REVIEW ON THEORY OF CONSTRAINTS

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ABSTRACT

Theory of constraints (TOC) is a philosophy of management put forth by Eliyahu M. Goldratt, which claims that each system has at least one constraint. Although initially in manufacturing method, TOC has now developed into a theory of Management: a powerful systemic problem structuring and problem solving methodology which can be used to develop solutions with both intuitive power and analytical rigour. This philosophy is applied in many functional areas of companies, ranging from production flow management, marketing, services and project management to being a tool of logical reasoning. The present work aims at highlighting the extant literature with respect to the application of TOC and summaries important findings on the theory and practice of TOC.

KEYWORDS: *Theory of constraints, Production flow management, marketing, services, project management.*

I. INTRODUCTION

The theory of constraints (TOC) was invented by Dr. Eliyahu M. Goldratt in 1984 in his book 'The Goal'[22], Israeli physicist turned business guru, developed a revolutionary method for production scheduling [21] which was in stark contrast to accepted methods available at the time, such as MRP. TOC is evolved from the OPT (Optimized Production Timetables) system and was later known under the commercial name of Optimized Production Technology (OPT) . Central to the TOC philosophy was that any organization or system has a constraint or a small number of constraints which dominate the entire system.

The theory of constraints (TOC) adopts the common idiom "A chain is no stronger than its weakest link" as a new management paradigm. This means that processes, organizations, etc., are vulnerable because the weakest person or part can always damage or break them or at least adversely affect the outcome.

The analytic approach with TOC comes from the contention that any manageable system is limited in achieving more of its goals by a very small number of constraints, and that there is always at least one constraint. Hence the TOC process seeks to identify the constraint and restructure the rest of the organization around it, through the use of five focusing steps. The secret to success lies in managing these constraints and the system as it interacts with these constraints, to get the best out of the whole system.

The main motivation for the research review reported in this paper was the realization that TOC is growing very rapidly, and we simply did not know what was "out here"; i.e. what had already been tackled. This review paper will first outline the background to TOC, and then report on the application of paradigms of TOC in various fields and the findings. The theory of constraints (TOC) is a management philosophy that has been effectively applied to Manufacturing processes and procedures to improve Organizational effectiveness [25]. In its brief 25-years history, TOC has developed rapidly in terms of both methodology ([9], [12]) and area of applications ([33], [46]).

Most of the work is carried out in the application of Logistics Paradigm in the field of Project Management. The literature concerning about the feeding buffers is well illustrated in ([24], [44], [36], [1], and [50]). The methodology used in the project management is critical chain project management to find the critical chain and to find the project buffers and the feeding buffers.
Three TOC Paradigms that have evolved over the last twenty-five years Logistics, Global Performance Measures and thinking process ([2], [14]). More recently [4] have referred to these paradigms as decision making, Performance Measurement system and thinking Process. The review of literature on TOC is spanned from the Logistics Paradigm to the Thinking process Paradigm. In section 2, we reviewed the Logistics Paradigm and application of logistics paradigm in the various fields. Where as in section 3, we reviewed the Global performance Measure Paradigm and application of the paradigm in the services. Section 4, deals with the Thinking process Paradigm and the various fact finding tools in that paradigm and finally in section 5, this paper concludes with some directions for further research on TOC.

II. LOGISTICS PARADIGM

Originally the Logistics Paradigms are looking for system constraints in order to increase throughput. The Logistics Paradigm of the TOC has evolved from the scheduling software called Optimized Production Technology (OPT) which in turn based on the following nine rules [24]. This included using Drum-Buffer-Rope (DBR) scheduling technique and the Five Focusing steps of TOC. The DBR methodology synchronizes resources and material utilization in an organization. Resources and materials are used only at a level that contributes to the organization’s ability to achieve throughput. Because random disruption is inevitable in any organization, DBR methodology provides a mechanism for protecting total throughput of the system by the use of Time-Buffers (T-Bs).

2.1 Application of Logistics Paradigm

The logistics paradigm was applicable in Manufacturing, supply Chain, Project Management and in services [6]. In this Section we reviewed the application of Logistics Paradigm in Manufacturing, Supply Chain, and Project Management and in services (Table 1).

Table 1: application area of logistics paradigm and references

Main area	Sub area	Reference
Logistics Paradigm	Manufacturing	[34], [15], [10], [11], [18], [53], [62], [49], [19], [39], [55], [70].
	Supply Chain	[28], [48], [71].
	Project Management	[24], [64], [38], [40], [69],[44], [36],[1],[50], [26], [65], [47], [66], [17], [72], [61], [35], [51], [27],[52].
	Services	[31], [6], [67], [63], [30], [46], [16], [54], [57].

Literature concerning TOC in Manufacturing can be broken down into four categories. TOC, Materials requirement Planning (MRP), Manufacturing Resources Planning (MRP II) and JIT Manufacturing. The buffer stock allocation in serial and assembly type of production lines, the key concept in this is the “Long Pull” (Constant Work-In-Process inventory) Kanban System [34]. A comparison is made between the TOC and the JIT manufacturing in [15]. The Drum-buffer-Rope scheduling technique can be used in services as well as in manufacturing ([10], [11], [53], and [19]). The comparison of Traditional JIT and TOC Manufacturing in a Flow shop in [18]. A survey based comparison is made between performance and in change of performance of firms using JIT and TOC and suggested that greatest performance and improvement in performance occurred to adopters of TOC [55]. JIT and TOC buffering philosophies are compared and suggested that improved system performance stems from the strategic placement of buffers in DBR, which maximizes protection of the constraint from variation rather than attempting to protect each individual station is given by [70].The DBR technique can be used to manage supply chains ([28], [48], and [71]) and to improve current production operations [62]

TOC project management process is a pull process that promotes low WIP level, time buffers to protect the critical chain of tasks and resources, and no multitasking- which is defined as splitting a worker's time between two or more priority projects, to the detriment of the overall schedules.

Literature concerning TOC in Project Management in Logistics Paradigm is that it was first popularized by the novel, '*The Goal*' [22] that applied the principles to operations management. Since 1997 it has found applications in two areas within project management. The first application is scheduling of a single project to reduce project duration and simply project control. This is the main theme of the novel *Critical Chain* [24]. A practical approach for implementing critical chain Management is suggested by [38]. The application of TOC in the scheduling of single project is investigated [64]. The Theory of Constraints Management system is investigated [40]. Planning and controlling multiple, simultaneous, independent projects in the resource constrained environment [69]. The TOC Project Management approach is to schedule all non-critical activities as late as possible, but with buffers. The objective of these buffers (called "feeding buffers" because they are placed where non-critical paths feed into the critical chain) is to prevent delay of the execution of work on the critical chain when work on a non-critical path is delayed. The illustration of the literature of these feeding buffers is given by ([24], [44], [36], [1], and [50]).A detail information of how these five steps provide the framework for coordinating and controlling activities in both manufacturing and project environment [26]. The literature review on application of TOC in Project Management is given by [65]. Critical chain scheduling is not only a technique for the development and tracking of project schedules it is coherence and comprehensive approach to project management that encompasses and affect other processes and practices associated with project management as well [47]. The TOC approach can also be applied to the other areas of Project Management such as project cost management and project risk management [66]. The application of theory of Constraints Multi-Project Management at the Boeing Commercial Airline Company, Highlighting project end date predictability, modified scheduling algorithm and balancing resources across multiple projects [17]. The comparison and contrast of the advantages and disadvantages of traditional project management and TOC project management [72]. Several examples of how placing buffers or blocks of unscheduled time to account for delays allows project manager to minimize their risks and achieve project success [61]. A number of sources of bias in performance of project to schedule and cost estimates and provides recommendations to size buffers that ensure your projects come in under your baseline schedule and budget [35]. Although Critical Chain Project Management has a number of valuable concepts, it does not provide a complete solution to project management needs and the organizations should be very careful about the exclusion of conventional project management techniques [51]. A development of five-step innovative approach for the application of the management philosophy Theory of Constraints is suggested by [27]. An algorithm to determine critical sets and critical clouds and applied to a sample project and the results are presented in a condensed, project manager friendly, graphical format [52].

The Logistics Paradigm in services is that the five step focusing process has been applied to processes and procedures within services. The focusing steps have been used to improve logistics functions with the military [67]. The five focusing steps can be used in re-engineering of administrative functions [63]. The five step process has been used to improve information flow ([31], [6], and [16]. It has been used to improve service times [46]. It has been used to improve sales [30]. It has been used in medical settings [54].

The drum- buffer-rope scheduling technique can be used in services as well. While manufacturing DBR uses to schedule machinery, services may use DBR to schedule people within the organization, to set appointments for customers, or to predict lead times for customers. The buffer management can be used to identify pr4oblems and weaknesses that will cause disruption to the system [57].

III. GLOBAL PERFORMANCE MEASURES PARADIGM

Under Toc all company performance measures are driven by the global goal of making money now and in the future. Throughout the methodology/ philosophy, the three measurements of throughput, inventory/ investment and operating expense serve to focus the improvement activity so as to achieve a global optimum. Throughput is defined as the rate at which the system generates money through sales. Inventory/ investment are defined as all the money the system invests in purchasing things the system intends to sell. Operating expense is defined as all the money the system spends in turning inventory into throughput [24]. These changes in definition provide more realistic measurements and targets for the organization's operations. This is accomplished by increasing throughput, reducing inventory and reducing operational expense. The measurements are also related back to general accounting methods for tax and reporting purpose [61]. All measurements and activity are linked to increasing throughput (T) first, reducing inventory/ investment (I) second and lowering operating expense (OE) third.

$$\text{Net Profit} = T - OE \quad (1)$$

$$\text{Return on Investment} = (T - OE)/I \quad (2)$$

$$\text{Cash Flow} = T - OE +/- \Delta I \quad (3)$$

The equations govern all activity and show the direct link to organizational profit ([13], [23], [60],]. Net profit is an absolute measure reflecting the company's ability to make money now and in the future, Return on Investment is a relative measure and finally Cash Flow is a survival Measurement [37]. TOC does not consider value added costs as part of inventory valuation. Similarly in operating expenses, no distinction is made between direct or indirect, long and short- term expenses.

Table 2: application area of global performance measure and references

Main Area	Sub area	References
Global Performance Measure	Services	([58],[59]), [67], [43], [41],[42], [29], [5], [69], [7],

Services share this goal, defining throughput based on sales. However services may have to be a little more creative when it comes to defining inventory and operating expenses (OE). Application of Global performance measure and its applications and the references are given in Table2. Under TOC the more effective statement of corporate goals are those that lead to more effective measures of inventory and operating expenses within the service is suggested by [41]. The most services will have limited amount of traditional inventory ([7], [42], and [43]), the service is often produced at the time of sale and cannot be carried in inventory, and inventory will be a smaller fraction of the service firm's assets than it would be for a manufacturing firm. Just because inventory is often a smaller fraction of assets for services, these global performance measures can still be utilized ([5], [41], [69], [29], [58], [59], and [67]).

IV. THINKING PROCESS PARADIGM

The major component of TOC that underpins all the other parts of the methodology is the TOC Thinking Processes. Goldratt states that managers make three decisions when dealing with constraints: What to change? What to change to? and How to cause the change? The TOC logical thinking process (TP) has evolved to answer these generic questions [63].The past ten to fifteen years have shown that it is often managerial policies are most often the main constraint [50] the thinking process also helps in these situations. The thinking process consists of "trees" or logic diagrams that provide a road map for change, by addressing the three basic questions of What to change, What to change to, and How to cause the change. In much the same way as the 5 Focusing Steps focus on the constraint, the Thinking Processes focus on the factors that are currently preventing the system from achieving its goals. As shown in Fig.1 the Thinking Process follows the cause-effect logic, necessary condition logic and verifying sound logic.

The current reality tree (CRT) depicts the current state of affairs, designed to identify the system constraint, link causes and effects within the current operation to reveal root causes of problems. Future reality trees (FRT) are used to test potential solutions by diagramming cause and effect relationship for events in the future. Transition trees (TT), also called a cause-and –effect trees, is a flow diagram describing the states of the system as it changes based on a prescribed action plan; it is an implementation plan that has been time sequenced. Two other tools are slightly different. The evaporating cloud (EC) and the prerequisite tree (PRT) are used to identify necessary conditions. These tools complete the sentence "In order to have—we must---" and are used to identify and overcome obstacles to meeting an objective or implementing a solution. The PRT provides a bridge between the future reality tree and the transition tree. As such, the PRT is also time-sequenced. Fig 2 shows the Thinking Process procedure for solving the problem.

Three of the trees (Current and Future Reality trees and the Transition Tree) use cause-and –effect logic. They are built up by constructing connections between observed effects and cause on the basis of "sufficient cause". Sufficiency can be of 3 types: "A is sufficient to cause C" or "If both A and B occurs together, then they will be sufficient to cause C" or "A and B (separately) both contributes to C, and between them is sufficient to cause C". The Evaporating Cloud and the Prerequisite Tree both use necessary condition thinking: "In order to achieve A we must have B". The logic rules are called the Categories of Legitimate Reservation ([12], [45]), and have been proposed for use in validating Systems Dynamics models [3]. An excellent straight forward explanation of these building blocks is given in [56]. A fuller description and examples of these logics were given in ([21], [45], [12], and [32]).

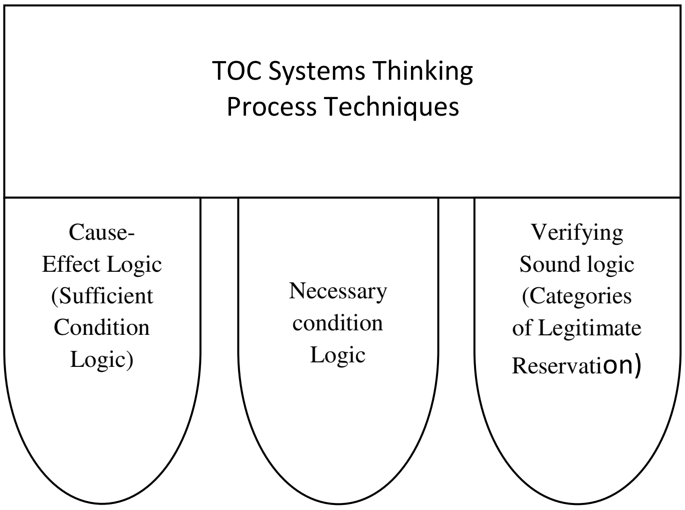

Fig 1: TOC Thinking Process

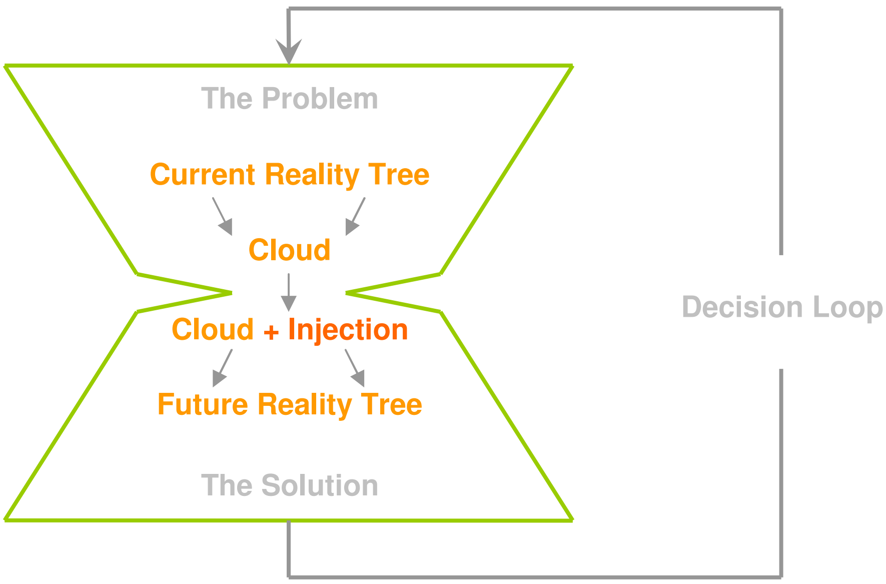

Fig 2: Thinking Process Procedure

4.1. Current Reality Trees (CRT)

An Existing condition is called as a reality [20]. The tools he has designed are intended to use to analyze and deal with a system condition, or reality, with which the TOC practitioner is unhappy. A Current Reality Tree as a logic structure which has been designed to depict that state of reality as it currently exists in a given system [12]. It is constructed from top-down: from observed undesirable effects, postulating likely causes for those effects, which are then tested via the CLR. One such test is to predict (and check for) other effects that would also arise if this cause did exist- hence the term Effect-Cause-Effect.

The CRT is designed to achieve the following objectives [12]:

- Provide the basis for understanding complex systems
- Identify undesirable effects (UDEs) exhibited by a system
- Relate UDEs through a logical chain of cause and effect to root causes
- Identify, where possible, a core problem that eventually produces 70% or more of the system's UDEs.
- Determine at what points the root causes and/or core problem lie beyond one's span of control or sphere of influence
- Isolate those few causative factors (constraints) that must be addressed in order to realize the maximum improvement of the system
- Identify the one simplest change to make that will have the greatest positive impact on the system. (P.64)

Dettmer described the CRT as functional rather than organizational and as such is blind to internal and external system boundaries. CRT's may also include positive feedback loops: generally there will be at least one feedback loop which constitutes a vicious cycle. The existence of a loop usually opens up more possibilities for the setting of remedial action: a change in or below a loop will have a significant effect.

4.2. Evaporating Clouds (EC)

Once the TOC practitioners have identified what to change, the second step in the process deals with the search for a plausible solution to the root cause; that is, what to change to. This task is accomplished with the aid of the Evaporating Cloud (EC) and the Future Reality Tree (FRT). Unlike the trees, the EC has a set format with 5 boxes. The practitioner identifies two opposing wants, that represent the conflict, the need that each want is trying to satisfy, and a common objective or goal that both needs are trying to fulfill. This direct conflict is often the same as that underlying the CRT. Traditionally in resolving these conflicts, managers have sought compromise solutions [20]. The EC start with an objective, which is the opposite of the core problem. The object has a minimum of two requirements listed. Each requirement has a prerequisite. From the objective, the requirements (minimum of two) are listed. Each requirement will have at least one prerequisite. It is the prerequisites that depict the tug-of-war. What is needed is a set of injections that can be used to break the validity of any one of the assumptions. This is the first step in freeing our self from the binding controversy. In constructing the EC, one injects the ideal answer, which would burst the cloud and thereby remove the problem. The EC is intended to achieve the following purposes [12]:

- Confirm that the conflict exists
- Identify the conflict perpetuating a major problem
- Resolve conflict
- Avoid compromise
- Create solutions in which both sides win
- Create new 'breakthrough' solutions to problems
- Explain in depth why a problem exists
- Identify all assumptions underlying problems and conflicting relationships.

4.3 Future Reality Trees (FRT)

Once a solution, called an injection, has been identified via the EC method practitioners assume for the next exercise that it has been achieved and start to build the Future Reality Tree (FRT). The tree is constructed and scrutinized to test the solution, once again using an effect-cause-effect method. The

FRT identifies what to change as well as considering its impact on the future of the organization. The Future Reality Tree is the thinking process that enables a person to construct a solution that, when implemented, replaces the existing undesirable effects with desirable effects without creating new ones (Goldratt, 1993) Step-by-step the solution is created, and each stem is scrutinized to logically show that once the injection are implemented, the desirable effects can be accomplished. The resulting tree originates in one or more injections and ends in desirable effects which really reflect the opposite of the UDEs in the CRT. Glodratt's Categories of Legitimate Reservation (CLR) provide guidelines for communicating any reservations about the validity of the elements and connections within the trees [12, 3]. The FRT serves the following purposes:

- Enables effectiveness testing of new ideas befor3e committing resources to implementation
- Determines whether proposed system changes will produce the desired effects without creating negative side effects
- Reveals through negative branches, whether proposed change will create new or collateral problems as they solve old problems, and what additional actions are necessary to prevent any such negative side effects from occurring
- Provides a means of making beneficial effects self-sustaining through deliberate incorporation of positive reinforcing loops
- Provides a means of assessing the impacts of localized decisions on the entire system
- Provides an effective tool for persuading decision makers to support a desired course of action
- Serves as an initial planning tool

4.4. Prerequisite Trees (PRT)

Once the practitioners have identified what to change to, the third step in TOC deals with implementing the solution. The one of the TOC principle is that "ideas are not yet solutions" [20]. It cannot be called a solution until implementation is complete and the system is working as intended.
The PRT is intended to identify obstacles that prevent the injection from the EC being implemented.
The PRT uses a different logic from the previous trees, both of which use sufficiency logic (which basically asks "Is this enough?") to establish cause and effect relationships. The PRT uses necessary logic, as does the Evaporating Cloud. Asking the following two questions to check whether a PRT is needed [12]:

- Is the objective a complex condition? If so, a PRT may be needed to sequence the intermediate steps to achieve it.
- Do I already know exactly how to achieve it? If not, then a PRT will help map out possible obstacles, the steps involved in overcoming them, and the appropriate sequence.

The PRT is used to achieve the following objectives [12]:

- To identify obstacles preventing achievement of a desired course of action, objective, or injection (solution idea arising from the Evaporating Cloud).
- To identify the remedies or conditions necessary to overcome or otherwise neutralize obstacles to a desired course of action, objective, or injection.
- To identify the required sequence of actions needed to realize a desired course of action.
- To identify and depict unknown steps to a desired end when one does not know precisely how to achieve them.

4.5 Transition Trees

The last tool in the TOC Thinking Process is the Transition Tree, [34] allow practitioners to determine the actions necessary to implement the solution. Practitioners use the effect-cause-effect method to construct and scrutinize the details of the action plan, called the Transition Tree. As in the construction of the FRT, each step is scrutinized using CLRs for negative branches.
The FRT as a strategic tool in which major changes can be outlined [12]. The implementation of these, however, will require complex interventions needing greater detail of action to be taken, which is the intended use for the Transition Tree. The Transition Tree as an operational or tactical tool.

The purpose of a Transition Tree is to implement change [12]. He says that the Transition Tree structure started off as a four-element tree, with a fifth element being added later. The use of the four or five element tree is situational. He states that the five-element tree is the preferred methodology when constructing step by step procedures and there is a need to explain to others exactly why each step is required. [12] outlined the original four elements of the Transition Tree as:

1. A condition of existing reality
2. An unfulfilled need
3. A specific action to be taken
4. An expected effect of the integration of the preceding three

Each succeeding level of the Tree is built upon the previous level, with the expected effect taking the place of the unfulfilled need. These build progressively upward to an overall objective or desired effect.

The fifth element added to the Transition Tree is:

5. The rational for a need at the next higher level of the tree.

The Transition Tree has nine basic purposes [12]:

- Provide a step by step method for action implementation
- Enable effective navigation through a change process
- Detect deviation in progress toward a limited objective
- Adapt or redirect effort, should plans change
- Communicate the reasons for action to others
- Execute the injections developed in the EC or FRT
- Attain the intermediate objectives identified in a PRT
- Develop tactical action plans for conceptual or strategic plans
- Preclude undesirable effects from arising out of implementation. (p. 284)

4.6 Summary of the Thinking Process

The five stage Theory of constraints thinking process begins with a Current Reality Tree, which diagnoses what, in the system, needs to be changed. The Evaporating Cloud is then used to gain an understanding conflict within the system environment or, as Goldratt prefers to call it, the reality that is causing the conflict. The Evaporating Cloud also provides ideas of what can be changed to break the conflict and to resolve the core problem. The Future Reality Tree takes these ideas for change and ensures the new reality created would in fact resolve the unsatisfactory systems conditions and not cause new ones. The Prerequisite Tree determines obstacles to implementation and ways to overcome them and the Transition Tree is a means by which to create a step-by-step implementation plan. All of Glodratt's tools are designed to overcome resistance to change by creating a logical path which can be followed.

V. CONCLUSIONS

In this paper we have synthesized large body of knowledge of three paradigms of TOC logistics, global performance measure and thinking process. The review shows that the vast majority of the papers have concentrated on the concept and philosophy enhancement of TOC. Several articles have been published in the production sector also. In the application category a number of articles reports the application of TOC concepts in the area of production and management accounting. Few papers have been published on the comparison of TOC with various Existing theories such as MRP and JIT. This review shows that most of the work is carried in the field of Project Management in the Logistics Paradigm. The review shows some of the applications in the field of services in the Logistics paradigm as well as in the Global Performance Measure paradigm.

The Theory of Constraints provides an effective, systematic approach for identifying constraints to the overall business and developing a plan to alleviate these constraints. TOC provides a global system methodology that promotes achieving the organizational goal of making more money both now and in the future.

From the analysis of these paradigms it is observed that there are some important elements which have not yet been adequately addressed. This analysis shows that some important issues in the Project Management is not adequately addressed

- Simulation of the case studies of organizations by identifying the bottleneck stations and developing a detail schedule for it.
- Validation of the network models with the simulation can be carried out in the Project Management.
- A comparison of the Project management network models with the CPM can be done.

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