AN EXPLORATORY ASSESSMENT OF PROJECT DURATION IN MULTIPLE-PROJECT SCHEDULES WHERE RESOURCES ARE ALLOCATED BY THE THEORY OF CONSTRAINTS METHOD

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ABSTRACT

The theory of constraints (TOC) method for managing multiple projects provides a relatively new and simple heuristic for allocating constrained resources to projects. While this method is increasingly being used, there is little information about its merit and it has not yet been subjected to extensive testing. In this paper literature relevant to the allocation of resources to multiple projects is first reviewed. Thereafter the TOC method for allocating resources to multiple projects is explained. Finally the paper reports on an exploratory study to evaluate the effect that the TOC method for assigning resources has on project duration.

OPSOMMING

Die “Theory of Constraints” (TOC)-metode vir die bestuur van veelvuldige projekte bied ’n relatief nuwe en eenvoudige heuristiek om beperkte hulpbronne aan projekte toe te ken. In die praktyk raak hierdie metode toenemend gewild maar daar is weinig inligting beskikbaar oor die meriete daarvan. Die metode is ook nog nie aan uitgebreide toetsing onderwerp nie. In hierdie artikel word ’n oorsig gegee oor die literatuur van hulpbrontoedeling. Tweedens word die TOC metode vir hulpbrontoedeling bespreek. Daarna word verslag gedoen oor ’n eksploratiewe ondersoek na die effek wat die TOC metode op die tydsduur van projekte het.

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1. INTRODUCTION

Most organisations do not deal with only one project at a time, but handle several projects concurrently [1, 2, 3, 4]. Maroto et al [5] mention a survey that indicates that 84% of companies in Valencia, Spain work with multiple projects. In most cases, many of the concurrent projects require resources from a common resource pool.

To manage multiple projects requires everything needed for managing an individual project. However, multi-project management is not just an aggregation of management efforts required for single projects [6], it requires additional procedures, structures and systems. For example, in a multiple-project environment, projects need to be selected to fit corporate strategy and balanced portfolios of projects need to be created. The design of the organisational structure also needs to be conducive to the handling of multiple projects and structures such as the matrix structure or project support offices could be considered. While these aspects are important, they are beyond the scope of this paper that focuses on one aspect only, namely the allocation of resources to concurrent projects.

Resource allocation is an important aspect of the managing of multiple projects. [4, 8, 9, 10]. Since projects use the same limited resources, they compete for those resources. If the company does not have a systematic way to allocate resources, individual project managers might build in excessive resource contingencies to cope with the risk of having insufficient resources. Such behaviour would reduce the availability of resources and lead to a vicious circle of resource shortages and increased competition for resources. New projects are typically also added to the list of active projects. Maintenance divisions, for example, often experience that work to repair a breakdown of equipment interferes with scheduled maintenance tasks. Furthermore, companies that operate globally have to take the geographic distribution of resources into account. The problem is often also aggravated by factors such as insufficient screening of projects admitted into the system, by failure to prioritise projects, by changes in the scope of projects and also by changes in the relative priorities of projects.

Two common approaches for allocating resources to concurrent projects are described in literature: the *multi-project approach* where projects are considered to be independent and the *single-project approach* where projects are artificially bound together to in a single project [7]. In this sense the approach described in this paper is a multi-project one.

Even without taking factors such as new projects that are being authorised or changes in project priorities into account, the problem of allocating shared, constrained resources to multiple, concurrent projects is complex. A very large number of alternative schedules is normally possible. For example, if one resource has to perform an activity on ten different projects, and the work could be done in any sequence, there would be 10! (more than 3,6 million) possible schedules. If n activities have to be done by m resources and all activities require all resources, there would be $(n!)^m$ possible schedules. It is not feasible to solve this problem of allocating resources by using normal polynomials (it is NP hard). While theoretical optimisation has been attempted, the computing time required for these methods increases exponentially with the size of the networks. Optimisation therefore requires intolerably large amounts of computing time that limits its application [11, 12, 13]. The use of heuristic rules, on the other hand, is simple, effective and provides acceptable solutions that are commonly used in practice.

While a number of other approaches have been reported, heuristic approaches (that often employ decision rules called *priority rules* (also called priority dispatching rules) to prioritise the activities of multiple projects for assigning limited resources to them) are popular. Many priority rules have been suggested. The Theory of Constraints Multiple Project Management method (TOC/MPM) suggests a relatively new, alternative method.

In this paper the literature relating to the conventional heuristics of allocating resources to multiple, concurrent projects, is reviewed. Following that, the TOC/MPM method is explained and finally the paper reports on an exploratory experiment to evaluate the effect of the TOC/MPM resource allocation method on the planned duration of concurrent projects.

The Theory of Constraints (TOC) method to manage an *individual* project is commonly referred to as Critical Chain Project Management (CCPM). This method claims to reduce project duration and to provide a critical chain that does not change as often as the critical path [14, 15, 16, 17, 18]. The alleged reduced duration would result from aggregation of contingency reserves and also from altered human behaviour. The investigation of these claims is beyond the scope of this paper. Certain pitfalls and merits are discussed by Herroelen and Leus [19]. However, the TOC method of allocating resources to *multiple projects* could also have an effect on project duration. It is an objective of this paper to explore this possible effect.

2. JOB SHOP AND MULTIPLE-PROJECT ENVIRONMENTS

In 1995 Adler et al [20] mentioned that little literature addresses the question of congestion in multi-project environments. In 1997 Levy and Globerson [6] confirmed this and in 1998 Walker [21] reported that, in a body of project management knowledge of more than 5000 articles, less than 90 had been published on multiple projects. Of these, less than one third addressed the problem of constrained resources. Since 1998, a number of articles on the management of multiple projects appeared, but the topic of allocating resources is still neglected. Although the problem of allocating resources to multiple projects is fundamentally the same as the problem of allocating jobs in a job shop, the above figures by Walker [21] do not include the large body of scientific work that exists on the scheduling of job shops.

Job shop scheduling or “machine scheduling” received ample attention in the 1970s and in the 1980s. While a relatively small number of papers have been published on the allocation of resources to *multiple projects* [21], the allocation of resources to jobs in *job shops* received much attention in the past, and publications on this topic still appear.

A "job shop" is typically a workshop for manufacturing low-volume industrial products. Such a workshop has a number of dissimilar resources, typically lathes, milling machines, drill presses and other manufacturing equipment, such as heat treatment facilities. Multiple jobs are routed through these resources. Each job typically has its own sequence of activities to be performed by the different resources - not dissimilar to the PERT/CPM schedules used on projects. For the purpose of scheduling, a job shop is defined as *any* facility that handles a variety of orders simultaneously and that treats each incoming order as a “mini project”. In other words a separate schedule is developed for each order, separate records are kept for each job and the progress of every job is monitored. Both multi-project facilities and job shops are characterized by a variety of deliverables for a variety of clients and a dynamic, stochastic operating environment. A “job” is, however, normally considered to be a smaller entity than a “project” [22] and normally has a shorter duration. These differences do not imply any fundamental dissimilarity between a job shop and a multiple-project environment regarding the allocation of resources. The parallel between capacity management in manufacturing environments and multi-project management has also been drawn by Levy and Globerson [6] and by Adler et al [20]. The project management fraternity should, therefore, draw on the body of knowledge of job shop scheduling.

A number of approaches for solving the resource allocation problem have recently been proposed. These approaches include, for example, the application of queueing theory [6, 20].

Most of the heuristic job shop scheduling procedures described in the literature are based on *priority rules* [23]. In the following sections a discussion of the common practice to use *priority rules* to allocate resources to multiple projects is followed by a discussion of the TOC/MPM method.

3. PRIORITY RULES

Meredith and Mantel [7] mention that, in *multiple-project environments,* heuristic solutions start with a PERT/CPM schedule, and then allocate scarce resources according to some priority rule. Priority rules are rules used to obtain a job sequence [24]. A resource is first assigned to the job with the highest priority. Simple rules to determine the priority of activities include, for example, the following:

- *Shortest processing time* (SPT) which dictates that activities with shorter duration receive priority. This rule is sometimes referred to as *shortest operating time* (SOT) [25]
- *First come, first served* (FCFS) that gives priority based on the time of arrival
- *Minimum slack* (MINSLK) also called *least slack* or *slack time remaining* (STR) that gives priority to activities with the least amount of float
- *Earliest due date* (EDD or DDate) that gives priority to activities of the project that have to be finished first. A variation of this rule is where priority is given to the job with the *earliest next operation* (OPNDD) [24].

Various other rules to assign resources to multiple, concurrent projects have been defined. [11, 26, 27, 28, 29, 30]. Panwalkar and Iskander [31] list 113 different priority rules.

4. IN SEARCH OF THE BEST PRIORITY RULE

A vast amount of work has been done in attempts to identify the best priority rule. However, different researchers used different objective functions [25]. Three main metrics that have commonly been used to evaluate priority rules are: (a) duration-based criteria, (b) minimization of work-in-process inventory, and (c) maximization of resource utilisation (minimization of idle time).

Two common variations of duration-based criteria are:

- Minimization of *lateness* where:
  lateness = Σ[Due date – committed date] for *all projects* and
- Minimization of *tardiness* where:
  tardiness = Σ[Due date – committed date] for *late projects only*

Further variations distinguish between *due dates* and the *total time* that a project spends in the organisation (from project authorisation to close-out).

Kurtulus & Davis [26] also used a measure based on the peak load of total resource requirements and another measure based on the rate of resource utilisation. Ferrell *et al* [32] use modified mean flow time and the total cost of earliness and tardiness while Boctor [33] mentions total project cost and project net present value.

In 1982 Kurtulus and Davis concluded that, after decades of research on priority rules, there was little consensus on a "best" rule or set of rules [26]. In 1988 Adams et al [23] reported that none of ten priority rules tested, outperformed all the others. However, some rules that are commonly believed to provide good results on duration-based criteria are listed in Table 1.

Some authors suggest different rules for different situations. Kurtulus and Narula [28] studied more than 3000 scheduling problems and recommend the MINSLK rule for a variety of situations. Other authors [13, 33, 34, 35] confirm the merit of MINSLK. Meredith and Mantel [7] confirm that the *minimum slack* (MINSLK) rule is popular, and also mention that the "shortest processing time" (SPT) rule is sometimes used as a secondary rule with MINSLK to break ties.

Approaches other than heuristics based on simple priority rules have been developed. For example Lawrence and Morton [35] describe a scheduling policy that takes into account the cost of a delay. Lova et al [36] developed a multi-criteria heuristic that performs better than some popular priority rules.

It makes sense to compare TOC/MPM with other simple heuristics such as the MINSLK rule rather than with computationally expensive methods. While other priority rules and approaches other than priority rules provide better results under certain conditions, there is ample evidence that the MINSLK rule performs well under many conditions. The authors also believe that it is widely used. The MINSLK rule is therefore considered to be a useful benchmark for an exploratory investigation and, in the experiment described later, the duration of TOC/MPM schedules with SPT as secondary rule is compared with the duration of MINSLK schedules with SPT as secondary rule.

Acronym	Name	Description of rule
MINSLK	Minimum slack	A resource is first allocated to the activity with the least amount of slack
MINLFT	Minimum late finish time	A resource is first allocated to the activity with the minimum late finish time
SASP	Shortest activity from shortest project	A resource is allocated to first finish the shortest activity that is ready on the shortest project
SPT, SOT or SOF	Shortest processing time, shortest operating time or shortest operation first	A resource is allocated to first finish the activity with the shortest duration
FCFS	First come, first served	A resource is allocated to projects according to the sequence in which the projects were authorised
LSSA	Late start, shortest activity	A resource is first assigned to an activity with the soonest late start time, if there is a tie, the activity with the shortest duration is performed first
CR	Critical Ratio	The difference between the due date and the current date divided by the planned remaining queue time
MAXTWK	Maximum total work content	A resource is first allocated to the project with the largest total work content
MAXPEN	Maximum penalty	A resource is first assigned to the project with the largest penalty
MINPDD, EDD (or Ddate)	Minimum project due date, Earliest Due Date (or Due Date)	A resource is first assigned to an activity on the project with the earliest due date
OPNDD	Operation Due Date	A resource is first assigned to the *activity* with the earliest *next operation*

Table 1: Resource allocating rules that could be expected to provide good results on duration-based criteria

[Adapted from 7, 24, 25, 26, 28, 29, 30]

5. THE TOC/MPM METHOD FOR ASSIGNING RESOURCES TO MULTIPLE PROJECTS

The TOC/MPM method is increasingly being used by practitioners but little information about its merit is available [38]. Fenbert & Fleener [39] reported on the implementation of the TOC/MPM method. They mention benefits that include improved on-time delivery.

The TOC method for multiple projects (TOC/MPM) retains any advantages that critical chain project management (CCPM) for individual projects might offer. It has the further objective of maximizing the number of projects that the organization can handle simultaneously to maximise the value of the throughput value of the organisation [14, 16, 18, 40]. The relatively new TOC/MPM method is described below.

Cohen et al [38] experimented with a number of identical small projects and compared TOC/MPM with approaches that utilise some priority rules. They found that performance with the MINSLK priority rule was not significantly different from the critical chain approach that used the TOC/MPM method for allocating resources. Their experiment, however, takes into account more than one effect of the critical chain and TOC/MPM methods and does not isolate the effect of the TOC/MPM resource allocation method. It is the intention of this paper to specifically evaluate the effect of the TOC/MPM resource allocation method in isolation of any other effect.

Both the critical chain approach for managing individual projects and TOC/MPM make use of buffers to convert complex stochastic problems into relatively simple deterministic ones. The problem investigated here is therefore a deterministic one.

The Theory of Constraints (TOC) prescribes that the constraint of a system has to be identified and attention focussed only on the constraint until it is no longer a constraint. For an individual project, the network path that determines project duration (the critical chain) is considered to be the constraint. In a multiple-project environment, a resource that is overloaded limits the number of projects that the organisation can execute, and thus presents a further constraint. While the concept of the critical chain removes resource contention *within a single project*, the TOC/MPM method provides a way to allocate scarce resources across concurrent projects and thus resolves resource contention *among projects*.

The Theory of Constraints (TOC) approach involves the following five steps [14, 41, 42, 43]:

1. Identify the constraint(s) of the system
2. Decide how to exploit the constraint(s)
3. Subordinate non-constraints to the decision(s) on exploiting the constraint(s)
4. Elevate the constraint(s) (in other words: take steps to “widen the bottleneck”)

5. By returning to Step 1 above, determine whether a new constraint has been uncovered, rendering the constraint under consideration as a non-constraint, or less critical.

Where concurrent projects depend on a pool of shared resources, one resource that is overloaded limits the number of projects that the organisation is able to execute, and thus presents a constraint. The objective of the method under discussion is to maximize the number of projects that the organization would be able to handle concurrently by systematically managing resources with high workloads.

Unlike the three metrics used to evaluate priority rules in a job shop environment (duration-based criteria, work-in-process inventory and resource utilisation), the emphasis of CCPM is on minimising project duration. An additional objective of the TOC/MPM approach is to maximise the value of the throughput delivered by the projects by *maximising the number of projects* that the organisation can handle simultaneously. [16, 18, 40]. The minimization of idle time ("keeping resources busy") is considered unimportant in this philosophy [41, 42]. While the metric of maximum resource utilisation is commonly used to evaluate priority rules for job shops, the TOC/MPM approach is at any point in time concerned only with the utilisation of a single, critical resource that is considered to be the constraint. Project duration and other duration-based criteria are related to the number of projects that the company can handle and these are therefore emphasised. Minimization of work in process and maximisation of resource utilisation would receive less emphasis in the TOC philosophy. In an exploratory assessment of TOC/MPM it makes sense to evaluate the approach against the criterion that it sets, viz. project duration.

TOC Step 1 implies that the resource (or resources) constraining the capacity has to be identified. This resource is referred to as the *drum resource*.

Most priority rules use attributes of the activities such as activity duration (processing time), due date, work content or slack [24, 31]. The notion of a drum resource differentiates the TOC/MPM method from these rules. Adams et al [23], however, also rank resources according to workload and give priority to the resource with the highest ranking to repeatedly solve one-resource problems. This is similar to the TOC/MPM approach. Their "shifting bottleneck" procedure provides better results than the best priority rule heuristics but, whereas TOC/MPM is a simple heuristic, their method appears to be relatively computationally expensive.

To identify the constraint (TOC Step 1), the resource with the highest workload should be selected. More than one individual might believe that his/her workload is the highest, and it might be difficult to identify which one actually does have the highest load. This is no problem since the fifth TOC step implies an iterative process.

To limit expenditure, organisations have to do with available resources. Only when Step 4 is reached is the capacity of the drum resource increased. When Step 5 is reached, there is an opportunity to select another resource as the constraint. Therefore, if there is a resource with a workload that is higher than that of the one that has initially been selected as the constraint, it will be addressed during a later iteration. Management should, therefore, steer clear of extended arguments regarding which resource to select, and simply select one that is considered to be under pressure.

Raz *et al* [45] mention that, at any time, there might be several constraining resources and also that, at different points in time, there might be different constraining resources. This could lead to conflicting schedules. They are of the opinion that the premise of a single constraining resource is based on a steady-state view of the work mix in an organisation. The reader should, however, note that the TOC/MPM process is iterative: The resource with the highest workload is identified as the "drum", and the workload problem of this resource is solved. Once this is done, the next resource with a workload problem would then be addressed. This ensures that the workload of all resources that are under pressure (and which could thus limit the capacity of the organisation to handle projects) receive systematic attention at an appropriate time. Managerial judgement might be needed in identifying the resource with the highest workload and, should management be wrong, it would not matter too much as the workload of all highly loaded resources would receive attention in due course. The fact that there could be more than one feasible schedule (depending on which resource is selected first as the "drum") should also be seen in the light of the fact that, in practice, it is virtually impossible to identify an optimum schedule. Like all other data used in scheduling (such as the duration of activities) the workload on a resource is a mere estimate.

TOC Step 2 is to sequence the work to be performed by the drum resource. Leach [16] defines three activities within this second step: (a) Prepare the critical chain schedule according to the CCPM method for each project independently. (b) Assign the drum resource to the projects in the order of their priorities. (c) Create a multi-project schedule for the drum resource that would allow the highest throughput for the company.

Scheduling of other resources is subordinated to this schedule (TOC Step 3). While it is acceptable for any other resource to wait for the work being performed by the drum, it is unacceptable for the drum to wait for work performed by any other resource.

To accomplish Step 3, a *drum buffer* is inserted before each task performed by the *drum resource* [16, 18, 40]. (It is sometimes also referred to as a "strategic resource buffer" or "bottleneck buffer"). Drum buffers prevent the drum resource from having to wait in case a preceding activity has been delayed. In this way, non-constraints are subordinated to the constraint (TOC Step 3). This means that the risk of a resource, that is not the capacity-constraining one delaying the capacity constraining one, is addressed.

To make the best possible use of the existing capacity before investing in additional capacity, additional resources are acquired (TOC Step 4) only after Steps 2 and 3 have already been taken.

Adding additional resources to alleviate the pressure on the drum resource might result in a situation where the resource under consideration is no longer the constraint. One should, therefore, to Step 1 to identify the current constraint (TOC Step 5). This ensures that the workload of all resources that are under pressure (and that could thus limit the capacity of the organisation to handle projects) receive attention at the right time. This provides a systematic and continuous process to eliminate any over-allocation of work to resources.

In general, there would be variability in the duration of work performed by the drum resource. A *capacity buffer* is therefore inserted to stagger projects [16, 18]. The purpose of this buffer is to prevent a possible delay on one project from influencing other projects, thus improving stability of the schedules.

During project execution, priority should be given to the task of the project with the highest risk of missing its committed date. This risk is indicated by the remaining fraction of the project buffer [45]. (The project buffer is a buffer inserted at the end of the critical chain to aggregate the contingency reserve of the activities on the critical chain).

Two further aspects of TOC/MPM are *first* that the release of projects is based on the workload of the drum resource [46]. *Secondly,* during project execution, the remaining fractions of project buffers could be used to adjust the relative priorities of projects. (The concept of a *project buffer* has been described elsewhere [14, 16, 17, 18]). For example, a higher priority could be allocated to a project that is at risk of missing its committed date as a result of a small fraction of the project buffer remaining. These aspects might provide additional benefits, but investigating such benefits is beyond the scope of this paper.

6. DESIGN OF THE EXPERIMENT

An experiment was performed to provide a first-order indication of the merit of the TOC/MPM resource allocation method. The experiment was designed to compare project duration of two small projects where resources are allocated according to the TOC/MPM method with the duration of the same projects when the resources are allocated according to the MINSLK rule. As the effect of resource allocation is isolated from other effects, the problem investigated is a deterministic one.

The following were defined for the purpose of the experiment:

$\mu_{TOC/MPM}$ = mean total duration of projects scheduled according to the TOC/MPM method

μ_{MINSLK} = mean total project duration of projects scheduled according to the MINSLK rule

$\mu_D = \mu_{TOC/MPM} - \mu_{MINSLK}$

Null hypothesis, H_0: $\mu_D \geq 0$

Alternative hypothesis, H_0: $\mu_D < 0$

Data set	Duration (TOC/MPM)	Duration (MINSLK)	Difference in duration	% Reduction in duration
1	24	24	0	0
2	23	23	0	0
3	27	27	0	0
4	21	21	0	0
5	17	17	0	0
6	24	24	0	0
7	24	24	0	0
8	25	27	-2	7.41
9	21	21	0	0
10	17	17	0	0
11	17	17	0	0
12	19	19	0	0
13	29	31	-2	6.45
14	17	17	0	0
15	21	21	0	0
16	18	18	0	0
17	17	24	-7	29.17
18	19	19	0	0
19	20	22	-2	9.09
20	17	17	0	0
21	17	17	0	0
22	21	21	0	0
23	18	18	0	0
24	19	19	0	0
25	23	23	0	0
26	24	24	0	0
27	17	17	0	0
28	24	24	0	0
29	19	21	-2	9.52
30	17	17	0	0
Min	17	17		
Max	29	31		
Average	20.5	21.1	-0.5	
Spread	12	14		
Std dev	3.431	3.681	1.408	

Table 2: Total duration for two projects scheduled by TOC/MPM and MINSLK

The authors were of the opinion that, for such an exploratory experiment, any two small projects could be chosen. The projects chosen were ones that Herroelen *et al* [19] used to investigate the scheduling of individual projects. As the objective was to compare only the performance of the two alternative ways for assigning resources, deterministic activity durations were assumed for the experiment. No buffers were inserted. It was assumed that the two projects had to be executed by a common pool of six resources. Each activity could only be performed by a specific resource, and for this purpose a random process was used to match activities and resources. The random process ensured an equal probability of allocating a resource to each activity within each of the two projects. It was assumed that activity durations required the resource to be allocated 100% to the specific activity, in other words resources were not split between activities. In addition, once a resource started an activity, it had to complete the activity before it could perform work on another activity (i.e. activities were not split). To create more than one case for comparison, the random process of allocating resources was repeated 30 times. One project was assigned a higher priority than the other. This implies that a resource would not start on Project B if it could perform work on Project A instead (regardless of whether or not any of the activities were on the critical chain of a project). Where any one of the two methods provided two or more alternative schedules, the *shortest processing time* (SPT) rule was used as a secondary rule to break the tie.

7. RESULTS

As indicated in Table 2, in five of the 30 cases, the TOC/MPM method produced a shorter total duration for the two projects than the minimum slack method. In these cases, the total duration was between 6,5% and 29% shorter than the schedules produced by means of the minimum slack method. In the other 25 cases, the two methods produced the same total duration (although the detail of the schedules differed). The average total duration for the 30 cases was 2,4% shorter when scheduled by means of the TOC/MPM method.

Based on a paired t-test, at a significance level of 5%, the null-hypothesis (that the mean project duration of schedules produced by TOC/MPM would be the same as or longer than ones produced by MINSLK) is rejected, p-value = 0,031. While further research would be required to evaluate the TOC/MPM resource allocation method this result provides the first-order indication of the merit of the method.

Although significant, the difference in mean project duration is small (2,4%) and the question arises whether or not there would be any practical significance. There are a number of factors that could play a role. These include the number of projects (in other words, would the difference be larger if more than two projects had to be executed concurrently?) Another question is whether the difference would have been larger if the project networks had been larger and more complex.

Another factor revolves around the relative workload on the resources: There were indications that TOC/MPM performed better than the minimum slack rule in those cases where there was a resource that had a significantly higher workload than the other resources. In cases where resources had more or less the same workload, TOC/MPM seemed to perform as well as the minimum-slack rule. This result should have been expected as a result of the emphasis that TOC/MPM places on the drum resource. TOC/MPM might, therefore, be more appropriate in situations where one resource is overloaded relative to the other resources than in situations where all resources have more or less equal workloads. If it were true (as speculated above) that TOC/MPM produces better results in cases with unequal workloads, it probably addresses a real scheduling problem. In a scenario in which all resources had a low (and possibly more or less equal) workload, there should be no problem in executing the work. If all resources had a high workload, the problem probably lies with project selection and screening rather than with the scheduling method. Therefore it seems that TOC/MPM might address the situation where a real need for improved scheduling exists.

Maroto et al [5] describe a number of parameters of projects. Any of these parameters could have an effect on the performance of TOC/MPM and in further experiments the effect of these parameters should be tested.

As indicated earlier, any reduction in project duration would be independent of the claim that CPPM reduces project duration. The reduction caused by the TOC/MPM resource allocation method is in addition to any effect that the critical chain approach for individual project (CCPM) or drum and capacity buffers might cause.

The main claim of TOC/MPM is that it increases income from sales by increasing the number of projects that are executed concurrently. The number of projects completed within a specified time period is obviously related to the speed of execution and it seems plausible that reduced project durations would increase the number of projects that a pool of resources could handle concurrently. However, the claim regarding an increase in the number of projects has to be verified.

8. PROPOSED FURTHER RESEARCH

The experiment reported in this paper was intended only as an exploratory investigation to provide a first-order indication of the duration of schedules created by means of the TOC/MPM method. It is believed that the results reported in this paper justify comprehensive investigation. Extensive computer simulation should be done to investigate the merit of the approach. While the effect of parameters such as project complexity and the number of projects should be investigated, potential benefits under conditions of unequal workload should receive special attention.

9. ACKNOWLEDGEMENT

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