A PRACTICAL APPROACH TO PROJECT SCHEDULING: CONSIDERING MULTIPLE CRITICAL PATH SCENARIOS IN PROJECT NETWORK

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The following faculty members have examined the final copy of the thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Industrial Engineering.

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DEDICATION

In memory of my late grandfather,

M. Jayaramachandran

EPIGRAPH

“No matter how your heart is grieving, if you keep on believing, the dreams that you wish will come true.”

— Walt Disney

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ABSTRACT

A well-managed project results in efficient scheduling of the interrelated components of work tasks, resources, stakeholders and budgets plans. The goal is for project managers to be able to generate an initial schedule at an early stage of product development. Due to complex product development, uncertainties and variabilities exists during manufacturing process. Variable processing times may lead to multiple critical paths within the system. Based on the real world demands of project managers two objectives are considered: Identification of multiple critical paths within the system and minimize completion time of the activity by optimal resource allocation. To solve this problem, a mixed integer linear programming model (MILP) is proposed. The Multiple critical path scheduling approach (MCPSA) is developed to identify multiple critical paths dominant in a system. A criticality index is used as performance metric to measure the intensity of the critical path in comparison to the project completion time. An interface of MS-Project with a simulation software (@RISK) is used to obtain the results. An application of two auger screws used in extrusion molding machines from a leading manufacturer in Kansas is used to illustrate the case study models and the MCPSA algorithm.

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ACRONYMS AND ABBREVIATIONS

CPM	Critical path method
PERT	Program evaluation and review technique
GERT	Graphical evaluation and review technique
MCPSA	Multiple critical path scheduling approach
OTCM	Optimal crashing method
MINSLK	Minimum slack first
MINLFT	Minimum late finish time
MAXTWK	Maximum total work content
FCFS	First come first serve
SASP	Shortest activity from shortest project
CI	Criticality index

CHAPTER 1

INTRODUCTION

1.1 Importance of project management

Humankind has been involved in projects since the beginning of history, since when the nature of projects and the environment have drastically changed. Many modern projects involve great technical complexity, substantial number of people, considerable amounts of equipment and material. Project managers face a great deal of problems when directing large and temporary projects of organizations. Such problems are often initiated by constrained resources, limited time, and environmental uncertainties.

The uncertainty in the project is often represented by stochastic distribution of an activity within it. Under these circumstances, project managers should address the schedule-time risk by identifying the main activities in the project that take longer to complete, so that overall completion time does not exceed estimates. This is important because late completion of the project may lead to penalty costs, job tardiness, depreciations in budget, market value, and market share. These issues necessitate the determination of the significance of project management in a manufacturing environment. They also imply that poor scheduling can lead to production delays, customer dissatisfaction, and excess idle inventory and resources.

The effects of project management on the overall manufacturing business environment in terms of associated cost can be broadly classified into two categories: fixed cost, which are cost-associated with initial investment in the project during its construction and variable cost, which are -those that change depending upon the length of the project during different system operations. Examples of latter include material costs, labor costs, and operating costs. The primary objective of solving any project scheduling problem is to minimize the time and cost involved in the completion of a project.

Scheduling any project involves managing auxiliary material and personnel, labor, and operating costs (all of which constitute variable costs). Important fixed costs in project scheduling include the cost of installation of different types of project management systems, the cost of construction, and costs of annual and pre-emptive maintenance.

Many different types of cost analysis conducted by researchers such as Hillier and Lieberman (2001) and Roseanau and Githens (2005) have depicted these costs to be conflicting in nature. For instance, acquiring more resources such as labor and equipment can shorten a project's duration, but it can also increase its initial cost of investment. Studies of project management have been conducted over many years, aiming to determine how to minimize the time and cost associated with the completion of a project. In this, thesis a new approach has been proposed to schedule multiple critical path scenarios (MCPSA) in a project by prioritizing the activities based on their criticality index. Based on this approach an optimal resource allocation model is formulated to minimize the overall completion time of the project. The following section describes the type of project scheduling techniques.

1.2 Types of project scheduling techniques

The main objective behind implementing a project scheduling technique is to identify the critical path associated with the project network, which causes the delay in the completion of the project. In a typical manufacturing environment, due to high variability, there could be more than one path dominant in the process flow. In such cases, every single critical path should be carefully analyzed so that overall project duration time can be effectively reduced. These differences in how to approach processes have resulted in a variety of project scheduling techniques, which are listed below.

Critical path method (CPM): CPM was developed in the late 1950s in response to problems associated with the scheduling of projects. The company DuPont, in collaboration with the Remington-Rand corporation, developed a computerized system for planning, scheduling, and controlling the projects associated with construction and maintenance operations. The main objective behind CPM is the scheduling of the total sequence of activities in a project to determine the maximum time taken to complete the process in the network. This is called the critical path.

Project evaluation and review technique (PERT): PERT deals with uncertainty by using three point estimates of time value for each activity involved in a project. It provides the means of assessing the effects of uncertainty on the project schedule. Three estimates are used to form a beta distribution for each activity in the network. The beta distribution is a continuous function of its variable. In PERT, the completion time is calculated by considering the longest and shortest duration time in the process to calculate the critical path in the process.

Graphical evaluation and review technique (GERT): GERT is an activity on the arc network with exactly one source node (the beginning time of the event of the project occurring is zero) and one sink node (the terminal project event). The network may also contain cycles, leading to multiple execution of activities during the project.

Fuzzy sets in scheduling: this method is used in the absence of historic data. Fuzzy scheduling addresses two distinct issues: (a) scheduling within flexible constraints and (b) scheduling in the context of incomplete or imprecise data. Fuzzy sets are used to model local or global requirements in the form of flexible constraints. Flexible constraints include due dates, release times, and durations of activities. Such fuzzy constrained scheduling techniques are usually used for solving job-shop problems, where most of the products requires unique set of process flow. However, finding paths or activities in a project that are critical under these constraints is not always possible, due to the imprecise data. Therefore, previous criticality analysis conducted based on the possibility and non-possibility of critical tasks were found to be incomplete. In general, manufacturing industries, such as aircraft manufacturing and ship building, implement CPM, when scheduling projects in industries. This is done to identify the criticality index involved in each project activity.

1.3 Project management system

Companies try to implement modern manufacturing systems that can complete projects on time and within an estimated budget. A successful project not only ensures project completion but also enhances the optimal use of resources, thereby increasing profit. Hence, satisfying customer demand with shorter lead times and achieving minimum project cost is important. Kerzner (2003) has suggested that project management is characterized by techniques that are recommended for their ability to maximize company profit.

Research conducted into quality management in the clinical area of Mount Clemens General Hospital. (Hoffmann P.A.,1991) indicated that CPM was implemented to improve the overall quality management in the clinical field. In this, the warm up period considered was among 44 patients, with critical path analysis being conducted after this. A complication rate of approximately 5% was detected in critical path, compared to a rate of 16% for no guided care. After identifying the critical path, a committee of members from the hospital was formed. This was for further assessment and included all staff members from the quality assurance, nursing, administration, and risk management departments. From the feedback, CPM was found to be an effective tool. To handle complex scheduling problems, project management systems generally use optimal scheduling network techniques. One of the main requirement for this is the ability of a project management system to integrate into project scheduling system. This can make significant contributions to the overall completion of the project. Even in complex projects, the use of a scheduling technique in project management systems improves the efficiency of project completion.

1.4 Current challenges and solutions in project management systems

The selection of a project scheduling system for any industry is a technical problem, which involves the assessment of numerous constraints of each part of the project activity in relation to respective task dependencies and resources to be scheduled. Each of these constraints affects the project's completion time, operation cost, and overall efficiency. Selecting the most economical method of scheduling depends upon the project manager's experience and knowledge. The following constraints should be considered,

- Time: project activities can either take a longer or shorter time to complete. The completion of the project depends on various factors, including the amount of skilled labor and what equipment is used. Time is often regarded as a vital factor, as adverse effects can result from a project not being completed by the expected deadlines. In general, the main reason for project delay is lack of resources. Therefore, the greater the probability that these conditions will occur, the more important it is that proper scheduling techniques adopted.
- Cost: the cost estimation begins by breaking the project into work phases (such as design, development, and fabrication) or into work packages. The project team members and team lead decide the cost budget that is required for the completion of project, which sets a maximum level for its development cost. Sometimes, additional resources are also allocated to meet the deadlines, which are later added as penalty costs.
- Scope: the scope of the project determines how far it has progressed towards completion. It consists of a list of deliverables that a project manager must address. A successful project

manager should be able to manage (in terms of both time and cost) the scope of the project efficiently.

The above three constraints are often regarded as the project management triangle. The most important aspect of project management is to deal with constraints so that the quality of the project will never be compromised. To overcome the project constraints, project managers can use several methods to keep the project progress by preventing stakeholders from shifting its scope and limiting the human resources and finance needed for its completion. It is the responsibility of the project manager to supervise the project from its beginning to its completion. The following further explores the duties of a project manager:

Defining the goals of the project, as well as the resources and personnel that it requires, and assigning tasks to team members;

- Setting project objectives
- Ensuring the team remains focused on their work
- Informing stakeholders about the day-to-day progress of the project and what resources it may need in the future
- Monitoring and assessing all risks associated with the project.

Spanning all these is the responsibility for proper integration, coordination, and direction of all the projects elements. These guidelines provide in themselves a detailed analysis of project scheduling problems and provide a systematic means of collecting the data that will form the basis of the final selection of a scheduling strategy. These desirable constraints help project managers to consider the problem and provide ideal solutions. So that the project managers could emerge into a firm decision of which parameters are most needed. They even determine which techniques satisfy the needs of existing problems.

Here are some examples of how previous attempts to solve these problems have failed:

Haga and Marold (2005) have proposed a simulation-based method to monitor and control projects. The output of this method is a list of dates. Through this, project manager should review the project to decide whether the activities need to be ended. These dates are called the crashing points in the project. However, although this is a very useful concept, a large simulation time is needed to evaluate a large project network. Moreover, if the network does not have at least one critical path, the algorithm would nearly end the project.

In addition, Bissiri and Dunbar (1999) have presented a simulation method to obtain the average time of each activity, the critical path, and the most likely critical path. A most likely critical path in the model that which has a length smaller than the original completion date but larger than the target completion date after crashing. Once the path is determined, a linear programming strategy is applied to analyze the optimum crashing strategy. However, the drawback of this method is the traditional CPM method, as the activity times considered are deterministic in nature.

1.5 Scheduling strategy for project management

The emphasis of project scheduling strategies has been shifted by advances in the field of technology and constant change in the demand patterns of customers (such as the inclusion of customized orders in manufacturing products). From a traditional, single-factory environment to the present, dynamic-factory environment, manufacturing industry has drastically changed over the years to satisfy its customers. These changes in the manufacturing environment challenge the profitability of the industry and others involved in process planning and control of orders in shop floor. The major factor defining the efficiency of the modern manufacturing market is the proper planning and scheduling of different operations of job and product. Most of the enterprise requires effective production planning and scheduling of jobs on the shop floor.

Besides achieving other end advantages, the design and implementation of these new techniques sought to reduce scheduling cost and time required to complete a project. However, significant research has been dedicated to workflow scheduling and resource-levelling scheduling in individual ways, as the two problems are inter-connected. It is observable that workflow scheduling provides the resource requests, and the resource-levelling schedule in turn provides the release time of operations on the downstream path of the workflow. It is possible to have a situation where a good workflow schedule provides a poor input to a resource-levelling schedule and vice versa, making the overall schedule worthless.

There has also been a recent development in production planning and control techniques, especially in the context of the manufacturing industry. This is the philosophy of enterprise resource planning (ERP), introduced in the late 1990s to expand the capabilities of materials resource planning (MRP) or manufacturing resource planning (MRP II). It's done as a computerized approach to planning and controlling the flow of materials during production.

Although there are many advantages to using ERP, its major drawback its ignorance of shop-floor capacity levels and its assumption of constant lead times for all production items, resulting in unrealistic data. Considering these capacity constraints, it is necessary to create achievable schedules on the shop floor. It is not simply the workflow path that creates the delay in project completion; non-availability of resources also plays a role. Therefore, simultaneous scheduling of workflow and resource levelling should be considered in order to reduce the make-span time and cost of the products produced.

As has now been demonstrated, work scheduling and resource-level scheduling problems are exactly same. In a manufacturing environment, some efforts that consider this integrated problem have been reported in the literature. Ahuja (1994) has investigated various simulation studies where the true characteristics of distributions of activity duration are considered, which in turn provides a better estimate of the completion time for a project. In the context of manufacturing, the scheduling problem is much simpler than in the context of the construction environment industry.

Gutjahr (2000) has proposed a stochastic branch-and-bound scheduling method, the objective of which is to determine the set of measures that would reduce the duration of the project, either by reducing or avoiding the penalty cost in the most cost-effective method. However, it is assumed that there is a set of measures that can be introduced, and each measure may considerably reduce the span of one or more activities in the project network. Every measure depends upon the binary variable that indicates whether or not the measure is chosen.

Many other authors have contributed to the consensus on the detailed study of project scheduling and management techniques. The literature was mainly focused on basic scheduling techniques: (a) guide proper scheduling network (Hillier & Lieberman, 2001; Wiest & Levy, 1969), (b) stochastic simulation study (MacCrimmon & Ryavec, 1964; Williams 2004), (c) stochastic scheduling strategy (Dong-Eun Lee, 2005 & Arditi, 2006), (d) project crashing method (Rosenau & Githens, 2005), and (e) project control (Haga & Marold, 2004).

1.6 Scheduling type approaches

The scheduling rule is usually used to prioritize the jobs in queue that are waiting to be processed. When the process becomes unoccupied the immediate job that is waiting has to be selected from the input queue for processing. A survey in scheduling by Panwalker and Iskander

(1977) reported that more than 100 scheduling jobs have been proposed in literature. The scheduling problems were classified into three groups: simple priority rules, heuristics rules, and a combination of these.

Several studies of project management have been conducted. A study of the scheduling problem in project management was performed by Wiest et al. (1969), which reported that CPM is a deterministic approach used to determine the completion time of the project while PERT is a probabilistic approach that considers uncertainty and variation in activity duration to determine the completion time of the project. CPM was developed for use in projects that could be used to estimate the duration of the activities for the new projects. Meanwhile, PERT was developed primarily for research and development projects, where it is difficult to estimate the duration of a project. In addition, CPM can be used in trade-offs between the cost and completion time of the project.

The research by Lu and AbouRizk (2000) introduced a CPM/PERT simulation model that includes both the discrete event simulation modelling approach and critical path identification approach. The authors stated that "in the CPM analysis, earliest start time (ES), latest start time (LS), earliest finish time (EF), latest finish time (EF) and total float time (TF) must be noted for every activity". The ES and EF are calculated during the forward pass of the project network, and the LS, LF, TF are calculated during its backward pass. TF is used to determine the criticality of a project network.

They found that the created model can only perform forward analysis of the network; with this forward pass, the entity arrival time (AT), departing time (DT) and waiting time (WT) can be determined, instead of ES and EF. The identification of critical activity can be determined by the WT, which is represented by the criticality index (CI), and required information are collected during the forward pass itself. The CI of the activity, “is the number of simulation runs in which the activity is critical, divided by the total number of simulation runs”.

Haga et al. (2005) have developed a simulation model to monitor and control a project. The simulation model optimizes the cost of the project. If the penalty for late completion is smaller than the crashing cost of the activities, this method allows the project to be completed late. This approach is a heuristic model that does not consider interactions between different activities in the network. However, it conducts a one-time evaluation of the crashing potential of the all the activities to identify which should be crashed.

As a result, the output of the method is basically a list of dates which a project manager must review to determine which activities must be crashed. These dates are called the crashing points, which are determined by the backward pass of the project. However, although the concept explained was very useful, its main drawback was that it required a large amount of simulation time to analyze a large project network. Moreover, if the project does not have any dominant critical path, the model is likely to end the project.

Pristker (1986) and Simmons (2002) have described some simulation models that can evaluate and analyze project networks. The simulation model created by them provides a histogram for the completed activity network distribution. Based on the activity distribution, the risk analysis can be performed to determine the actual completion time of the project. Among these project scheduling rules, CPM and PERT are identified as the preferable scheduling priority rules, and the simulation technique combined with either one of the scheduling criteria provides a better performance than the other scheduling strategies.

1.7 Gap in current approaches

According to Goldratt (1997), the majority of project review scheduling problems are static in nature. This leads to a difference between the expected and actual performance of a project scheduling system.

When researchers consider dynamic aspects of the system for scheduling, they limit the research to the current scenario of events that happens within the manufacturing system. Most of the researchers avoid studying the impact of future events that can happen in the project management field. The variation and the uncertainty involved in evaluating every complex project, based on scheduling the workflow and resource levelling may need to be taken into consideration in such a study. Project completion time is the primary parameter that should be considered when solving any project scheduling problem. However, these approaches do not account for dynamic behaviors of this system.

1.8 Need for future-based analysis

Most of the previous research into scheduling strategies has attempted to minimize the total completion time of the project and provide a balanced resource levelling schedule to be enhanced on the shop floor. In contrast, there has not been a great deal of research into tackling multiple critical path scenarios and predicting the probability of the event that causes the system to be critical recurring in the system. While managing the project, it is necessary to use an optimal and viable scheduling technique that reduces the total completion time of the project. Studies have shown that optimal scheduling of activity networks with proper knowledge in scheduling techniques can result in a highly effective scheduling strategy.

To cope with complexity and variability in the project networks, Haga and Marold developed a simulation-based method that considers the time-cost trade-off involved during the optimal crashing method (OTCM) of the project. They proposed that complete distributions of the project completion time should be considered while crashing a project. The simulation model optimizes the cost of the project; if the penalty for late completion is smaller than the crashing cost of the activities, this method allows the project to be completed late. Although the OTCM was useful as a theoretical concept, it was made practically useless, because model needed many simulations runs to evaluate a large project network.

The OTCM is comprised of two main execution steps. The first step, a static phase, is to apply the traditional PERT method to end the project. The second step involves testing each activity of the project network that is not crashed to the limit to determine whether the crashing activity would further reduce the estimated average total cost of the project (Haga et.al., 2004). This model attempts to optimize the cost of the project: the project is allowed to be completed late only if the penalty cost for late completion is smaller than the crashing cost of the network activities. In this, the OTCM method determines what the project activity should do to minimize the total completion time of the current event in the activity network.

Some of the negative facets of the concept are as follows.

- The method does not provide a suitable way to monitor crashing activities, which can result in unnecessary crashing of the activities in the project network.
- The heuristic model created does not consider interactions between different activity networks in the project. It essentially performs a one-time assessment of the crashing potential of all the activities to identify which should be crashed.
- The method mainly focuses on a traditionally defined time-cost trade-off decision problem (static evaluation phase) to obtain an optimal solution for a single critical path.

- In the case of a large project network, the OTCM necessitates the execution of a great number of simulation runs that must be evaluated.
- The algorithm crashes the project completely if it does not find one single dominant critical path in the overall project network.

Therefore, this method involves challenges with evaluating and executing part of the model. From its inception, if the model were to start the entire scheduling process with the near forecast of the workflow and resource levelling order, a definite improvement in project completion would be plausible. This leads to introduction of the multiple critical path scheduling approach (MCPSA) for the optimal scheduling of large projects. MCPSA is a scheduling approach developed on this premise and its effectiveness in the managing complex project networks.

The MCPSA model would provide the base for scheduling and identifying multiple critical paths that are prominent in the modern manufacturing environment.

1.9 Objective of thesis

This thesis attempts to develop a scheduling strategy solving complex project networks that have multiple critical path scenarios. The objective of this problem is to develop a feasible schedule that minimizes the project total completion time.

The thesis is divided into two phases. The first phase develops the MCPSA for project networks that have complex activity networks. The MCPSA is an attempt to obtain an optimized method for the scheduling of activities with respect to uncertainty associated with project networks. Experimental case study models and heuristic procedures are developed to test the concept of MCPSA. The second phase examines the effects of resources associated with every activity in the project network and the impact of the time associated with the project completion, by formulating a mixed integer linear programming model.

1.10 Thesis outline

A literature review of various scheduling rules and recent studies of project scheduling techniques and related fields is provided in Chapter 2. The methodology is developed in Chapter 3. Chapter 4 examines details of the implementation of the research, as well as the case studies developed for different scenarios. Chapter 5 offers some conclusions and suggestions for further research. A list of references is provided at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

In recent years, manufacturing industries have learned to adapt to increasing market demand and improve their survival rate under the complexities faced during the completion of large projects. A survey exploring the completion of construction projects in Saudi Arabia, showed that almost 76% of the project contractors experienced delay by 10-30% due to project duration Assaf and Al-Heji (2006).

To avoid such delays, a project is dependent on the efficient exchange of orders and material flow when the project is ongoing. Project scheduling has become an integral part of any manufacturing environment; it is the fulcrum behind the successful completion of any project. According to Kerzner (2003), project management is characterized by scheduling techniques that are intended to enable the efficient use of resources, which can have a substantial impact on the profitability of an organization. The feasibility for efficient scheduling is only possible if the current challenges addressed by the project managers during the scheduling phase is determined. The following section, discusses the current challenges of project scheduling and resource allocation problems.

2.1 The challenges of project scheduling

The two most commonly used methods in project scheduling are CPM and PERT. CPM was developed for use in projects that had access to data from similar predecessors, which could be used to estimate the duration of new activities in the project. PERT was developed for research and development projects, the time duration of which is difficult to estimate. Even though the original version of CPM and PERT have some contradictions, they also have some similarities, resulting in them coming to be viewed as a single technique called the PERT/CPM (Hillier and

Lieberman, 2011). The common characteristics of the CPM and PERT methods are the activities in the project network to identify the critical path of the project.

The project network is the pictorial representation of the project, which shows the precedence relationships between the activities in the project. It determines the set of activities that connect a project's beginning and end. The CPM and PERT methods consider the length of the critical path to be the expected project duration. The critical path is the path in the project network that has the longest activity duration. It should be noted that a single project can have multiple critical paths. Hillier and Lieberman (2001) introduced the concepts of CPM and PERT to identify the critical path. The concept consists of following steps:

- Identify the ES and the EF of every activity. This process begins at the start of the network and passes through all the activities until the end of activities in the project network. This is called the forward pass. For every activity, the EF is equal to the ES plus the activity duration, while the ES is equal to the largest EF of the activities.
- Determine the LS and LF of the activity. This is called the backward pass through the activity. For every activity, the LS is equal to the LF minus the activity duration.

Identify the slack time of each activity. The slack time is the amount of time an activity can be delayed without delaying the project completion time. For every activity, the slack is equal to LF minus EF. Activities that have no slack time belong to the critical path. For calculating the critical path in CPM, the duration of each activity is considered, whereas in PERT, an estimate of the expected duration is considered. This is because PERT deals with uncertainty by considering the three point estimates of the activity duration (most likely [m], optimistic [o], and pessimistic [p]) and assumes that the distribution of activity follows beta distribution (Hillier & Lieberman, 2001).

Previously, Ahuja (1994) proposed that, during PERT analysis, only the estimates of the expected duration are considered when calculating the critical path, thus ignoring the variances of the activity networks. In the event of any kind of uncertainty in the activity duration, it is necessary to firstly analyze the probability of completion time of the project. The following assumptions are made by the CPM/PERT method to calculate the probability of the activity occurring.

- The mean critical path will be the longest path in the activity distribution. In the project network, if the duration of each activity is equal to its mean, then the path is called the mean critical path.
- The duration of all the activities in the mean critical path are statically independent.
- A normal distribution is followed by the project duration.

From these assumptions, it is possible to determine the mean project duration and the variance in project duration, which are required to calculate the probable completion time of the project. The mean project duration is equal to the length of the mean critical path. The variance associated with the duration of the activity is equal to the sum of variances of all the activities that form the mean critical path. Since the project distribution is normally distributed, the variable is defined by using the following expression:

$$Z=X-\mu/\sigma$$

X, is the probability of completion $P(X<x)=P(Z<z)$, where $Z= X-\mu/\sigma$.

MacCrimmon and Ryavec (1964) have stated that one of the drawbacks of the PERT is that, when there are multiple paths to be followed to complete a project, the project duration is always less and never greater than the project mean. This bias in the event activity is referred as “merge event bias”, as these cases are evident where the path durations are similar to each other.

By conducting a stochastic simulation study, the characteristics of the activity distribution are evaluated to provide a better estimate of the expected completion time of the project (Ahuja et al., 1994). Moreover, the simulation results cannot be generalized without much more experimentation.

Generally, the simulation of project networks is used to enhance the effectiveness and efficiency of the PERT analysis. Williams (2004) has suggested the use of the Monte Carlo simulation as a common tool to simulate a project network. This involves sampling of an activity time from the probability distribution representing the duration of each activity and using the sampled data to identify the critical path.

Dong-Eun Lee (2005) has introduced a software tool – called the stochastic project scheduling simulation (SPSS) – to determine the probability of completing a project by a target due date, as specified by the user of the software. The SPSS software has the potential to simulate activity duration with many probability distribution functions, including uniform, triangular, and normal distributions. SPSS also calculates the CI associated with all the activities in a project.

Lee and Arditi (2006) have presented a new simulation system called the stochastic simulation-based scheduling system (S3), which is an improvement of the SPSS software. The major drawback of this method is that PERT leads to an overoptimistic estimate of project duration, since it ignores all the subcritical paths in the network. However, one advantage of this method is that it calculates the confidence interval and the mean duration. So that the required number of simulation runs are determined to provide the necessary results.

Pristker (1986) and Simmons (2002) have described some simulation models that can evaluate and analyze project networks. The simulation model created by them provides a histogram for the completed activity network distribution. Based on the activity distribution, the risk analysis can be performed to determine the actual completion time of the project.

2.2 Resource allocation problem

Scheduling and resource allocation for multiple projects is a non-polynomial hard problem and more complex than a single project, Garey and Johnson (1979). Traditional optimization methods have been used to solve multi-level project scheduling problems. Pristsker et al. (1969) reported a zero-one programming approach to solve a multi-level project scheduling problem. Mohanty and Siddiq (1989) investigated the problem by assigning the due dates to the projects. They have used an integer programming to generate an initial schedule and simulation mechanism for testing the heuristic rules for choosing the best schedule. Deckro (1991) formulated the multi project scheduling problem as general integer programming model and used decomposition approach to solve large size project network problems. Jolayemi (2012), used integer programming for project scheduling and considered the penalty and reward function in the objective function. A similarity in these studies is that project scheduling problems of small size network problems can be easily solved by the traditional optimization techniques.

The problem become more complex only when the number of activities, size of the project and the number of projects increases. Furthermore, the complexity increases when a variety of resources are considered. several researches are being made to find out more efficient algorithms to generate the multi- project schedules. These research work mainly focus to increase the efficiency of the heuristic methods and develop new methods with inferior computation time Rezaie and Ostadi (2007). Researchers have also used artificial intelligent techniques to generate resource constrained project schedules Ranjbar et al. (2008). However, when the size and the number of the projects increase, the computational efficiency of these methods also decreases. Kim et al. (2005) applied a combined genetic algorithm to generate the initial schedule of a multi project scheduling problem. They minimized the total completion time and penalties for a general delay. Kumanan et al. (2006) used GA with heuristic method for generating the schedule of the multi projects and the performance of the schedule was measured against the project completion time. Damak et al. (2009) also used GA through a local search strategy to generate the schedule of the multiple projects with resource constraints and the project delay as the performance metric to measure the performance of the schedule. Chen (2011) reported that there is a need to develop efficient methods to ensure the quality and the computational efficiency of the solutions of resource constrained multiple project scheduling problems.

The key challenge for project managers is to deal with pressure from the project sponsors to complete the project within the deadline. In this situation, it is critically important to find out a solution to schedule resources for multiple critical activities in a project. Project managers must pass all the instructions to the team members to complete their tasks in a timely manner to meet the deadline of the projects. In this context, priority rules are the most efficient methods to generate the schedules in a very simple and rapid manner. Several priority rules are reported in this chapter. Vidhya et al. (2013) provide a brief review of multi project scheduling techniques. Fendley (1968) used multi projects and considered three efficiency measurements in the analysis, project slippage, resource utilization and in process inventory.

They found that the priority rule of MINSLK was most efficient with the three response variables. Kurtulus and Davis (1982) designed multi- project scheduling problem where projects had 34 to 63 activities and resource requirements for every activity was between 2 and 6 units.

They devised six new priority rules and showed MAXTWK and SASP as the best algorithms to schedule the multi-projects when the objective was to minimize the mean project delays, by measuring the unconstrained critical path duration. Kurtulus and Narula (1985) modified the earlier rules proposed by kurutulus and Davis (1982) by adding penalties to the project delay. They had three projects in which the number of activities varied between 24, 33 and 50-60 for small sized and large sized problems. Four set of new priority rules were formed, namely, maximum duration and penalty, Maximum penalty, Maximum total duration penalty and slack and penalty. They concluded that the priority rule maximum penalty was the best algorithm to minimize the sum of the project weighted delays.

Dumond and Mahert (1988) studied the problem of assigning due dates to the projects in a multi-project environment. Each project was assigned 6 to 49 activities with the resource requirements of one or three types of resources in their research work. They considered five resource allocation heuristics. They confirmed that priority rule of FCFS with the strategy scheduled finish time due date rule as the best algorithm to minimize the mean completion time, mean lateness, the standard deviation of lateness and minimize the total tardiness. Lawrence and Morton (1993) studied the due date setting problem of scheduling multiple resource constrained projects with the objective of minimizing the weight tardiness cost.

Christodoulou (2012) optimize the allocation of resources by use of entropy metric. Shankar and Nagi (1996) proposed a two-stage hierarchical approach consisting of planning and scheduling stages. A linear programming for the planning stage and simulated annealing for the resource scheduling stage were used. Lova et al. (2000) developed a multi-criteria heuristic that consisted of several algorithms based on feasible schedules. The proposed method improves the feasibility of the multi project schedule obtained from heuristic methods based on the priority rules, MAXTWK and MINLFT, also the project management software – Microsoft project, time line, project scheduler. Dalfard and Ranjbar (2012) used simulating annealing approach for generating the schedule of resource constrained multiple project problems. The results were compared with 20 existed priority rules in terms of project completion time.

The simulated annealing approach proved better results than priority rules. Saleru (2012) developed the resource constrained project schedule of a software industry by using the project management software primavera. Zhang et al. (2013) proposed an algorithm for generating the schedule of resource constrained multiple project problems. The robustness of the algorithm was measured in terms of various project parameters like order strength, resource constraints and uncertainty level. The result proved the effectiveness of the solution algorithm and showed that these parameters have impact on the robustness and make-span of projects.

2.3 Project time and cost trade-off decision analysis

When scheduling a project, there are certain dates that a master scheduler must consider, Examples include the expected completion date requested by the customer and the target deadline for the project to be completed. If the project is completed after the target completion date, a penalty cost is estimated, and if the project is completed before the target completion date, an extra benefit is realized. In some cases, the master scheduler may realize that it is possible with existing resources to complete the project before its completion date or deadline. There are also scenarios where the duration of certain activities of the project can be minimized to avoid any penalty cost.

Because management in the corporate world is based on cost incurred, it is the responsibility and decision of the master scheduler to evaluate the trade-off between the reduction in project completion time and the cost associated with this reduction. This is done to ensure that expediting this completion would make economic sense. Hillier and Liebermann (2001) addressed the time-cost trade-off problem that was similar to CPM method of time-cost trade-off, so they referred the method as CPM crashing method. As Rosenau and Githens (2005) have stated, crashing means spending money on a project to expedite completion of scheduled activities This method is used to find the crashing point of the project with the lowest cost that minimizes the estimated duration of the project by a selected value.

The crashing alignment in the project determines those activities that should be crashed and indicates the extent to which the activity can be crashed. Crashing of an activity means taking measures to minimize its duration by providing additional personnel time and resources. To apply CPM crashing method, the crashing potential of every activity must be known, so that the maximum reduction of time and cost for each activity can be achieved. This method assumes that a reduction in the time of the activity by 1 unit reduces the duration of project by 1 unit. Usually, a CPM crashing method is executed by a linear programming model.

The main limitation of the CPM crashing method is that it considers the estimated average duration of activities, thus ignoring the variabilities related to the duration of activities in the project. These variabilities play a significant role during the project crashing, as they provide a better understanding of the real effect that a crashing alignment can have on project duration. However, although the estimated average duration of the activity is considered while crashing a project, the expected completion time of the project is a tentative value to the desired target.

Haga and Marold (2004) have concluded that the probability of completing a project within the desired target is only 50% and that this may be smaller in scenarios where there are multiple critical paths. In these situations, it is possible to change the distribution of completion time to a suitable point where the probability of late completion is comparatively low.

To overcome these limitations in the CPM crashing method, several simulation methods for crashing projects have developed with the objective to obtain a suitable crashing alignment that reduces the project cost and time.

This heuristic model does not consider interactions that take place between different activity network in the project. The method primarily focuses on a traditionally defined time-cost trade-off decision problem (static evaluation phase) to obtain an optimal solution for a single critical path. In the case of large project networks, the OTCM method requires the execution of many simulation runs that must each be evaluated. The algorithm crashes the project completely if it does not identify a single dominant critical path in the overall project network.

Gutjahr (2000) has proposed a stochastic branch-and-bound scheduling method, which is designed to select the set of measures that would most cost-effectively reduce the duration of the project by either reducing or avoiding the penalty cost. However, it is assumed that there is a set of measures that can be introduced, and each measure may reduce the span of one or more activities in the project network by a considerable amount. Every measure depends upon the binary variable that indicates whether the measure is chosen.

Previously, Bissiri and Dunbar (1999) introduced a crashing method that used the simulation to obtain the average time for each activity in the project network and identified the critical path and possible critical paths during every iteration of the simulation. The possible critical path in this method is that of a duration smaller than the original completion date but larger than the target completion date, once the project is crashed. After crashing the path, a linear programming model is formed to identify the optimal crashing point in the project. All the above-discussed methods provide a required foundation for solving any time-cost trade-off decision problems. The following section explains the significance of @RISK simulation software used for this research.

2.4 Scheduling via simulation

In the case of stochastic time-cost trade-off problems, the master schedulers are often interested in identifying the optimal crashing alignment that would minimize project cost and duration. The simulation-based scheduling methods explained in the literature are usually heuristics. However, there is a possibility to introduce a method that would solve the stochastic time-cost trade-off problem. During simulation, dynamic scheduling is designed to identify the possible critical scenarios in the project network. In a stochastic medium, the emergence of critical paths continues to shift from being a single occurrence to occurring throughout the project. Consequently, there could be more than one path that is dominant always. In such cases, scheduling is completed through "@RISK Analysis for project management". @RISK is the simulation and risk analysis add-in developed by the Palisade corporation to analyze risk and uncertainties in a wide variety of industries.

@RISK software can be applied to a wide range of discrete simulation scheduling problems. The scheduling procedure implemented by @RISK is a step-by-step procedure, divided into the following four phases.

- Develop a model: define problem using MS Project as a user interface.
- Identify uncertainty: identify the inputs in the model that are uncertain and sort these by the suitable probability distribution function.
- Analyze the model using simulation: run a simulation model to determine all possible probability outcomes that have been identified.

- Plan: finally, with the output retrieved, a decision should be made. Since the stochastic time-cost trade-off problem is suitable for DSvS, @RISK is a suitable candidate for use as a scheduling strategy.

2.5 Summary

This chapter has reviewed different types of project scheduling, simulation, cost estimation, and crashing techniques that can be used to solve diverse scheduling problems. A brief description of simulation techniques used to solve various industry-related problems is also provided. Based on this review, it is felt that there is still a need to develop a methodology that could not only optimize the duration but could simultaneously be generalized as a project management tool to solve scheduling problems in any project. This thesis proposes such an approach (MCPSA), and the following chapter explains its methodology.

CHAPTER 3

METHODOLOGY

In project scheduling, an activity is defined as a group of tasks or activities and a set of precedence constraints that expresses a set of tasks that cannot be started before other tasks are completed in a proper order of sequence. The project scheduling problem that MCPSA seeks to solve is based on the following assumptions. A project network consists of “n” number of activities, each activity consisting of a finite set of tasks that must be completed according to the precedence order. The activities are assigned under the given set of resources (operators).

Every activity is assigned a given number of operators. The operators’ assigning patterns are changed according to the project needs. For example, additional workers are assigned if an activity takes longer to complete. Thus, the operator assigning pattern is changed in accordance with the outcome of the critical risk in the project activity. Every commenced activity must be completed without interruptions, meaning that the activity pre-emption is not possible. The precedence order of all the activities in the project is fixed.

This chapter broadly explains the creation of the MCPSA model in Section 3.1, the operational structure of the MCPSA approach in Section 3.2, the scheduling interface with a MS Project interface in Section 3.3.

3.1 The first phase of the MCPSA approach

The first phase of MCPSA introduces the concept of scheduling multiple critical path scenarios in a project network by allocating resources (operators) required during the project so that project completion is not delayed. This represents an attempt to minimize the overall project completion time and cost. The purpose of this phase is to develop a dynamic, simulation-based analysis method for scheduling time-cost trade-off problems that effectively answers the following questions.

- Which activities must be scheduled first to reduce the overall duration?
- On what basis can the criticality of an activity be identified?
- To what extent should the activities be scheduled?
- When should the scheduling configuration be changed?

The main objective of the MCPSA method is to obtain the optimal scheduling configuration that minimizes the total project duration. Stochastic activity time is considered, meaning the uncertainty associated with activity is represented by probability distribution. The first phase of MCPSA procedure involves the following:

- Defining project parameters (such as activities, predecessors, activity times, and operators) involved in each activity and their related costs and costs for late completion;
- Creating a simulation model of the project network;
- Utilizing the stochastic simulation and probabilistic Gantt chart tool from the @RISK model to determine the probability of critical tasks in the project activity;
- Evaluating the effect of scheduling the project by comparing the results before and after the scheduling was performed;

The first step of the approach is to specify the parameters that define the project network and the scheduling problem. These parameters include the number of activities, the probability distribution associated with the completion time of activities and the precedence order of activities.

A simulation model of the project network is created once the input parameters are provided. This simulation model represents all the activities in the project and the precedence constraints that exist among them. The model is used to analyze the various scheduling configurations in the project. Analyzing a scheduling configuration involves running a definite number of iterations of the project network under the scheduling configuration that is considered. This is used to estimate the average cost and duration of the project resulting from the scheduling configuration. Running the iterations of the simulation model represents the sampling of the activity time of each duration of the activity, calculating the start and ending time of all the activities with respect to the precedence constraints and computing the cost associated with completion of the project.

Once the simulation model is executed and all the critical tasks are identified, it is possible to implement the scheduling program phase. The simulation-based MCPSA method is designed to improve the performance measure of the project. When the simulation model is executed for the first time, the potential critical path is identified and the original project duration and the cost associated with the project duration is calculated.

Once the delay in the activity duration is determined, those activities are assigned additional operators, the simulation model is executed, and the results are compared with the original completion time and cost of the project. This is done to determine the effectiveness of the scheduling approach. In the following section, the structural design of MCPSA approach is described in the Figure 1.

3.2 Structural design of MCPSA

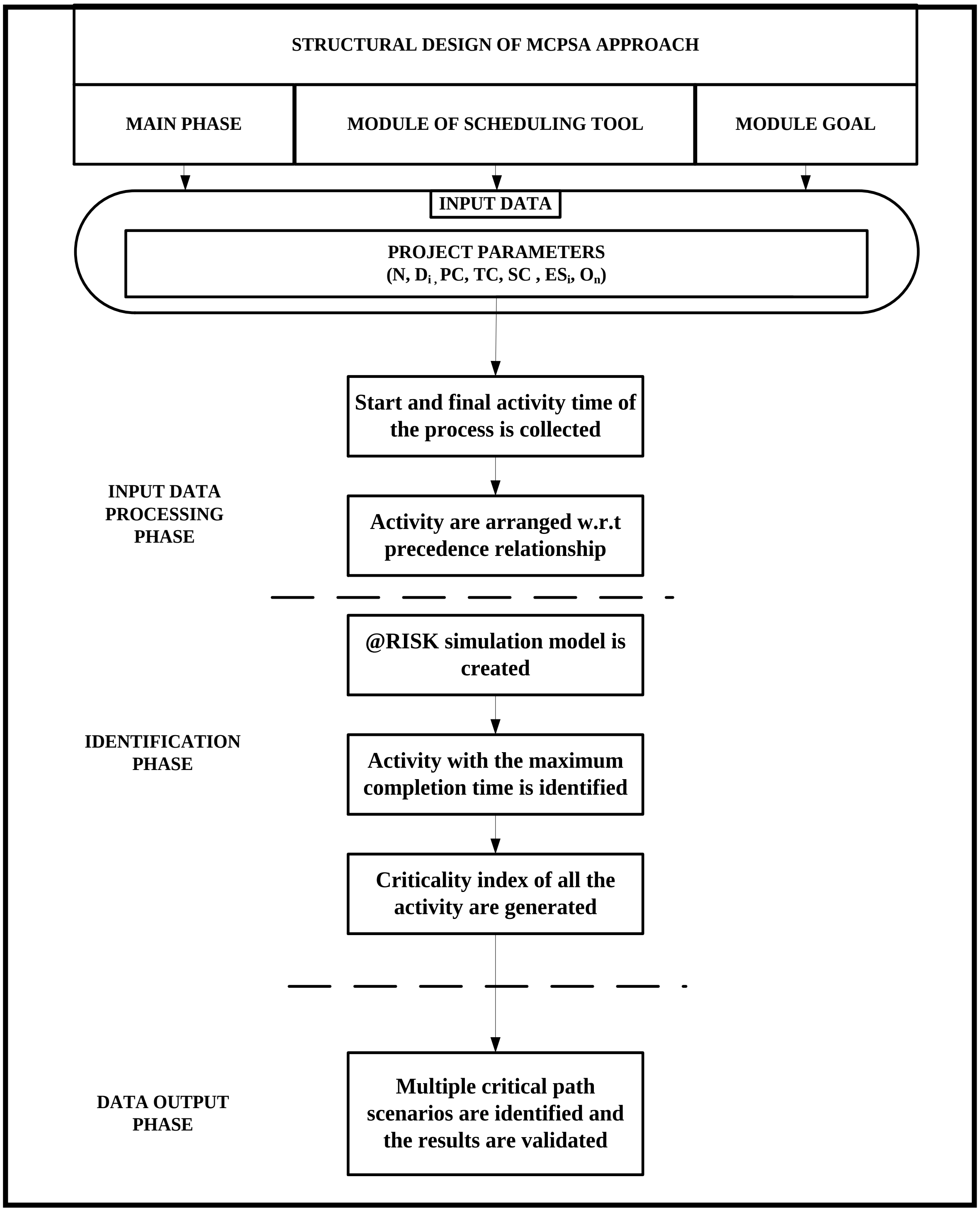

Figure 1: Structural design of MCPSA

The structural design of the MCPSA is divided into three phases: the input processing phase, the identification phase, and the data output phase.

- **Input processing phase –** The first step of the process is to specify the project parameters that define the project network, in terms of the number of activities (N), precedent constraints (PC), duration of the activities ($d_{i)}$. $ES_{i,}$ start and TC, completion times of all activities are entered, $O_{n,}$ number of operators assigned. All the activities in the network are arranged with respect to the precedent constraints.
- **Identification phase –** The simulation model is constructed in this phase, based on the input parameters acquired during the input processing phase. The @RISK simulation model represents all the activities in the project and the precedence relationships that exist among them. The @RISK model is used to evaluate various critical path scenarios that could arise from a project network. Evaluating a simulation model involves running a specified number of replications of the project network under the scheduling configuration considered. Subsequently, the activity that requires the maximum duration for completion is identified, along with its CI. The CIs of all activities are identified, and all the activities are ranked accordingly.
- **Data output phase –**The critical paths of all the activities are obtained by analyzing all elements from the source to the destination in the network model. All possible critical path scenarios are identified, and the results are validated in the form of a histogram. This scheduling tool helps the project manager to form a priority list of activities that must be prioritized while scheduling the project. In the following section, a scheduling interface with MS-Project is explained in the Figure 2.

3.2.1 Scheduling via MS Project interface

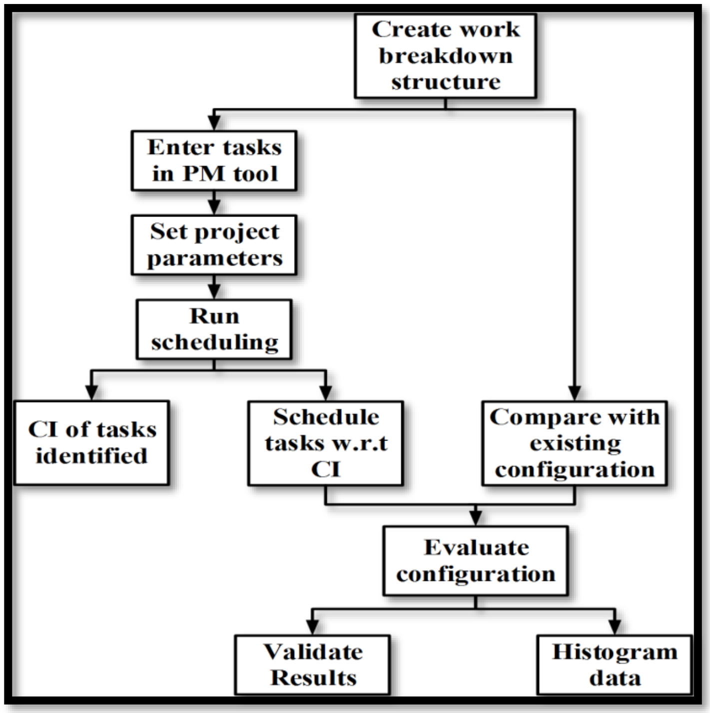

Figure 2: Scheduling via MS Project interface

To apply the MCPSA to a real project, the @RISK simulation software is interfaced with Microsoft Project (2010). The interface designed assists project managers in tracking potential risks in their project. The scheduling interface via MS Project simplifies the method by retrieving the data directly from that program, where project parameters like the number of activities in the project, their start times, their duration, their completion times, and the precedence relationships between them are entered. The next step is to evaluate the project network by running the scheduling for a specified number of replications to identify the desired scheduling configuration. Once the simulation is completed, the probabilistic Gantt chart is generated, which provides the critical indices of all the activities. The activities are arranged in the order of highest to lowest CI. Finally, the critical path is identified, and the results are validated in the form of a histogram. The operational flow chart of MCPSA is described in Figure 3.

3.2.2 Operational flow chart of MCPSA

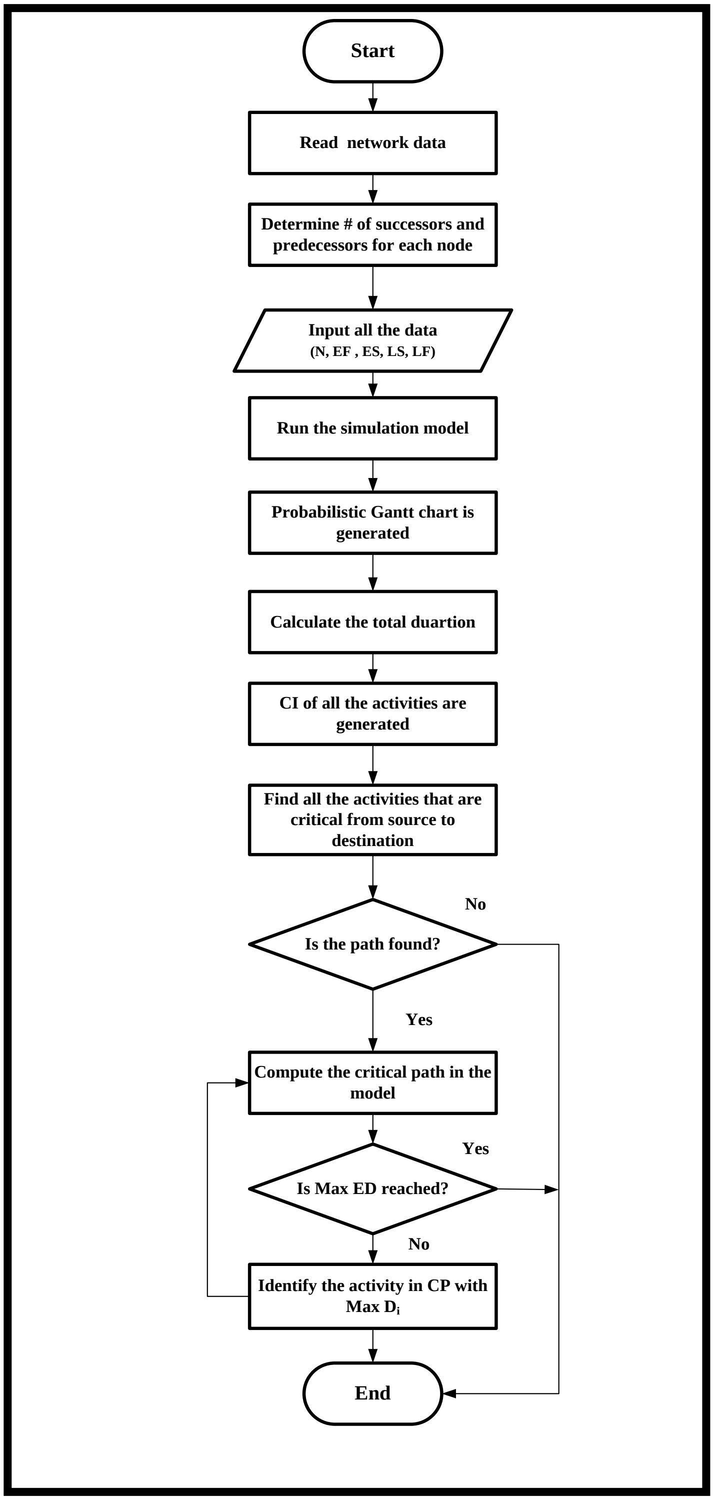

Figure 3: Operational flow chart of MCPSA

3.2.3 Steps involved in the first phase of MCPSA

Step 1: the network configuration is determined, involving the source/destination points, the number of activities, the precedence relationships, the duration of all activities, and their early start and finish times. All the network configuration is entered in the MS Project database.

Step 2: From the @RISK add-in in MS Excel, the data from the MS Project is imported to the MS Excel @RISK and all activities are assigned a suitable probability distribution.

Step 3: After assigning the probability distribution to all the activities, the probabilistic Gantt chart option is selected from the project option icon and the network model is replicated until a desired scheduling configuration is generated.

Step 4: Once the desired configuration is obtained, the total durations and CIs of all the activities in the network are generated.

Step 5: The CIs of all the activities determine how often an activity was on the critical path during the analysis. Activities with the highest CI are most probably the cause of delays in the project. However, after the replications, if an activity has 100% CI, this means that it remains in the critical path, even if the project duration is varied. Thus, that activity plays a key role in completing the project on time.

Step 6: The critical path in the network model is identified, based on the critical index obtained for all the activities.

Step 7: In the final step, if the maximum expected duration of the project is determined, then no more simulation runs are conducted. The results obtained are updated into the network model by highlighting the critical path within it. In the following section the operational flow chart of the second phase of MCPSA is explained in Figure 4.

3.2.4 Operational flow chart of the second phase of MCPSA

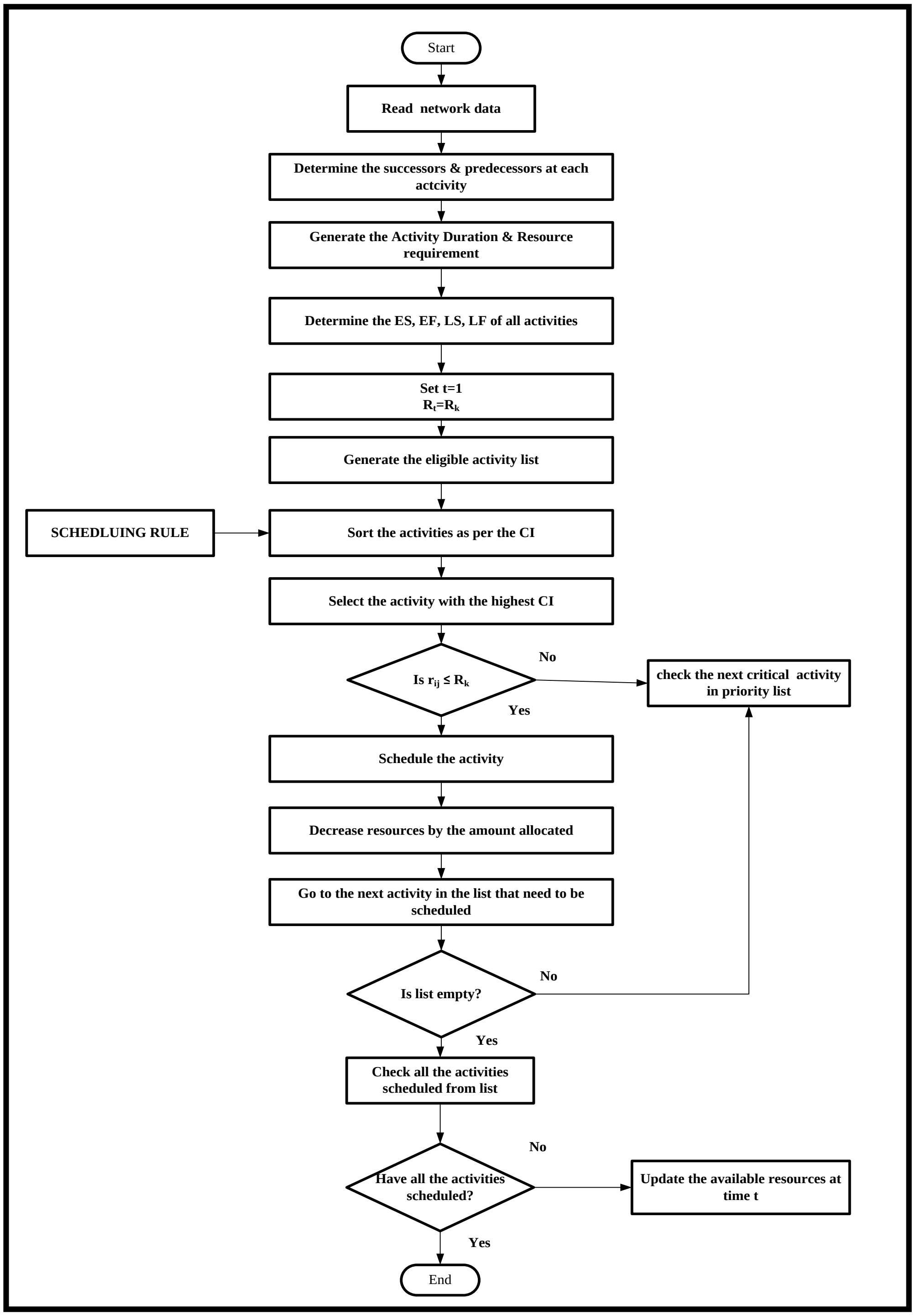

Figure 4: Operational flow chart of the second phase of MCPSA

3.2.5 Steps involved in the second phase of MCPSA

Step 1: In the initial step, all the network input parameters are entered to project model. These include the number of activities, the precedence relationships, the duration of all activities, and their early start and finish times.

Step 2: An initial schedule of all the activities is determined by the CPM, without considering the resource constraints. Based on this approach, all the activities are then prioritized by their respective CIs.

Step 3: The current time is set as t=1, the resources at the time t are set as $R_{t,}$ and the total resources available are set as R_k, where ($R_t = R_k$).

Step 4: All activities that are precedent dependent are arranged into an eligible activity list, sorted based on the priority scheduling rule.

Step 5: All activities are scheduled based on this rule. According to their level of priority, resources are assigned to them at time t.

Step 6: For each activity, this procedure is checked to see if the required amount of each resource available throughout the activity's duration. If there are enough resources, the activity is scheduled to start on time; otherwise, the procedure will check whether the activity is critical or non-critical.

Step 7: If the activity is critical, resources are taken from activities that are non-critical, so that the former is prioritized.

Step 8: If the priority list is empty, the procedure will check whether all the activities are scheduled; if not, the critical activities are analyzed from the list to make sure that all the activities in the priority list are scheduled.

CHAPTER 4

RESOURCE CONSTRAINED MULTIPLE CRITICAL ACTIVITIES SCHEDULING PROBLEM

4.1 Introduction

Project schedule is the main tool for monitoring and controlling all the activities in a project network. The project scheduling is a process of allocation of resources to the activities to estimate the start and finish time of each activity. The resource allocation during project scheduling is performed during two scenarios: (a) when resource level is adequate but the demand level varies drastically over the life of the project, in such situation it is applicable to allocate the resources from non-critical activities to critical activities, thereby increasing the resource utilization. This process is called resource levelling. (b) If the resource level is not adequate to meet the required demand, then the start of some of the activities must be delayed so that duration of the project can be increased. This process is called the resource constrained scheduling.

A typical approach followed by many industries to mitigate the project scheduling pressure is to crash project activities. Crashing activities involves allocating more resources to activities (such as labor, materials and machines) than actual requirement to expedite a project Kessler and chakrabarti (1999). In the recent years a wide range of objective functions have been used for solving the resource constrained project scheduling project. Minimizing the project duration by Baker (1974) has been used most widely. Other project scheduling objective function include minimize the total project delay, lateness by Kurtulus and Davis (1982), minimize average project delay Lova and Tormos (2001), minimize the total penalty Kurtulus (1985), minimize overall project cost by Talbot (1982), minimize the cost of delay Kurutulus (1978); Kurutulus and Narula (1985), and maximize resource levelling Woodworth and Willie (1975).

In this research, we are dealing with a project scheduling problem for a single project with multiple critical activity scenarios. This approach mainly accounts for reducing the overall completion time of project associated with multiple critical activities, that may occur due to improper resource allocation. A mixed integer linear programming model is proposed to solve the project scheduling problem considering the multiple critical activities scenarios. The section below explains the problem description followed by mathematical model.

4.2 Problem description

Duration of an activity in the project play a significant role in project completion. The duration of project can be classified into two types (a) normal duration (b) crashing duration. The normal duration is the time taken to complete an activity from start to finish, which is longest duration in a project, (b) crashing duration is the time taken to reduce the activity duration by allocating more resources to shorten the project completion time. The problem we explore in this research focusses on reducing the time duration of the critical activities along the critical path so that the overall project completion time is minimized. The project time, considering the RCMCASP, is minimized under the following assumptions:

- Once the activity started are never interrupted
- Every activity is assigned with given number of resources
- Reallocation of resources is possible depending upon the criticality of the activity
- The critical activity time is bounded by the crashing time
- The activity cannot be replaced as every activity are precedent dependent

4.3 Mathematical model formulation

Previous approaches to solving the project duration problem include the mixed integer programming approaches by Wiest (1963) and linear programming approaches with integer variables Brucker and Knust (2006). Below, we describe a mixed integer linear programming approach that incorporates RCMCASP. In RCMCASP, every activity is assigned with the respective due date for completion on time. If an activity exceeds the due date, then the activity is considered critical and must be crashed so that overall completion time of the project is minimized. In this research, we are dealing with a project that have three types of resource levels, we are considering only the human operators in all the three levels. During scheduling, the activities that are critical are allocated with sufficient resources so that the activity can be crashed to meet the project deadline. The model emphasis on the significance of resource-time tradeoff for the successful completion of the project. The duration of the activity, the resource allocation and completion time are the main decision variables of the model. The notations of the model are discussed below:

Indices

j is the activity index, j =1,….J

r is the resource index, r =1,…R

t is the time period index, t =1,…T

Decision variables

d_j, is the duration of activity j

$Q_r{}^{k}{}_{jt}$ is 1, if the number of resources of type *k* are added to or taken off from activity j in time t; otherwise 0.

X_{jt} is 1, if all the activities are completed exactly once, otherwise 0.

Parameters

$N_r{}^{k}{}_{jt}$ is the number of resources of type *k*, assigned to the activity j in time t before crashing

ND_j is the normal duration of activity j

CD_j is the crash duration of activity j

$X_r{}^{k}{}_{jt}$ is the amount of resources of type *k* allocated to activity j in time t

R^k is the total amount of resources od type *k* available for completing the project

TĎ is the delay in the project

H_j is the reduced time for the activity j

DL_j is the deadline of completing the activity j

4.4 Objective function

The objective function of the model is to minimize the overall completion time of the project

Minimize Z = $\sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{t=1}^{T} [ND_j * N_r{}^{k}{}_{jt} + CD_j * (N_r{}^{k}{}_{jt} \pm Q_r{}^{k}{}_{jt})] + T\check{D}$

Subject to:

- All the activities must be completed exactly once.

  $\sum_{j=1}^{J} \sum_{t=1}^{T} Xjt = 1$ …………………………………………………………...(1)

- The resource allocated to the activity does not exceed the total amount of resource allocated to the project.

  $\sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{t=1}^{T} dj\ X_r{}^{k}{}_{jt} \le R^{\mathbf{k}} \quad \forall\ k, t$…………………………………… (2)

- The crashing time for each activity cannot be reduced by more than its maximum time reduction

  $\sum_{j=1}^{J} \sum_{r=1}^{R} \sum_{t=1}^{T} CDj * (Nrkjt \pm Qrkjt) \le H_j \quad \forall\ j$……………………… (3)

- All the activities must be completed within the respective deadline

$$\sum_{j=1}^{J}\sum_{r=1}^{R}\sum_{t=1}^{T} dj\ X_r{}^{k}{}_{jt} \leq DL_j\ \forall\ j \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

- Non-negativity constraint:

$d_j \geq 0,\ Q_r{}^{k}{}_{jt}\ \epsilon\ (1,0)\ ,\ X_{jt}\ \epsilon\ (1,0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$ (5)

4.5 Constraints involved in the PSASMCP

The above formulated model has five constraints. Constraint (1) states that all the activities must be completed exactly once. Constraint (2) states that the resource allocated to the activity cannot exceed the total amount of resource allocated to the project. Constraint (3) states that the crashing time for each activity cannot be reduced by more than its maximum time reduction. The constraint (4) ensures that All the activities must be completed within the respective deadline and the constraint (5) are the non-negative constraints.

CHAPTER 5

IMPLEMENTATION

This chapter describes the implementation of the developed algorithm in various project networks, which vary in the variabilities and the uncertainties in their projects. As discussed earlier, this thesis is divided into two phases. The first phase is the identification phase, where the multiple critical paths are identified in a real-life production system through the MCPSA approach. The second phase goes on to demonstrate the effects of costs associated with every activity in the project network and the impact of the cost associated with the project network when a project is not completed on time.

This chapter is itself divided into three sections. Before executing the MCPSA case study, a concise review of its development and significance is provided. Section 4.1 explains the theory of implementation and execution. Section 4.2 describes the case studies implemented to validate the methodology and the results of the case studies.

5.1 MCPSA development and implementation

Project management is a system of managing the nine areas concerning projects: time, cost, scope, quality, procurement, risk, communication, integration, and human resources. The interplay of these nine areas makes project management a complex decision-making process. Currently in a manufacturing industry with uncertainties and variabilities, production efficiency and delivery of products to consumers at the right time are often paramount factors in competitiveness. The Business enterprises do appreciate the available manufacturing systems and the need to use their resources to their maximum capacities, even when there are only a few competitors in the market.

The manufacturing industry examined in this research is a metal-processing industry that consists of multiple tasks assigned to every operation. Every operation is allotted a given period for its completion. However, due to uncertainties and variabilities within the process, there are delays in the actual completion of the projects. Therefore, there could be more than one critical path that causes delays in the process.

The first phase of the thesis identifies the multiple critical path scenarios by addressing two case studies: (a) when the project has multiple critical paths with low variability in activity time, and (b) where a project has multiple critical paths with high variability in activity time. During this phase, the critical paths with highest critical index are identified. So, that project manager can prioritize those critical paths during the second phase. The second phase is the scheduling phase, where every critical path is allocated with appropriate amount of resources for the effective completion of the project without any delay. This is executed with the help of a mathematical model. Based on this model, it is known exactly how many activities in the critical path have to be crashed, so that the project completion time is effectively minimized.

5.2 Case study 1: MCPSA

The production system considered here for case study models is a screw manufacturing plant with several complex flow paths. The basic manufacturing process steps for screw manufacturing are blanking, core drilling, CNC rooting, simulation, straightening, thread milling, welding, polish, and inspection. Each of these major operations is carried out with a series of tasks and operations associated with each department. The entire process is repeated several times to ensure the required thickness of the screw. After the operations are completed, the screws are boxed and shipped in the boxing area. For all these departments, a specific number of operators and amount of material handling equipment is provided. In this research, the customized motorized carts (CMC), the jib cranes, and the operators are the three resources that are taken into consideration. The classification of types of product and resource are shown in Table 1.

Table 1: Classification of types of product and resource

S. No	Type of Product Family	Type of Work	Level of Resources	Duration (Days)
1	TP-140/33	New	3	128
2	CM-80/84	Coating	3	196

5.2.1 Case study 1: Project with low variability in activity time

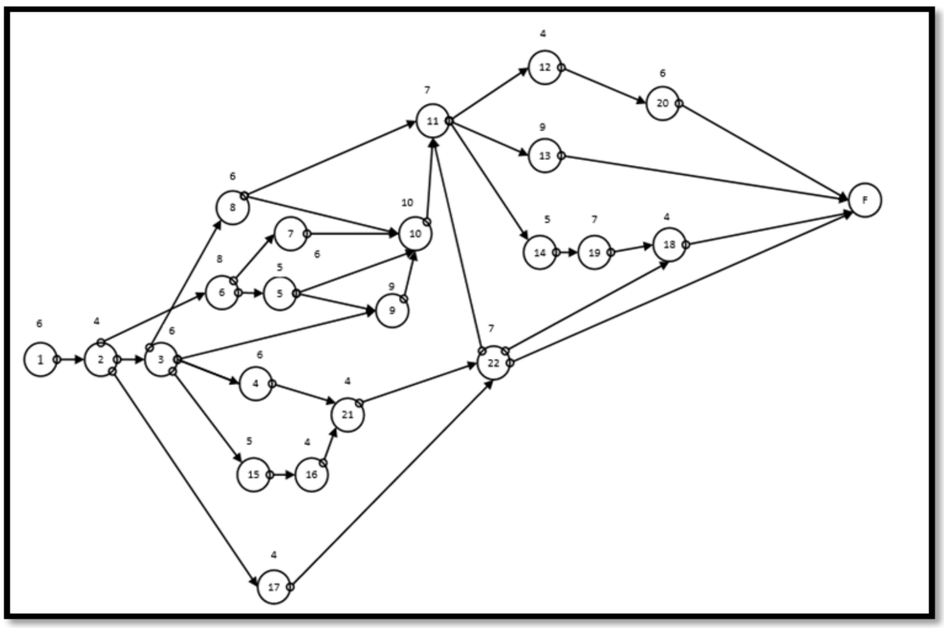

Figure 5: MCPSA case study 1- project network

The project network with 22 activities is depicted in Figure 5. Case study 1 considers a project network with low variability in activity time. The type of product family analyzed is TP-140/33. The activity times are represented by triangular distribution. The effect of variability is assumed to show the multiple critical path scenarios for this experiment.

The target due date for the completion of this project is 128 days. Three types of resources are utilized during every activity. The simulation model is simulated for 500 replications to determine how many paths exceed the actual due day of completion and to calculate the CI. The duration estimates used to fit all the activities are shown below in Tables 2. The three estimates of the activity duration are given by X (minimum), Y (most likely), and Z (maximum). All the durations are in days.

Table 2: MCPSA experiment case study 1 – low variability in activity time

Activity	X (Days)	Y (Days)	Z (Days)	Activity	X (Days)	Y (Days)	Z (Days)
1	5.5	**6**	6.5	**12**	3.5	**4**	4.5
2	2.5	**4**	5.5	**13**	8.5	**9**	9.5
3	5.5	**6**	6.5	**14**	4.5	**5**	5.5
4	5.5	**6**	6.5	**15**	4.5	**5**	5.5
5	4.5	**5**	5.5	**16**	3.5	**4**	4.5
6	7.5	**8**	8.5	**17**	2.5	**4**	5.5
7	5.5	**6**	6.5	**18**	2.5	**4**	5.5
8	5.5	**6**	6.5	**19**	6.5	**7**	7.5
9	8.5	**9**	9.5	**20**	5.5	**6**	6.5
10	4.5	**10**	5.5	**21**	3.5	**4**	4.5
11	4.5	**7**	7.5	**22**	6.5	**7**	7.5

Table 3 provides the input data of all the resources allocated to them. This data is in turn used by the model. In the section below, the criticality index calculation is discussed.

Table 3: MCPSA experiment case study 1- resource allocation to activities

Activity	Type 1 Operator	Type 2 CMC	Type 3 Cranes	Activity	Type 1 Operator	Type 2 CMC	Type 3 Cranes
1	1	2	2	**12**	0	0	1
2	1	2	2	**13**	1	1	1
3	1	1	0	**14**	1	0	0
4	1	1	1	**15**	0	0	2
5	1	0	1	**16**	1	1	2
6	1	0	0	**17**	0	1	0
7	1	1	0	**18**	0	1	0
8	0	0	1	**19**	1	1	0
9	1	2	0	**20**	1	2	1
10	1	1	0	**21**	0	1	0
11	0	1	0	**22**	1	0	0

5.2.2 Criticality index (β)

The criticality index (CI) is a performance metric, used to identify those activities that are critical in a project network. The CI is a tool to identify how often an activity remains critical during the critical path analysis. The criticality index of the activities is classified into three types: high, medium and low. If CI of the activities lies between 90-100%, then the activity is highly critical, medium critical if CI of the activities lies between 50-80%, and activities that have less than 50% CI are considered less critical in the project. In this research, the criticality index of the activities is calculated as shown below.

$$\text{Criticality Index } (\beta)\% = \frac{\text{Total exceeded time of the path * \# of time exceeded}}{\text{Max (Total exceeded time of the path * \# of time exceeded}}$$

The number of replications required for the criticality index calculation is determined by,

$$\boxed{Nr = [\, z_{\alpha/2}\ S / E\ ]^2}$$

Number of replications N_r, n is the number of iterations needed, S is the estimated standard deviation of the output, E is the desired margin of error (in this case, 5 units). Table 4 provides the number of replications used in case study simulation models.

Table 4: Number of replications in case study models

Case study models	**Number of replications, N_r**
Model 1	500
Model 2	800

In the section below, the multiple critical paths are identified, and their CI is calculated in section 5.2.3(a). The probability of completion by target due day period is discussed in section 5.2.3(b). The cost associated due to the delay of the project completion is shown in section 5.2.3(c) respectively.

5.2.3 Results of case study-1

5.2.3(a) Criticality index calculation

For the case study model 1, the simulation model was executed with low variability in activity durations. The model was replicated for 500 simulations, to get the desired result. Once the simulation runs were completed, we found some activities that were critical throughout the simulation runs. Once the critical activities were identified, the path associated with those critical activities in the network were formed. We found that there are nine dominant critical paths in the network. To measure the criticality of all the critical paths, a CI index is assigned to every path. The criticality index calculated for every path is shown in Table 5.

Table 5: MCPSA experiment case study 1 results - criticality index of all critical paths

S. No	Critical Paths Identified	Total exceeded time of path (Days)	# of times exceeded	Criticality index (β) (%)
1	1-2-3-4-21-22-F	39	65	**100**
2	1-2-6-7-10-11-13-F	47	53	**98**
3	1-2-3-8-10-11-13-F	37	51	**74**
4	1-2-3-9-10-11-13-F	33	47	**61**
5	1-2-6-5-10-11-13-F	29	52	**59**
6	1-2-3-4-21-22-18-F	31	47	**57**
7	1-2-3-15-16-21-22-F	29	52	**47**
8	1-2-3-8-11-12-20-F	28	43	**41**
9	1-2-3-4-21-22-11-13-F	32	35	**40**

For example; criticality index calculation for Path $(\beta)_1$ = 39*65/2535*100 = 100%, similarly the CI for all other paths are calculated. Based on the results obtained the project manager can prioritize the activities in the beginning of the initial schedule and maintain a low criticality index rate for all the activities in the project. The results obtained are identified in the network model and graphically represented in the figures below.

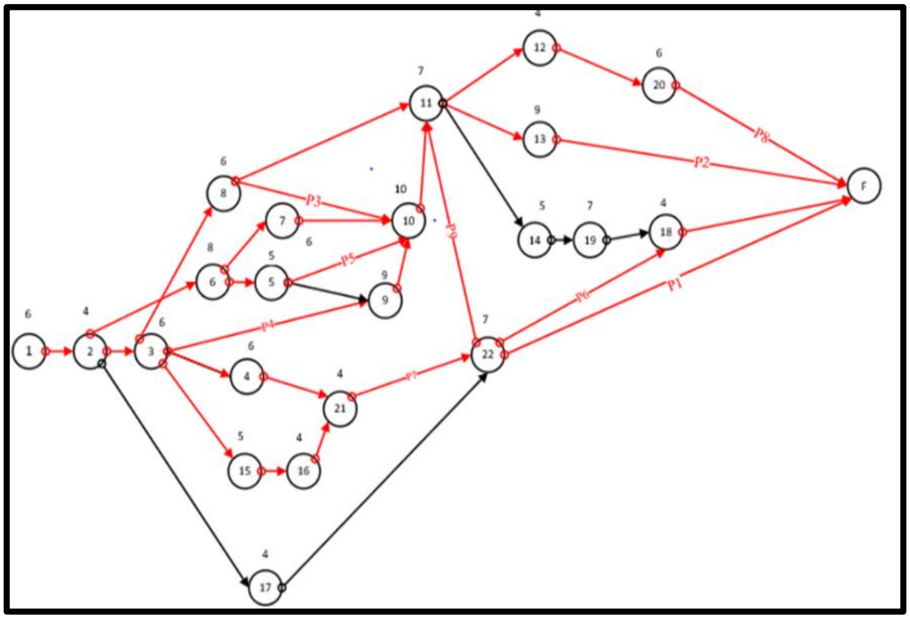

Figure 6: MCPSA case study 1 results – multiple critical paths

In Figure 6, the critical paths identified are highlighted and every path is assigned with their respective path number. The criticality index calculated for every path is plotted in the form of Pareto chart as shown in the Figure 7.

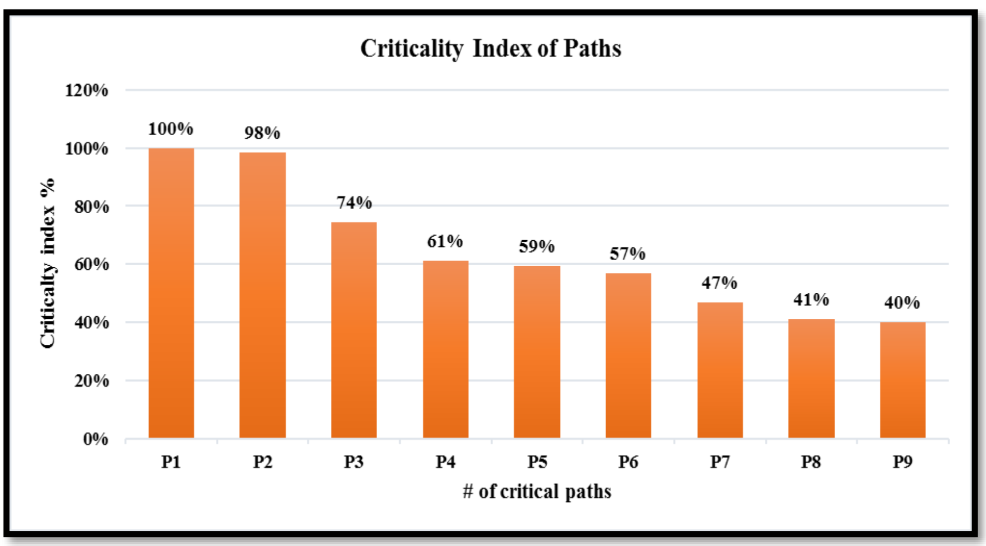

Figure 7: MCPSA case study 1 results – criticality index of paths

5.2.3(b) The target completion time of project

The expected time for all the activities in the critical path, is calculated to determine the target completion time of a project. The expected time is the sum of all the activity duration along the critical path. The target completion time of all the critical paths is calculated using the formula, $Z= T_s- T_e/\sqrt{V}$, where T_s is the target completion time, T_e is the sum of all the activity durations in the critical path and V is the variances of all the activity in the critical path as mentioned by John and Herman (2012). The target completion time determines the “highly likely” completion of the project within the due date. In this case study, we have assumed 95% confidence interval for calculating the probability of completion. In Table 6, the probability of target completion of all the critical paths are calculated as shown.

Table 6: MCPSA experiment case study 1 results – target completion time

S. No	Critical Paths Identified	Expected duration, T_e (Days)	Target completion, T_s (Days)
1	1-2-3-4-21-22-F	33	36
2	1-2-6-7-10-11-13-F	44	47
3	1-2-3-8-10-11-13-F	48	51
4	1-2-3-9-10-11-13-F	51	54
5	1-2-6-5-10-11-13-F	49	53
6	1-2-3-4-21-22-18-F	31	33
7	1-2-3-15-16-21-22-F	36	39
8	1-2-3-8-11-12-20-F	39	42
9	1-2-3-4-21-22-11-13-F	49	54

5.2.3(c) Cost associated due to the delay of the project

The delay in the project completion is determined by the difference between the expected time of completion and the target completion time of the activities in the critical path. In table 7, the total delay time in the project is calculated as shown below. The delay in project completion is given by the formula:

Total delay (Ď) = Target completion – Expected time

Table 7: MCPSA experiment case study 1 results – delay time of project

S. No	# of Critical Paths	Expected duration, T_e (Days)	Target completion, T_s (Days)	Total delay (days)
1	1-2-3-4-21-22-F	33	36	3
2	1-2-6-7-10-11-13-F	44	48	4
3	1-2-3-8-10-11-13-F	48	51	3
4	1-2-3-9-10-11-13-F	51	54	3
5	1-2-6-5-10-11-13-F	49	53	4
6	1-2-3-4-21-22-18-F	31	33	2
7	1-2-3-15-16-21-22-F	36	39	3
8	1-2-3-8-11-12-20-F	39	42	4
9	1-2-3-4-21-22-11-13-F	49	54	5
Total delay in project (days), ∑(Ď)				**29**

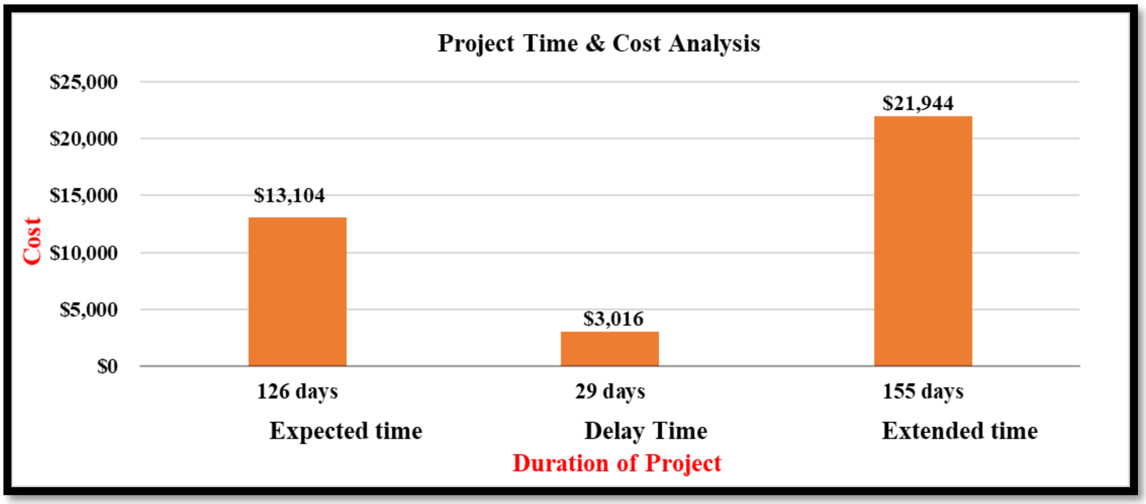

Figure 8: Case study 1 – project time vs cost analysis

Total delay of the project (Ď):

∑ (Total exceeded time) – (Original completion time) = (155) – (126) = 29 days

In Figure 8, time and cost invested between the original completion time and the exceeded time is graphically represented, the total delay in the project is found to be 29 days and the penalty cost incurred due to the delay is about $3016 (29*104) for one product (TP-140/33). The duration between the original time and the exceeded time must be reduced (crashed), so that the project can be completed within the due date without any delay. In Table 8, the cost estimation of original time, delay time and the exceeded time is calculated as shown below.

Table 8: MCPSA experiment case study 1 – time vs cost analysis

Original completion time	**Duration delayed**	**Extended time of completion**
126 days	29 days	155 days
Cost of original completion time	**Cost of Penalty**	**Total compensation cost**
126*104 = $13,104	29*104 = $3016	155*104 = $21,944

* $104, shop floor rate in the company

5.3 Case study 2: MCPSA

5.3.1 Case study 2: Project with high variability in activity time

Case study 2 considers project networks that have high variability in activity time. The type of product family analyzed is CM-80. The activity times are represented by triangular distribution. The effect of variability is assumed to show the multiple critical path scenarios for this experiment. The project network with 40 activities is depicted in Figure 9. The target due date for the completion of this project is 196 days. Three types of resources are utilized during every activity. The simulation model is simulated for 800 replications to determine how many paths exceed the actual due date and to calculate the CI.

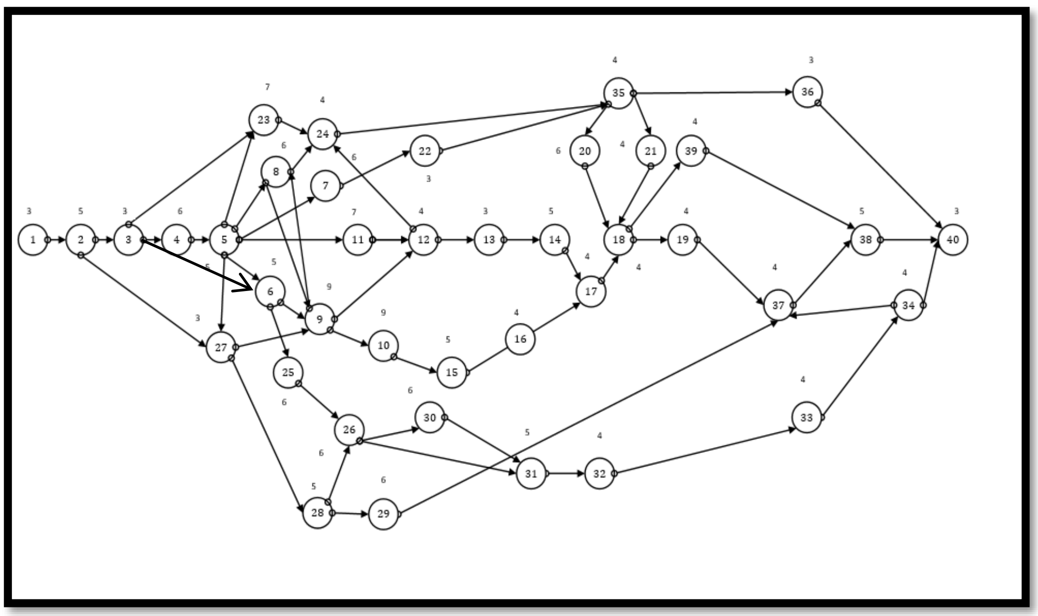

Figure 9: MCPSA case study 2 – project network

The duration estimates and resource allocations used to fit all the activities are shown below in Tables 9 and 10, respectively.

Table 9: MCPSA case study 2 – high variability in activity time

Activity	X (Days)	Y (Days)	Z (Days)	Activity	X (Days)	Y (Days)	Z (Days)
1	1	**3**	5	**21**	1	**4**	7
2	2.5	**5**	7.5	**22**	1	**3**	5
3	1	**3**	5	**23**	2	**6**	10
4	1.5	**6**	4.5	**24**	1.5	**4**	6.5
5	4.5	**5**	5.5	**25**	4	**6**	12
6	2	**5**	8	**26**	2	**6**	10
7	2	**6**	10	**27**	1	**3**	5
8	1.5	**6**	10.5	**28**	2	**5**	8
9	2	**9**	16	**29**	3	**6**	9
10	4	**9**	14	**30**	2	**6**	10
11	2	**7**	12	**31**	2	**5**	8
12	1	**4**	7	**32**	1	**4**	7
13	1	**3**	5	**33**	2	**4**	6
14	2	**5**	8	**34**	3	**4**	5
15	1	**5**	9	**35**	1	**4**	7
16	2	**4**	6	**36**	1	**3**	5
17	1.5	**4**	6.5	**37**	2	**4**	6
18	1	**4**	7	**38**	1	**5**	9
19	2	**4**	6	**39**	2	**4**	6
20	2	**6**	10	**40**	1	**3**	5

Table 10: MCPSA experiment case study 2 – resource allocated to activities

Activity	Type 1 Operator	Type 2 CMC	Type 3 Cranes	Activity	Type 1 Operator	Type 2 CMC	Type 3 Cranes
1	1	1	0	**21**	1	0	1
2	1	0	0	**22**	1	1	1
3	1	1	0	**23**	1	1	0
4	1	1	1	**24**	1	0	1
5	1	0	1	**25**	1	2	0
6	1	0	0	**26**	1	1	0
7	1	0	0	**27**	1	0	0
8	0	0	1	**28**	1	0	0
9	1	1	0	**29**	1	1	1
10	1	0	0	**30**	0	1	1
11	1	1	0	**31**	1	0	0
12	0	1	1	**32**	1	1	0
13	1	1	0	**33**	0	0	1
14	1	0	1	**34**	1	0	0
15	1	0	0	**35**	0	0	1
16	1	0	1	**36**	1	2	0
17	0	0	1	**37**	1	1	1
18	1	1	1	**38**	1	1	0
19	0	0	1	**39**	1	0	2
20	1	1	1	**40**	1	0	1

5.3.2 Results of case study-2

5.3.2(a) Criticality index calculation

For the case study model 1, the simulation model was executed with low variability in activity durations. The model was replicated for 800 simulations, to get the desired result. Once the simulation runs were completed, we found some activities that were critical throughout the simulation runs. Once the critical activities were identified, the path associated with those critical activities in the network were formed. We found that there are 16 dominant critical paths in the network. The criticality index calculated for every path is shown in Table 11. For example; criticality index calculation for Path $(\beta)_1$ = 28*33/924*100 = 100%, similarly the CI for all other paths are calculated.

Table 11: MCPSA experiment case study 2 – criticality index of all critical paths

S. No	Critical Paths Identified	Total exceeded time of path (Days)	# of times exceeded	Criticality index (β) (%)
1	**1-2-3-4-5-8-24-35-36-40**	28	33	**100**
2	**1-2-3-23-24-35-36-40**	27	34	**99.35**
3	**1-2-27-28-29-34-37-40**	26	31	**87.22**
4	**1-2-27-9-10-15-16-17-18-19-37-34-40**	23	34	**84.60**
5	**1-2-27-28-29-37-38-40**	21	33	**75.30**
6	**1-2-3-4-5-8-9-10-15-16-17-18-39-38-40**	21	32	**72.00**
7	**1-2-27-9-8-24-35-36-40**	21	29	**68.10**
8	**1-2-3-23-24-35-20-18-19-37-34-40**	17	29	**65.90**
9	**1-2-3-23-24-35-21-18-19-37-38-40**	18	25	**53.35**
10	**1-2-3-6-25-26-30-31-32-33-34-40**	17	26	**48.50**
11	**1-2-27-9-8-24-35-36-40**	21	32	**47.80**
12	**1-2-3-4-5-7-22-35-36-40**	17	23	**45.20**
13	**1-2-27-28-26-30-31-32-33-34-40**	17	23	**42.30**
14	**1-2-3-4-5-23-24-35-36-40**	14	26	**39.80**
15	**1-2-27-28-26-31-32-33-34-40**	16	22	**39.00**
16	**1-2-3-4-5-27-9-12-24-35-36-40**	15	24	**38**

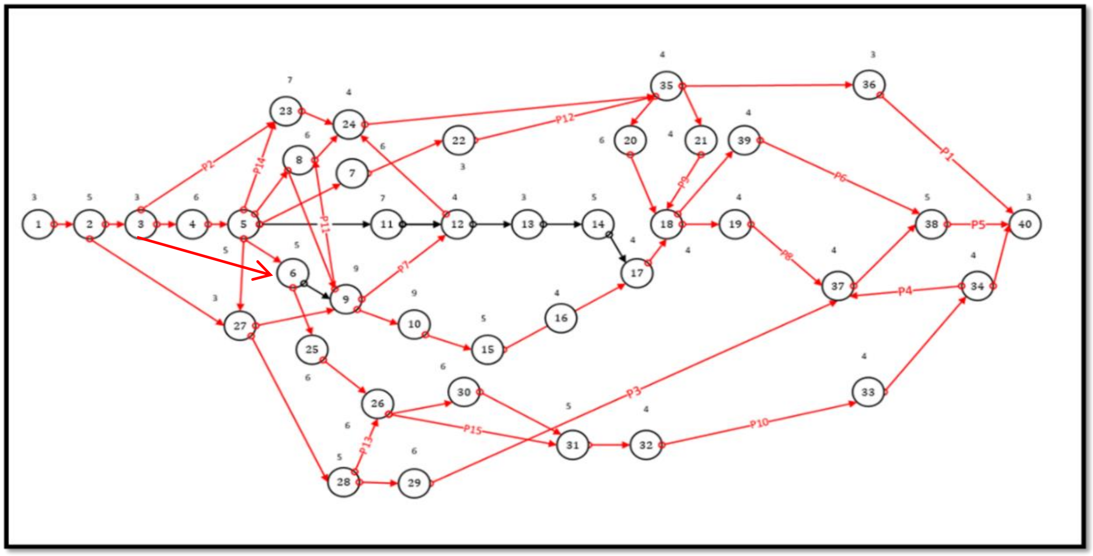

Figure 10: MCPSA case study 2 – critical paths

In Figure 10 the critical paths identified are highlighted and every path is assigned with their respective path number. The criticality index calculated for every path is plotted in the form of Pareto chart as shown in the Figure 11.

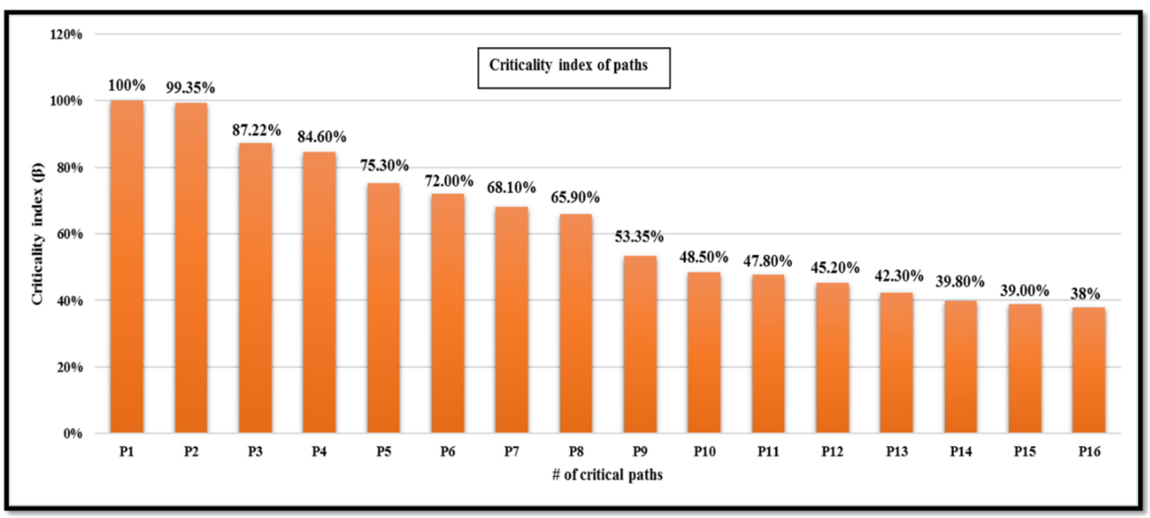

Figure 11: MCPSA case study 2 – criticality index of path

5.3.2(b) The target completion time of project

The expected time for all the activities in the critical path, is calculated to determine the target completion time of a project. The expected time is the sum of all the activity duration along the critical path. The target completion time determines the likely completion of the project within the due date. In this case study, we have assumed 95% confidence interval for calculating the probability of completion. In Table 12, the probability of target completion of all the critical paths are calculated as shown.

Table 12: MCPSA experiment case study 2 results – target completion time

S. No	Critical Paths Identified	Expected duration, T_e (Days)	Target completion, T_s (Days)
1	**1-2-3-4-5-8-24-35-36-40**	42	45
2	**1-2-3-23-24-35-36-40**	44	47
3	**1-2-27-28-29-34-37-40**	48	52
4	**1-2-27-9-10-15-16-17-18-19-37-34-40**	58	61
5	**1-2-27-28-29-37-38-40**	49	52
6	**1-2-3-4-5-8-9-10-15-16-17-18-39-38-40**	31	34
7	**1-2-27-9-8-24-35-36-40**	36	40
8	**1-2-3-23-24-35-20-18-19-37-34-40**	39	42
9	**1-2-3-23-24-35-21-18-19-37-38-40**	53	55
10	**1-2-3-6-25-26-30-31-32-33-34-40**	47	51
11	**1-2-27-9-8-24-35-36-40**	37	41
12	**1-2-3-4-5-7-22-35-36-40**	42	46
13	**1-2-27-28-26-30-31-32-33-34-40**	52	56
14	**1-2-3-4-5-23-24-35-36-40**	38	41
15	**1-2-27-28-26-31-32-33-34-40**	45	48
16	**1-2-3-4-5-27-9-12-24-35-36-40**	52	55

5.3.2(c) Cost associated due to the delay of the project

The delay in project completion is given by the formula: Total delay (Ď) = Target completion – Expected time. In table 13, the total delay time in the project is calculated as shown below.

Table 13: MCPSA experiment case study 2 results – delay time of project

S. No	# of Critical Paths	Expected duration, T_e (Days)	Target completion, T_s (Days)	Total delay (days)
1	**1-2-3-4-5-8-24-35-36-40**	42	45	3
2	**1-2-3-23-24-35-36-40**	44	47	3
3	**1-2-27-28-29-34-37-40**	48	52	4
4	**1-2-27-9-10-15-16-17-18-19-37-34-40**	58	61	3
5	**1-2-27-28-29-37-38-40**	49	52	3
6	**1-2-3-4-5-8-9-10-15-16-17-18-39-38-40**	51	54	3
7	**1-2-27-9-8-24-35-36-40**	36	40	4
8	**1-2-3-23-24-35-20-18-19-37-34-40**	39	42	3
9	**1-2-3-23-24-35-21-18-19-37-38-40**	53	55	2
10	**1-2-3-6-25-26-30-31-32-33-34-40**	47	51	4
11	**1-2-27-9-8-24-35-36-40**	37	41	4
12	**1-2-3-4-5-7-22-35-36-40**	42	45	3
13	**1-2-27-28-26-30-31-32-33-34-40**	52	56	4
14	**1-2-3-4-5-23-24-35-36-40**	38	41	4
15	**1-2-27-28-26-31-32-33-34-40**	45	48	3
16	**1-2-3-4-5-27-9-12-24-35-36-40**	52	55	3
Total delay in project (days), ∑(Ď)				**53**

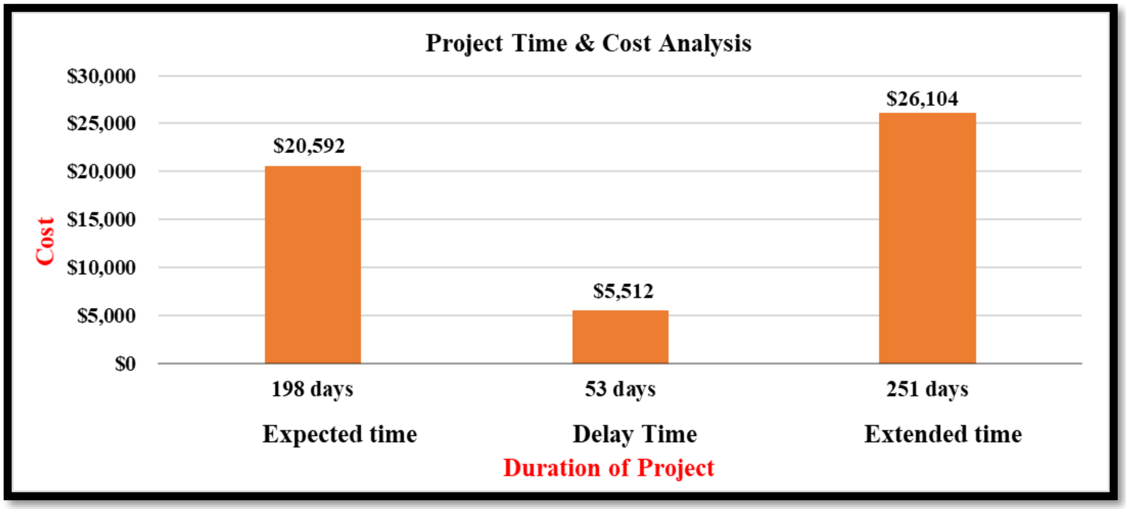

Figure 12: MCPSA case study 2 - project time vs cost trade-off analysis

Total delay of the project (Ď):

∑ (Total exceeded time) – (Original completion time) = (251) – (198) = 53 days

In Figure 12, time and cost invested between the original completion time and the exceeded time is graphically represented, the total delay in the project is found to be 53 days and the penalty cost incurred due to the delay is about $5512 (253*104) for one product (CM-80/84). The duration between the original time and the exceeded time must be reduced (crashed), so that the project can be completed within the due date without any delay. In Table 14, the cost estimation of original time, delay time and the exceeded time is calculated as shown below.

Table 14: MCPSA experiment case study 2: Time vs cost analysis

Target completion time	**Duration delayed**	**Extended time of completion**
198 days	53 days	251 days
Cost of target completion time	**Cost of Penalty**	**Total compensation cost**
198*104 = $20,592	53 *104 = $5512	251*104 = $26,104

* $104, shop floor rate in company

CHAPTER 6

CONCLUSION AND DISCUSSION

This chapter concludes the thesis and provides insights into opportunities for future work associated with this field of project management and scheduling procedures using MCPSA. This chapter is divided into three different sections. Section 6.1 summarizes the research, section 6.2 offers some concluding remarks, section 6.3 describes conclusion and section 6.4 examines likely future work in this field.

6.1 Research summary

In this study, an attempt was made to integrate a project's priorities with the development of its schedule. The MCPSA algorithm was developed to accomplish this task. This is a new method of generating the schedule of any resource-constrained project suffering from scheduling problems, where each project has a defined criticality.

The proposed method was validated through application in various case studies. The experimental results were compared with existing priority rules. In a real project management environment, a penalty is imposed if a project is not completed within its due date. Some projects carry higher penalty than others. In this context, project managers can make a trade-off among the project's penalties and develop a cost-effective project schedule that satisfies customer requirements. In this context, the proposed algorithm would be beneficial for project managers in dealing with these conditions.

6.2 Environmental analysis

The effectiveness of any new method is judged by how it copes with the internal and external environments it is designed to be used in. Factors internal to the applied method are known as its strength and weakness; those external to the applied method can threaten its existence and are known as threats and opportunities. Environmental or SWOT (strength, weakness, opportunities, threats) analysis is an effective technique used to test any existing method or system. Analysis using the SWOT framework allows for the identification of areas where the organization is lagging and where great opportunities lie.

Strengths

The strength of the MCPSA approach is discussed below;

- Resources are assigned to reduce uncertainty in activity durations
- The availability of resources, both now and in the future, is known.
- It is known which path in the shop floor needs more attention in terms of scheduling resources.
- MCPSA identifies the exact number of critical paths in a process, meaning that the project manager can schedule resources accordingly.
- MCPSA helps to identify situations where it may be possible to postpone the completion of the current activity to a later time to reduce the total completion time of this activity and the subsequent "n" activities.

To appreciate the flexibility of the developed methodology, case studies were carried out in the same manufacturing company, in which various critical paths were identified. Throughout the simulations, there were situations where more than one path was dominant. From these dominant paths, the activities that needed greater allocation of resources were identified. The result of the case study 1 and 2 is shown graphically in Figure 13.

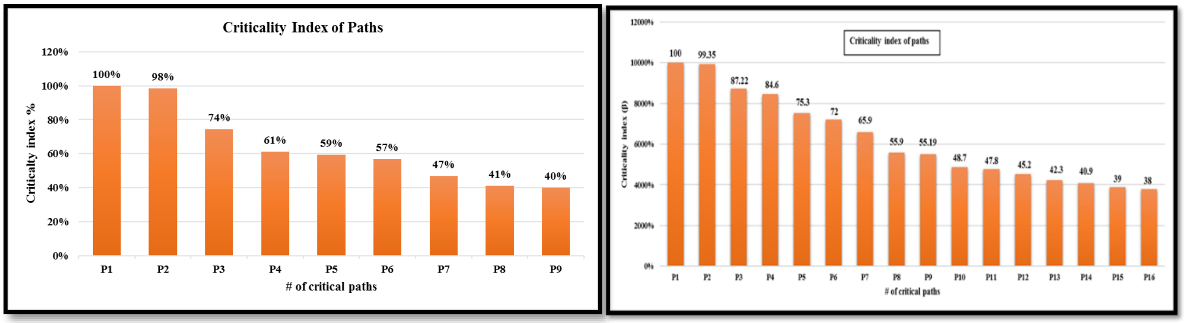

Figure 13: Results of case study 1 & 2

Weakness

MCPSA is not applicable for scheduling multiple projects at the same time.

Threats

One of the major threats to MCPSA is that of a disruptive event. During such cases, activities must stop for some time. In these circumstances, the penalty cost will also increase, as the project is increasingly delayed. Having considered the possibility of such events, the project manager should be able to provide some additional slack time during the start of the project.

Opportunities

MCPSA can be adapted to solve scheduling problems in multiple projects by reducing delays and improving completion rates of all projects in an organization.

6.3 Conclusion

From this study, it can be concluded that use of MCPSA in scheduling jobs can facilitate obtaining near optimal solutions. The objective function can only be achieved by using the developed MCPSA scheduling approach, which optimizes the completion time of the activities in the project by identifying multiple critical paths within the system, thereby reducing the overall delay time and cost of the project.

6.4 Future Works

In the future, research could explore the possibility of integrating other knowledge areas into the development of project schedules, such as risk management and procurement management. MCPSA can be adapted to solve scheduling problems in multiple projects, thereby reducing delays and improving the completion rates of all projects in an organization.

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APPENDIX

Steps involved in MCPSA

STEP 1
- Create the project network in MS- Project

STEP 2
- Interface the created project network in @RISK simulation software

STEP 3
- Define every actvity with the respective probability distribution

STEP 4
- Decide the number of replications and select the proabalistic gantt chart

STEP 5
- The actvity with CI are identified from the probabalistic gantt chart

Probabilistic Gantt chart