured manner, so it was not effective since the operator might choose to check just some of the relevant parameters. The single flowchart created a structured process control. It may not be the 'best' process but it is a satisfactory one and certainly improved the operators' performance.

The decision to switch from Lotus Notes® to Microsoft® Access was critical to the maintainability of the knowledge. Both tools are adequate to support the expert system application from a technological perspective; however, from the organizational aspect the tool which was widely used in AOR is preferable, since it does not require special efforts to update the knowledge base.

The operators must use the system and record their actions on special screens which are an integrated part of the system. Yet, it is still a decision support system, and the operators have discretion whether to follow its recommendations. The involvement of top management in the system development and implementation stages encouraged the preliminary use of the system, but it would have been abandoned had it not been perceived as valuable (Davis 1989, Davis *et al.* 1989, Agarwal and Prasad 1997). Nevertheless, the expert system requires additional efforts from the operators and their supervisors. Hence, its contribution to AOR should be evaluated and acknowledged recurrently.

8. Conclusions

The expert system would not have been successful without the introduction of TOC and focused management philosophies and tools for top management, mid-management and workers. The understanding and assimilation of these concepts were a necessary condition to their successful implementation.

Nowadays, organizations are coping with increasingly complex processes in a dynamic environment where operational human decisions can have a major impact on their profitability. An expert system may help many organizations to manage their experts' knowledge effectively. However, building and implementing a successful expert system is a challenging task. This paper presented a case study that analysed the development and implementation of an expert system which assisted the Ashdod oil refinery in coping with frequent shifts from internal to external constraints, and resulted in more than $3 million of benefits during its first two years of use. This is the first research article describing a successful expert system which was developed under the TOC approach.

Although a case study is naturally limited to its specific circumstances, nevertheless other organizations may learn from this case how to design their own successful solutions. Yet, this expert system implementation was not an isolated initiative; it was developed as an integral part of an overall effort to implement the focused management way of thinking at ORL. People were already aware of the philosophy's potential to provide significant improvements, and it influenced their willingness to cooperate and their motivation to contribute their knowledge.

Further research is required on other areas where expert systems can be accompanied by TOC. Expert systems for supply chain management that incorporate the concept of buffer management can create value for manufacturers, distributors and retail chains.

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