

Management Science, Theory of Constraints/Optimized Production Technology and Local Optimization

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This study uses a controlled laboratory experiment to compare the performances of Management Science (MS), Theory of Constraints/Optimized Production Technology (TOC/OPT) and Local Optimization (LO) approaches to production planning. The OPT game was used as the experimental instrument. The subjects were given hint sheets based on MS, TOC/OPT and LO approaches. The results show that production planning by MS and TOC/OPT approaches improve the performance more than the LO approach. Additionally MS was found to improve the performance more than TOC. Statistical power analysis of the data suggests that the laboratory experiment had a high power and the tested approaches had a medium to large effect on performance. © 1997 Elsevier Science Ltd

Introduction

The concepts of Theory of Constraints (TOC), Optimized Production Technology (OPT) or Synchronous Manufacturing have received wide attention from practitioners and academic researchers since the publication of Goldratt's [1] management novel *The Goal* in 1984. A number of articles and books by Goldratt and other authors have elaborated on the main ideas behind TOC [24]. A number of other articles summarize the principles behind TOC and/or compare TOC with other operations management (POM) approaches [5-11]. Theory of Constraints can be defined as a management approach which focuses on improving bottleneck processes to continuously improve the performance of manufacturing operations. Using a number of concepts (e.g. TOC thinking process, TOC five step approach, nine OPT rules, VAT classification of plants, drum-buffer-rope scheduling), TOC attempts to answer the following three questions relevant to a manufacturing organization: (1) what to change; (2) to what to change to; and (3) how to cause the change? Early publications related to the Theory of Constraints often compare it with the 'conventional' management or Local Optimum (LO) approach [1, 3, 12]. Goldratt and Fox [3] define LO as the management approach that assumes that the only way to reach the global optimum is by ensuring local optima. They list nine rules which summarize the main ideas behind the LO approach (see Appendix A). They argue that the use of LO in manufacturing operations is the main reason behind the failure of a large number

of companies in western economies. Earlier, Skinner[13/ presented a similar argument regarding the conventional or LO approach. For example, Skinner stated that LO involves improving the efficiency of the direct labor work-force and not the entire manufacturing organization. Skinner also noted that professionals in different functional areas within the same organization often attempt to achieve goals which, although valid and traditional in their fields, are not congruent with the goals of other areas.

Even though TOC is claimed to be about 'new global principles of manufacturing', several authors have noted the similarities between TOC and Management Science (MS) concepts. For example, Ronen and Starr [10] show that TOC concepts are based on total systems theory, mathematical programming techniques, queuing theory, the Pareto rule and Japanese production experience. Luebbe and Finch [14] compared the five step TOC approach and Linear Programming (LP, a MS problem solving technique) and found that both methods yield at the same result. Lee and Plenert [15] solved another example problem and found that both TOC and LP arrived at the optimal solution for a product-mix problem. We also compared TOC and LP for solving a simple product-mix problem (see Appendix B for details). This example is taken from a leading operations management textbook [16]. The textbook provides the solution to the problem using TOC concepts as a profit of \$240. We solved the example problem using both LP and Integer Programming (IP) and found the optimum profit to be \$286.36 and \$280, respectively (see appendix B). In other words, we found that LP and IP methods outperform TOC for a product-mix problem.

Even though a number of articles have noted the similarities and differences between MS and TOC concepts, none has compared the two approaches under a controlled experimental setting. The objective of this article is to compare the performance of the three methods: LO, TOC and MS in production planning. The paper reports the result of a controlled laboratory experiment conducted to test the effectiveness of these three approaches. The rest of the paper is organized in the following manner: first, the concepts behind CO, TOC and LO approaches are reviewed; second, the results of controlled laboratory experiment are presented; third, strategic implications of this study are discussed; and fourth, the limitations of the study and directions for future research are presented.

A Review of MS, TOC/OPT and LO

Management Science Approach

Management Science (MS) is commonly described as a scientific approach to decision making that involves the operations of organizational systems [17, 18]. In particular, the process begins by carefully observing and formulating the problem and then constructing a scientific and logical model that abstracts the reality. MS adopts an organizational point of view and attempts to resolve the conflicts of interest among the components of the organization in a way that is best for the organization as a whole. In other words, the MS approach is a search for

the global optimum [17-20]. The MS approach uses the following steps in problem solving and decision making [21]:

1. Identify and define the problem.
2. Determine the set of alternative solutions.
3. Determine the criterion or criteria that will be used to evaluate the alternatives.
4. Evaluate the alternatives.
5. Choose an alternative.
6. Implement the selected alternative.
7. Evaluate the results, and determine if a satisfactory solution has been obtained.

Different MS scientists may disagree on the exact steps described above, but they will all agree on the same focal theme – identification and selection of the alternative which results in the best overall performance. The constrained optimization (CO) theory of MS described above represents the causal relationship between one or more objectives and the factors that limit the attainment of objectives (known as constraints). Fifty or so years of advancement in MS have led to the development of a number of algorithms and heuristic procedures that can be used to solve a variety of problems represented as CO. The objective of this review is neither to get into the specifics of these algorithms, nor to discuss which type of problems can be solved by certain algorithms, rather to understand the general concepts behind them. Therefore, the following section lists a number of characteristics of the MS approach without reference to any particular algorithm:

1. Binding and non-binding constraints: binding constraints limit the attainment of the objective. Non-binding constraints do not affect the value of the objective function.
2. Only by considering all the constraints simultaneously can the 'best' solution be obtained. Considering a few constraints at a time will only give rise to a local optimum which might or might not be the same as the global optimum. In fact, the sum of local optima is never better than and usually worse than the global optimum.
3. Variability in the system can and should be modeled. There are several MS procedures which obtain near-optimal solutions for stochastic problems.
4. Further improvement in the system's performance can only be achieved by 'breaking' the binding constraints. Breaking non-binding constraints will not change the performance of the system.

The above review of the MS philosophy suggests that an accurate model can not only help achieve the best current performance, but also act as a guideline for improving the process. Even if it is not possible to get an accurate mathematical model of the system, the general problem solving steps identified earlier will help achieve a better performance.

Theory of Constraints Approach

Theory of Constraints (TOC) had its beginning in Israel in the 1970s [7]. Eliyahu Goldratt applied a technique for predicting the behavior of a heated crystalline atom to optimize the

large number of variables in a work schedule [7]. Subsequently, Creative Output Inc. opened in the United States in 1979 [7]. Since then, several corporations have purchased and used Optimized Production Technology (OPT) scheduling software which is based on Goldratt's procedure. Earlier Jacobs [5], and more recently *Fry et al.* [22], summarized the significant features of the OPT software. Goldratt's [1, 12] management text, *The Goal: A Process of Ongoing Improvement*, explains in a novel format the main ideas behind the OPT software. The book elaborates on several important OPT concepts like OPT goals, OPT rules, bottlenecks and the drum-buffer-rope scheduling concept. Goldratt's recent publications explain the fundamental principles behind *The Goal*, OPT software and other OPT concepts. Together these concepts are known as the *Theory of Constraints*.

According to the TOC "the goal of an industrial organization is to make money in the present and in the future." TOC uses the commonly used financial measures to quantify its overall goal of making money: net profit, return on investment and cash flow. These financial goals are translated to operational goals in the following manner: "In order to make money in the present as well as in the future, an operating system should increase its *throughput* and simultaneously reduce its *inventory* and *operating expenses*" [1, 12].

TOC supports a continuous improvement philosophy. In order to accomplish this task, TOC looks for answers to the following questions [2]:

1. *What to change*: every organization in a real environment is overwhelmed with problems and/or opportunities which need the managers' attention and/or corrective actions. However, limited time, effort and resources make it difficult to act on all such problems or opportunities. Hence, the manager has to find what should be changed, to effectively improve the performance.
2. *To what to change to*: once the core problems have been identified, the next step is to find the solutions. If sincere effort is not directed towards finding solutions to the core problems chaos and panic will result.
3. *How to cause the change*: perhaps the most difficult of the three questions is to find out how to cause the change in a system. In addition to the time, effort and capital required, managers often face the problem of emotional resistance by people in the organization who perceive change as a threat to their security. If 'to what to change to' is identified, but it is not possible to cause that change, then the solution is not of much use.

The Theory of Constraints suggests the following five steps to answer the above three questions and to continue the process of ongoing improvement [1, 2]:

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 the first step.

TOC uses a number of concepts to identify relevant techniques, and follows the above five steps to continue the process of improvement. Several of these concepts (for example, effect of statistical fluctuations, effect of dependent events, bottlenecks and non-bottleneck processes) can be easily identified in different MS approaches while some other concepts (drum-buffer-rope scheduling, classification of VAT plants) remain unique to TOC. Several of the TOC concepts are translated into nine OPT rules that can be used by operations managers for day-to-day management of manufacturing operations [1, 4, 12]. Therefore, the controlled laboratory experiment reported in this paper operationalized TOC by the nine OPT rules (see Appendix A).

Local Optimum Approach

Local Optimum (LO) or the conventional approach has been defined earlier in this paper as a method which assumes that the overall optima value of the objective can only be obtained by ensuring local optima (see Appendix A) [1, 3, 12, 13]. Over the last several years, a number of management publications have emphasized that local optimization does not result in increased performance for the whole manufacturing plant. Skinner [13] argues that several operations managers tend to optimize the performance of their respective departments without considering the objectives and constraints of other departments within the same plant or organization. He further argues that different managers have their unique mental models of plant operations because of their dissimilar backgrounds. Therefore the conventional or LO approach leads to a sum of local optima which is often worse than the overall optimum performance.

A number of practical approaches have been proposed which help operations managers avoid falling into the local optima trap. For example, Skinner [13] suggests using a focused factory approach to achieve better plant performance. A kanban-based production system can also be characterized as a method which attempts to achieve better performance by avoiding local optima. TOC criticizes conventional operations management by challenging several of its assumptions. For example, the LO approach does not differentiate between bottleneck operations and non-bottleneck operations. Therefore, if a machine is idle, whether bottleneck or non-bottleneck, equal costs are assigned. TOC on the other hand argues that "an hour lost at the bottleneck is an hour lost for the whole plant, but an hour lost at a non-bottleneck is only a mirage." Like TOC, MS also recognizes the difference between binding (bottleneck) and non-binding (non-bottleneck) constraints. For example, Linear Programming (a MS approach) assigns a non-zero shadow price to binding constraints. A shadow price of zero is assigned to the non-binding constraints.

In summary, past research suggests that the LO approach is not an effective operations management approach. Therefore it is easily hypothesized that the performance of a manufacturing operation implementing the LO approach will be lower than the performance of plants implementing TOC or MS approaches.

Experimental Work

An exploratory laboratory experiment was conducted to evaluate the performance of the three approaches described earlier for a production planning situation. The MS approach is hypothesized to improve the performance more than the TOC or LO approaches. The TOC approach is hypothesized to improve the plant performance more than the LO approach.

The OPT game developed by Creative Outputs Inc. was used as the experimental instrument. This computer game was originally developed to explain the main ideas behind TOC using the nine OPT rules (see Appendix A). The OPT game was chosen because the game was designed to resemble the day-to-day operations of a typical manufacturing plant and because the nine OPT rules are supposed to operationalize the TOC concepts. This game is an appropriate instrument because it forces the decision-maker to make trade-offs similar to actual production planning.

The OPT game illustrates some of the main activities of a typical manufacturing plant and the problems that may arise when attempting to manage it profitably. The player is the operations manager of a production facility. He/she has to make three different types of decisions: types and quantities of raw materials to purchase; product mix; and scheduling of two machines that are required to complete the work. Figure 1 illustrates a simple diagram of the plant.

Figure 1 shows the routing of raw materials (RM1 and RM2) through the plant. A unit of RM1 or RM2 costs \$10. Positions A and C represent two tasks of a single *Blue Machine*. At any given time, the *Blue Machine* can be used at only one location, either A or C. Similarly, at any given time, the *Green Machine* can be used at either B or D. Both machines have non-zero set-up times. P, P1 and P2 are the products manufactured by the plant (P is an assembly of P1 and P2). The plant can sell all the P manufactured but the total sales of P1 or P2 are limited to the amount of P already sold. The selling prices for products P, P1 and P2 are \$60, \$30 and \$30,

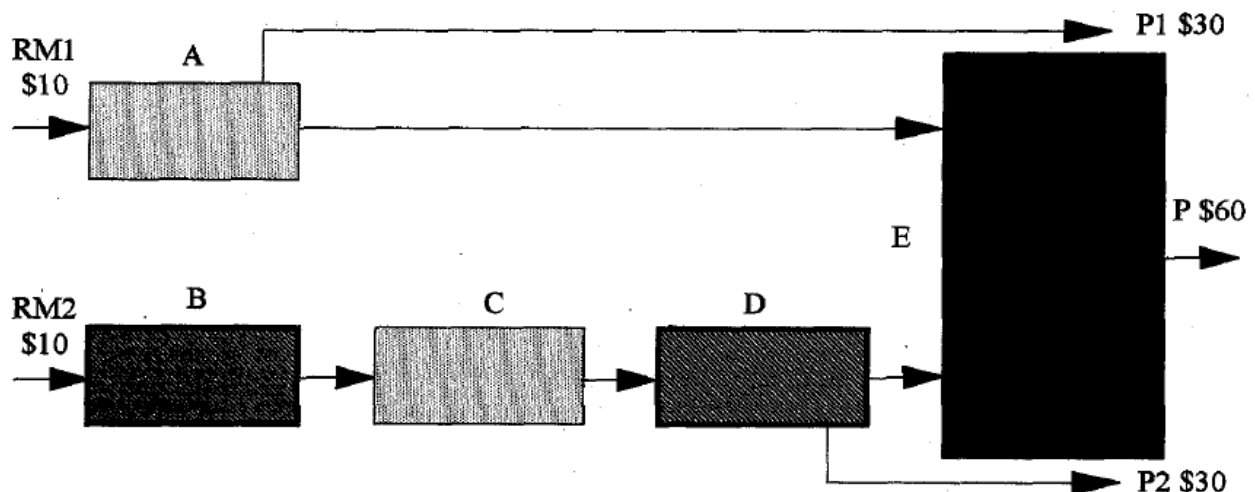


Fig. 1. A simple diagram of manufacturing plant in the OPT game.

respectively. The game is played over a 6 week period with 40 h per week. The objective of the game is to make as much money as possible. The players are given starting cash of \$1500 and in order to avoid bankruptcy they are required to manufacture and sell enough products every week to recover the weekly operating expenses of \$2500. The OPT game comes with a self-teach module which explains the game in detail.

Since the publication of two editions of *The Goal* (total sales over a million copies) and a number of other publications describing TOC, it is difficult to randomly select operations managers who are not biased towards or against TOC. Also, because operations managers in organizations do not have the same educational background and/or experience, it is possible that the differences in performance during the experiment might be influenced by their personal background/characteristics. Since this laboratory experiment is exploratory in nature, 92 business school students from a required senior level Operations Management class were asked to participate in this study. The students were purposely chosen as subjects because it is less likely that they will be biased towards any particular approach of managing operations. (Note: The instructors of these classes are not part of this research team). The instructors agreed not to bias the students towards or against any particular approach during previous class sessions. The students received class credit for participating in this experiment. They also stood a chance to win a cash prize either through a raffle or by getting the maximum score.

The experiment was conducted in a large computer laboratory. The subjects were randomly assigned into four groups: the control group, the Local Optimum (LO) group, the Theory of Constraints/Optimum Production Technology (TOC/OPT) group and the Management Science (MS) group. To ensure that the subjects in a particular group were not influenced by subjects from any other group, the groups were seated in different rows. Additionally, there was enough space between the two computer tables to ensure that a particular subject was not influenced by his/her neighbor. All the subjects were asked to go through the self-teach program before starting the game. After the self-teach program, the subjects were asked to play the game. They were asked to record their weekly performance (net revenue generated by selling P, P1 and P2). Net revenue generated is an aggregate measure of performance because it is based on the products sold, operating expenses, scheduling of machines and the cost of raw materials.

After the first game, each subject received a hint sheet. Subjects in different groups (control, LO, TOC and MS) received different hint sheets. The subjects were told that their performance would improve if they used the help sheet when they played the OPT game again. They were allowed to keep the hint sheets and were encouraged to look at them before and during their second game. After completing the experiment, the subjects mentioned that they referred to the hint sheets several times during their second game.

Appendix A shows the hint sheets used by subjects in different groups. The hint sheets for the TOC group contained the OPT rules [3]. The LO hint sheet contained the so-called conventional rules. These rules are taken from a book co-authored by Goldratt and Fox [3]. The

hint sheet for the MS group was based on conclusions derived from the general MS approach described above. The subjects did not get any help other than the hint sheets.

Results

Table 1 presents the descriptive statistics for the four experimental groups. The two measures of performance analyzed in this study were the net revenue generated in the second game (Game#2), and the difference between the net revenues generated in the two games (Game#2 - #1). Table 1 shows that among the three groups, group means are highest for the MS group and lowest for the LO group. It is surprising that the control group (which essentially did not receive any hints) performed better than the LO and TOC groups.

A one-way ANOVA was performed to test if there are differences in the performance of the groups because of their training. If the between group variation in performance were found to be much larger than the within group variation, then the F-ratio calculated during ANOVA should be statistically significant. Since the nature of this laboratory experiment was exploratory a significance level of 0.1 (i.e.=0.1) was used. A number of empirical studies in operations management have used the same significance level [23]. The one-way ANOVA results are presented in Table 2. Because the control group had the smallest sample size and a large standard deviation, ANOVA was performed with and without considering the control group. Therefore a total of four ANOVA tests were performed (two dependent variables with either three or four groups).

Three out of the four ANOVA results were found to be statistically significant at $\alpha = 0.10$. The P-value of the fourth test (test #C in Table 2) was only slightly higher than the selected α

| Test # | Dependent variable | Groups | F-ratio | P-value |
|--------|--------------------|----------------------|---------|---------|
| A | Game#2 | Control, LO, TOC, MS | 2.7299 | 0.0487 |
| B | Game#2 | LO, TOC, MS | 4.8516 | 0.0106 |
| C | Game#2 - #1 | Control, LO, TOC, MS | 2.1304 | 0.1021 |
| D | Game#2 - #1 | LO, TOC, MS | 3.2947 | 0.0428 |

Table 2. One way ANOVA results

| Test # | Dependent variable | Statistical power | Effect size |
|--------------|--------------------|-------------------|-------------|
| A (4 Groups) | Game#2 | 0.738 | Medium |
| B (3 Groups) | Game#2 | 0.897 | Large |
| C (4 Groups) | Game#2 - #1 | 0.650 | Medium |
| D (3 Groups) | Game#2 - #1 | 0.797 | Medium |

Table 3. Statistical power and effect size for ANOVA tests at $\alpha = 0.10$

level. These results suggest that there is a significant difference between the performance of different experimental groups. This means that the differences in the performances of the groups were not because of random errors but were caused by the training procedure used for the different groups. Duncan's multiple range test with three groups (LO, TOC and MS) also showed significant differences between the MS and other groups at the 0.10 level [24].

Table 3 shows the results of a power analysis for the ANOVA tests reported in Table 2 [25, 26]. Statistical power represents the probability of rejecting the null hypothesis when the alternative hypothesis is true. It can be interpreted as the probability of making a correct decision when the null hypothesis is false. Statistical power is an important measure of a statistical test because it represents the degree to which the results may be duplicated when an experiment is repeated. Cohen [26], a well-known expert in the area of statistical power, recommends that the statistical power of an experiment should be such that the ratio of Type II error (β) and Type I error (α) is less than or equal to 4:1. Since statistical power is defined as $(1 - \beta)$, an acceptable power level for the ANOVA tests reported above should be 0.6 or more (since $\alpha = 0.1$, therefore $\beta \leq 0.4$ is needed to get $\beta : \alpha \leq 4:1$). The statistical powers of the ANOVA tests were computed by a software program developed by Borenstein and Cohen [25]. The results of the power analysis presented in Table 3 show that all four ANOVA tests have acceptable power levels. Additionally these values suggest that the statistical power of the tests reported here are well above the median power of empirical tests in previous operations management articles [23]. Borenstein and Cohen's [25] *Statistical Power Analysis* program also calculates the effect size. Effect size is an index which measures the strength of association between the populations of interest [26]. The effect size index is important because it helps researchers distinguish between a meaningful and a trivial effect and between the relative magnitude of effects. A small but significant F-ratio for an ANOVA test might suggest the presence of a trivial effect that was detected by a particularly powerful study, while a medium but a non-significant F-ratio might suggest the possible presence of an important effect that was not detected because of a serious lack of statistical power. Table 3 presents the effect size calculations for the four ANOVA tests. For the sake of convenience and ease of understanding the effect sizes are presented as large, medium or small using Cohen's rule [26]. The estimated effect sizes for the four ANOVA tests are from medium to large, which implies that the difference in performances of different groups are not because of a trivial effect. In other words, the above analysis suggests that the performance differences between the groups should not be treated as unimportant.

Next, a series of one-tail t-tests was conducted to test if the group means were different from each other. Again $\alpha = 0.1$ was used. These t-tests were conducted for both the dependent variables. The results presented in Table 4 show that all t-tests were statistically significant at the $\alpha = 0.1$ level. Hence it can be concluded that the MS approach improves the performance more than the TOC or LO approaches. The results also show that the TOC approach improves performance more than the LO approach.

| Dependent variable | Groups | t-value | 1-tail prob. pooled variance | 1-tail prob. separate variance |
|--------------------|------------|---------|------------------------------|--------------------------------|
| Game#2 | LO and TOC | - 1.31 | 0.0980 | 0.0875 |
| Game#2 | LO and MS | - 2.73 | 0.0045 | 0.0025 |
| Game#2 | TOC and MS | - 1.93 | 0.0300 | 0.0295 |
| Game#2 - #1 | LO and TOC | - 1.43 | 0.0800 | 0.0735 |
| Game#2 - #1 | LO and MS | - 2.21 | 0.0160 | 0.0111 |
| Game#2 - #1 | TOC and MS | - 1.49 | 0.0715 | 0.0705 |

Table 4. t-test results

Since multiple t -tests are conducted using the same experimental data, there is a probability of accumulation of Type I error across different t -tests [24]. Since $\alpha = 0.1$ was used to conduct three t -tests, this means that among the three tests the total probability of making a correct decision is only $(1 - 0.1)^3 = 0.729$. Therefore $\alpha = 0.1/3 = 0.033$ should be used to keep the overall probability of Type I error close to 0.1 [24]. Even with the above α correction, t -tests for the dependent variable Game#2 show that the MS group performs better than the TOC and LO groups. However, the difference between the TOC and LO groups is not significant at $\alpha = 0.033$. The dependent variable Game#2 - #1 only shows one statistical difference in performance (between CO and LO groups).

Discussion

The objective of this paper was to test the usefulness of TOC, LO and MS approaches in production planning. The paper presented a brief review of the three approaches and hypothesized that the MS approach will perform better than the TOC approach, which will perform better than the LO approach. The article presented the results of a controlled laboratory experiment conducted to evaluate the usefulness of the three approaches.

The example problem presented in Appendix B showed that both linear programming and integer programming (IP) formulations of a product-mix problem achieve better profit than the TOC approach. Both the LP and IP algorithms are designed to arrive at the optimum solution for the given set of constraints. Therefore, whenever a constrained optimization production problem is formulated as an LP or an IP, the result obtained is better than or equal to results from other methods. TOC also prefers the optimum solution to 'just any good' solution. However, the TOC approach failed to reach the optimum level because the TOC/OPT rules provide suggestions on 'how to' move towards the optimum solution but they do not formulate the problem completely like LP or IP. Therefore, it is possible that for more complex problems (with a large number of variables and/or constraints), the TOC approach might perform comparably to LP or IP. Additionally, LP and IP can guarantee optimality only when the objective function and constraints are linear. The TOC does not impose any such restrictions. Therefore it is also possible that TOC and non-linear MS approaches might arrive at comparable results.

The results of the laboratory experiment suggest that the MS approach indeed performs better than the other two approaches. The LO approach appears to perform the worst. These results are not surprising in view of past research, which has shown that management approaches that avoid local optima and focus on achieving the global optimum tend to perform better. The hint sheet for the MS group emphasized the need for global optimization. It suggested that the best performance will not be achieved if the decision-maker focuses his/her attention on only a small part of the problem. For example, a player will not perform well if he/she assumes that the schedules for the *Blue Machine* and the *Green Machine* should be determined independently. Since the raw material flows through both the machines, the schedules for the two machines and the production batch sizes are inter-related decisions. The

hint sheet for MS was based on the total systems approach and attempts to achieve the global optimum. The TOC approach also attempts to achieve the global optimum. However, the TOC approach represented as nine OPT rules were not found to be as effective as the simple rules based on the MS approach.

The performance of the control group was found to be higher than the TOC and LO groups, which is surprising. This result suggests that the 'mental model' of subjects in the control group was better than the hint sheets of subjects in TOC and LO groups. Since no additional data were collected from the subjects, it is not possible to test this hypothesis. However, additional data should be collected in future research projects to explore the above issue.

The relatively high significance level ($\alpha = 0.1$) used in the ANOVA tests is not a reason for concern because generally exploratory experiments (like the one reported in this paper) are conducted to 'map the territory' and to take a first look at a possible phenomenon. Additionally, the results of the statistical power analysis suggest that the reported tests have a reasonable degree of repeatability and that they explore important effects.

Over the past several years, a number of academic conferences (for example, those of the Institute For Operations Research and Management Sciences and of Decision Sciences Institute) have conducted sessions related to the relevance of MS-based methods in the 1990s. Several individuals felt that MS does not take the applied nature of business into account and hence will lose its relevance in the future. However, the results presented in this paper show that general rules or hints based on MS philosophy are very valuable for effective management of production processes. In other words, this study shows that MS concepts can not only be used as specific problem solving techniques, but also as general guidelines for improving the performance of an operating system.

Limitations and Directions for Future Research

Even though this paper presents interesting results related to the MS, TOC/OPT and LO approaches for production planning, the study contains a few limitations which should be dealt with in future research projects. This section discusses some of those limitations and provides directions for future research projects.

The experimental study reported in this paper was based on only one instrument -- the OPT game. Even though the OPT game resembles the day-to-day operations of a small manufacturing facility, it does not allow the decision-maker to make all types of production planning decisions. For example, the assumptions that there are no quality problems (and therefore no cost for quality control or scrap) and that all the product manufactured is sold, immediately simplify the task of the operations manager. Future experimental work should be based on more than one instrument to test the production planning approaches in a variety of settings.

It is clear that the difference in the performance of the groups results from the hint sheet. However, it might be argued that the hint sheets do not measure the effectiveness of the three approaches directly because the hint sheets do not measure how much information was actually assimilated by the subjects. One might argue that one set of hint sheets was easier to understand than the other. One might also argue that the experiment should attempt to evaluate the performance of the subjects who have 'mastered' different approaches. Therefore future research should include more than one method of operationalizing different approaches for providing validity to the experimental results.

The third limitation of the study is regarding the sample sizes of the four groups. In order to conduct the experiment with all four groups at the same time, this study kept the sample size to 92 (because of space and resource limitation). Even though the statistical results (significance levels, statistical power, effect size) provide support for the validity of the results, the small sample size makes it difficult to generalize and build/develop theories based on a single laboratory experiment. With a larger sample size it may also be possible to support the conclusions derived in the current study at higher statistical significance levels without sacrificing statistical power.

In order to obtain more generalizable results, future projects should use managers as experimental subjects. Additionally, experimental work should be combined with empirical data collected from field research for the purpose of building and testing possible theories for effective production planning and operations management [11]. The empirical research combined with computer simulation-based research can further validate and test such theories. The current study only considered one measure of performance, the net revenue. However, in most actual operations, there are multiple layers of business processes between the production function and the actual sale of a product. Hence, other measures of production performance should also be considered. For example, work-in-process inventory levels and cycle times are two other measures of operations performance.

To our knowledge, this article attempted for the first time to evaluate three operations management concepts/approaches under a controlled experimental setting. The results of this particular study might be controversial but are expected to stimulate debate within the discipline. It is hoped that others will conduct similar experimentation to test and validate the findings of our study. It is also hoped that similar studies would be undertaken to test other theories/approaches related to operations management.

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Appendix A

A1. OPT Game Hint Sheets

A1.2. Group 1: control group

An individual makes the best decision if it is based on his/her own experience and background. Hence, the best way to solve the OPT problem is to think about it and decide a course of action.

A1.2. Group 2: Local Optimum (LO) approach

The only way to reach a global optimum is by insuring local optima.

The following rules are based on the above motto. By following these rules you will be able to get a sum of several local optima and hence achieve the global optimum. Use these rules to improve your performance in the OPT game.

1. Balance capacity, then try to maintain flow.
2. Level of utilization of any worker is determined by his/her own potential.
3. Utilization and activation of workers are the same.
4. An hour lost at a bottleneck is just an hour lost at that resource.
5. An hour saved at a non-bottleneck is an hour saved at that resource.
6. Bottlenecks temporarily limit throughput but have little impact on the inventories.
7. Splitting and overlapping of batches should be discouraged.
8. The process batch should be constant both in time and along its route.
9. Schedules should be determined by sequentially: predetermining the batch size, calculating the lead time, assigning priorities, setting schedules according to lead time, adjusting the schedules according to apparent capacity constraints by repeating the above three steps.

A1.3. Theory of Constraints (TOC) approach

The sum of local optima is not equal to the global optimum.

The following rules are based on the above motto. Since we are trying to achieve the global optimum (i.e. the best performance of the whole system), using these rules will improve your performance of the OPT game.

1. Balance flow, not capacity.
2. The level of utilization of a non-bottleneck is not determined by its own potential but by some other constraint in the system.
3. Utilization and activation of a resource are not synonymous.
4. An hour lost at a bottleneck is an hour lost for the total system.
5. An hour saved at a non-bottleneck is just a mirage.
6. Bottlenecks govern both throughput and inventories.

7. The transfer batch may not, and many times should not, be equal to the process batch.
8. The process batch should be a variable and not fixed.
9. Schedules should be established by looking at all of the constraints simultaneously. Lead times are the result of a schedule and cannot be predetermined.

A1.4. Group 4: Management Science (MS) approach

The best decision is made by identifying all the constraints in the system with respect to the objective. Considering them simultaneously results in the best decision.

Think of this problem as a big linear programming (LP) problem. It is very difficult to actually model the OPT game as a linear program. However, it is not difficult to identify some rules from LP and conceptually apply them to the OPT game. Since LP gives the best value of the objective function, the following rules based on LP should help you in improving your performance of the OPT game.

1. The best decision is made by considering the whole system at the same time.
2. Identify which variables are limiting the output of your system.

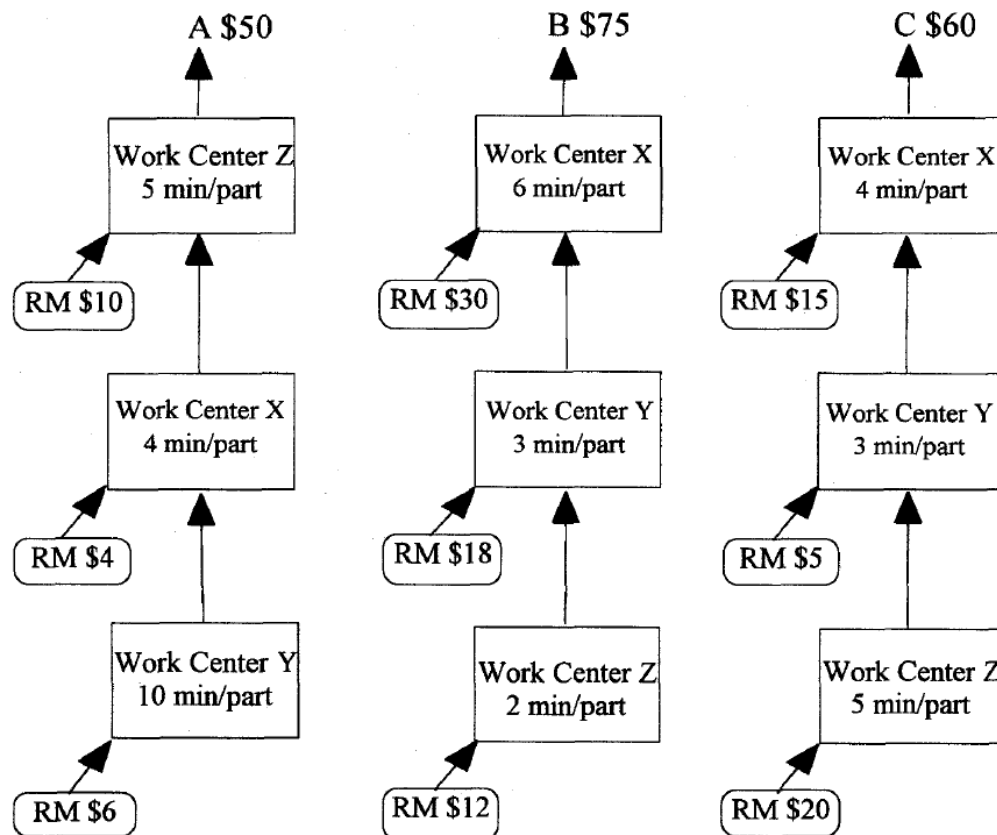


Fig. B1. A sample problem

3. Identify how the above variables limit the output of your system.
4. Only by considering all constraints simultaneously can 'best' objective be obtained.

5. The binding constraints need to be fully utilized to get the maximum objective. The more the utilization of binding constraints, the more the output of the system.
6. Non-binding constraints need not (and should not) be fully utilized to get the best objective. More utilization of non-binding constraints does not mean that output of the system will increase.
7. The objective can be increased in more than one way. Hence, choose 'a mixture of ways' such that they improve the objective.

Appendix B

B1. A Sample Problem

Source: Chase and Aquilano, Production & Operations Management, 7th Edition, Irwin, 1995 [16].

Three products, A, B and C are sold in a market at \$50, \$75 and \$60 per unit, respectively. The market will take all that can be supplied.

Three work centers, X, Y and Z process the three products in the manner shown in Fig. B1. Processing times for each work center are also shown. Note that each work center works on all three products. Raw materials, parts and components are added at each work center to produce each product. The per unit cost of these materials is shown as RM.

Which product or products should be produced?

B1.1 Mathematical programming formulation of the problem

Maximize: $(50 - 10 - 4 - 6)A + (75 - 30 - 18 - 12)B + (60 - 15 - 5 - 20)C$

Subject to: $4A + 6B + 4C \leq 60, 10A + 3B + 3C \leq 60, 5A + 2B + 5C \leq 60$

B1 Solution

| | TOC (from the text) | Linear programming | Integer programming |
|--------------------------------|---------------------------|-----------------------|------------------------|
| Objective function value | \$240.00 | \$286.36 | \$280.00 |
| A | 0 | 2.73 | 3 |
| B | 0 | 2.73 | 2 |
| C | 12 | 8.18 | 8 |

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