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Time-cost-quality trade-off analysis for construction projects

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Time-Cost-Quality Trade-off Analysis for Construction Projects

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Abstract

The main objective of construction projects is to finish the project according to an available budget, within a planned schedule, and achieving a pre-specified extent of quality. Therefore, time, cost, and quality are considered the most important attributes of construction projects. The purpose of this study is to incorporate quality into the traditional two-dimensional time-cost trade-off (TCT) in order to develop an advanced three-dimensional time-cost-quality trade-off (TCQT) approach. Time, cost, and quality of construction projects are interrelated and have impacts on each other. It is a challenging task to strike a balance among these three conflicting objectives of construction projects since no one solution can be optimal for the three objectives.

The overall performance of a project regarding time, cost, and quality is determined by the duration, cost, and quality of its activities. These attributes of each activity depend on the execution option by which the activity's work is completed. It is required to develop an approach that is capable of finding an optimal or near optimal set of execution options for the project's activities in order to minimize the project's total cost and total duration, while its overall quality is maximized. For the aforementioned purpose, three various Microsoft Excel based TCQT models have been developed as follows:

- First, a simplified model is developed with the objective of optimizing the total duration, cost, and quality of simple construction projects utilizing the GA-based Excel add in Evolver.

- Second, a stochastic model is developed with the objective of optimizing the total duration, cost, and quality of construction projects applying the PERT approach in order to consider uncertainty associated with the performance of execution options and the whole project.

- Third, an advanced multi objective optimization model is developed utilizing a self-developed optimization tool having the following capabilities:

1. Selecting an appropriate execution option for each activity within a considered project to optimize the objectives of time, cost, and quality.

2. Considering the discrete nature of duration, cost, and quality of various options for executing each activity.

3. Applying three various optimization approaches, which are the Goal Programming (GP), the Modified Adaptive Weight Approach (MAWA), and the Non-dominated Sorting Genetic Algorithms (NSGAII).

4. Analyzing both TCT and TCQT problems.

5. Considering finish-to-finish, start-to-start, and start-to-finish dependency relationships in addition to the traditional finish-to-start relationships among activities.

6. Considering any number of successors and predecessors for activities.

7. User-friendly input and output interfaces to be used for large-scale projects.

To validate the developed models and demonstrate their efficiency, they were applied to case studies introduced in literature. Results obtained by the developed models demonstrated their effectiveness and efficiency in analyzing both TCT and TCQT problems.

الْحَمْدُ لِلَّهِ الَّذِي هَدَانَا لِهَذَا وَمَا كُنَّا لِنَهْتَدِيَ لَوْلا أَنْ هَدَانَا اللَّهُ

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Dedication

To my parents and my family, Inspirations of my life

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Glossary of Abbreviations

A.O.A	Activity On Arrow
A.O.N	Activity On Node
ACO	Ant Colony Optimization
AHP	Analytical Hierarchy Process
ANOVA	Analysis of Variance
CPM	Critical Path Method
CPS	Critical Path Segments
DC	Direct Cost
DP	Dynamic Programming
DTCTP	Discrete Time Cost Trade-off Problem
EA	Evolutionary Algorithm
EF	Early Finish of an activity
EM	Electromagnetism Mechanism
ES	Early Start of an activity
FF	Finish to Finish
FS	Finish to Start
GA	Genetic Algorithm
GP	Goal Programming
IC	Indirect Cost
IP	Integer Programming
LF	Late Finish of an activity
LP	Linear Programming
LS	Late Start of an activity
MA	Memetic Algorithms
MACROS	Multi-objective Automated Construction Resource Optimization System
MAWA	Modified Adaptive Weight Approach
MOO	Multi Objectives Optimization
MSC	Monte Carlo Simulation
Npop	Number of Population of GA

Ngen	Number of Generations of GA
NSGA	Non-dominated Sorting Genetic Algorithm
P.T.M	Purchase Time Method
Pcr	Crossover rate
PDM	Precedence Diagram Method
PERT	Program Evaluation and Review Technique
PGA	Pareto Genetic Algorithm
Pm	Mutation rate
Pmi	Initial Mutation rate
PSO	Particle Swarm Optimization
QA	Quality Assurance
QBS	Quality Breakdown Structure
QC	Quality Control
QPI	Quality Performance Index
SF	Start to Finish
SFL	Shuffled Frog Leaping algorithms
SS	Start to Start
TCQT	Time Cost Quality Trade-off
TCT	Time Cost Trade-off
Te	Expected mean Time for an activity
TF	Total Float of an activity
Tm	Most likely or normal Time estimate for an activity
To	Optimistic Time estimate for an activity
Tp	Pessimistic Time estimate for an activity
VBA	Visual Basic for Applications
WBS	Work Breakdown Structure

Chapter I: Introduction

1.1 General Introduction

The construction industry is one of the most important industries in the world and is considered one of the most economy contributing ones. That is why construction engineering and management research is of great importance to the success of that vital industry. According to construction management references, a project is defined as "a temporary endeavor undertaken to create a unique product or service." (PMI, 2008). In other words, a project is a sequence of unique and connected activities having one goal that must be completed by a specific time, within a budget and according to specifications. Any unique project has a planned duration, a defined scope, an estimated budget, and pre-specified specifications. Therefore, time, cost, and specifications are the three constraints that are limiting the project success. Specifications of projects include but are not limited to quality, safety, sustainability, and many other technical or contractual details (Hegazy, 2002). For the proposed research, the basic goal of any construction project is to finish the project according to an available budget, within a planned schedule, and achieving a required extent of quality. Figure 1.1 shows the three main attributes associated with construction projects.
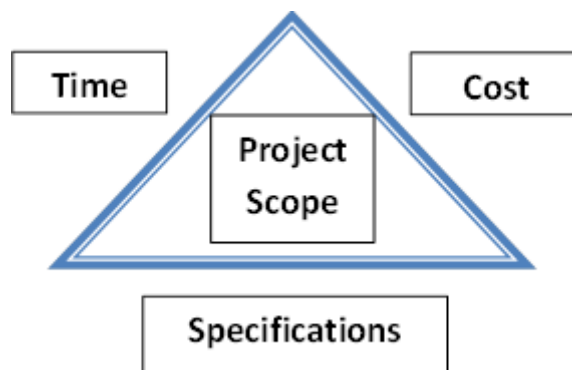
Figure 1.1: **Construction projects' framework** (PMI, 2008)

Time, cost, and quality of an activity are interrelated and have impacts on each other since the reduction or increase of one factor would be at the expense of the other. Usually, utilizing resources that are more expensive to complete an activity increases its direct cost and reduces its duration (Pour et al., 2012). On the other hand, the activity duration usually increases and its direct cost decreases when less expensive resources are used. Quality has a strong impact on both time and cost of construction activities. For instance, improving quality may increase the cost and duration of projects; however, poor quality management will significantly increase the cost and time of projects because of the additional time and money required for repairs, rework, or removal of low quality defects, which are much higher than using strict quality control procedures. Activities' durations increase when using quality control procedures such as tests or inspection procedures but low quality control does not reduce durations since the time needed to solve a problem or repair a defect may be much longer than the time spent in quality control procedures.

Duration, cost, and quality of an activity are affected by the utilized construction method, crew formation, materials, equipment and subcontractors, which create many options to complete the work of such an activity. For the time-cost relationship of Figure 1.2, executing the activity using option 1 results in a reduced duration and a higher cost; however, executing it utilizing option 3 results in a longer duration and a less cost. For the quality-cost relationship, executing the activity using option A results in improved quality and a higher cost; however, executing it utilizing option C results in poor quality and a less cost. On the other hand, the time-quality relationship cannot be represented by a general relationship. For instance, applying poor quality control procedures to an activity may reduce its duration; however, utilizing an advanced construction method may also reduce the activity's duration and increase its quality performance as well.

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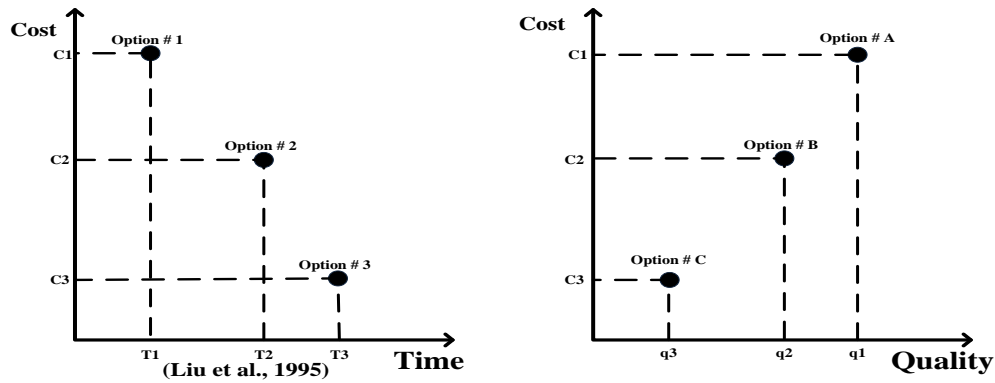
Figure 1.2: Time-cost and quality-cost relationships for the activity level

For the project level, the total project direct costs, which include the costs of materials, labor, equipment, and subcontractors, usually increase when the project is accelerated. The total project indirect costs, which are usually proportional to the project duration, decrease when its total duration is reduced. To obtain the total project time-cost relationship, the direct and indirect time cost relationships are combined as shown in the left part of Figure 1.3. On the other hand, costs of prevention or appraisal, which are the costs of quality control procedures undertaken to ensure that the project meets a desired quality level or to avoid defects or failures, increase when the project quality is improved. Costs of failures, which are the costs associated with rework or repairing defects, decrease when the project quality is improved. The optimum cost of quality of projects is obtained as shown in the right part of Figure 1.3.
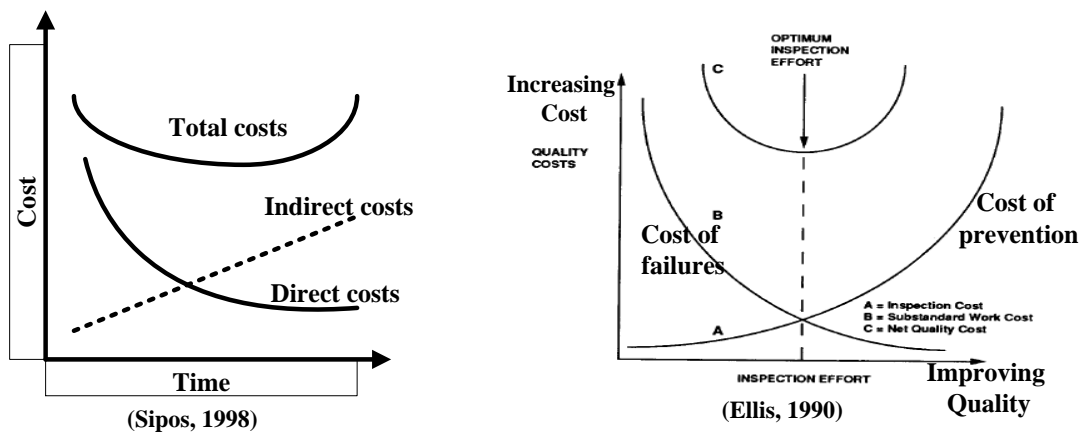
Figure 1.3: Time-cost and quality-cost relationships for the project level

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Time-cost optimization or time-cost trade-off analysis (TCT) is considered one of the most important features of projects' planning and controlling. The main idea of TCT is to strike a balance between the decreased indirect costs and the increased direct costs of activities when the project is accelerated. According to Hegazy (2002) and (2006), TCT may be applied to accelerate construction projects for one or more of the following reasons:

1) There is a predefined deadline date to be met.

2) There is a bonus incentive for early completion.

3) There is a penalty for late completion.

4) Minimizing indirect costs and overhead costs.

5) Costs of additional resources for accelerating the construction process are minor.

6) The owner loses income for every day the project is incomplete, in money producing investment projects such as hotels or factories.

7) There is a possibility of signing a more profitable contract.

8) Lower risk of inflation, labor shortage, and weather conditions if the project duration is shortened.

9) Improve the project cash flow.

Despite its significant impact on the total cost and duration of construction projects, quality was not considered by most reported research of traditional TCT. It was assumed uniform for all resource utilization options of each activity (Pollack-Johnson & Liberatore, 2006). As shown in Figure 1.4, different TCT curves for different quality levels illustrate that the curve of a higher quality level lies above and to the right of that for a lower quality level. Therefore, the quality performance of each execution option or construction method should be incorporated into the trade-off analysis. In other words, it is required to convert the traditional two-dimensional TCT into an advanced three dimensional time-cost-quality trade-off analysis (TCQT). The main purpose of TCQT analysis is to determine an optimal or near

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optimal trade-off among the total cost, time and quality of a considered project, which means to complete the project before a defined deadline, while its total cost is minimized and its overall quality is maximized.
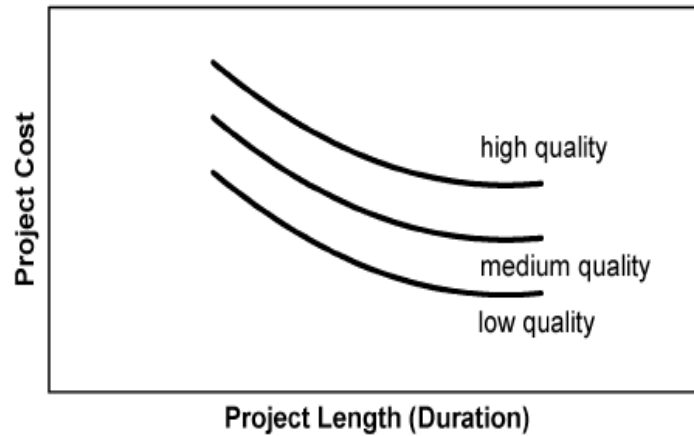
Figure 1.4: TCT for different quality levels (Pollack-Johnson & Liberatore, 2006)

1.2 Research Motivation

Despite the extensive research conducted about TCT and TCQT, there are motivations for further research on these topics. The following are instances of motivations to conduct this research:

- It is a challenging task to attain balance among multiple conflicting objectives of time, cost, and quality within a considered project. Obviously, the minimum total cost, minimum total duration, and maximum overall quality cannot be located at the same point. For instance, to reduce the duration of an activity, it is required to use additional resources, which results in additional direct costs. On the other hand, using fewer resources results in extended activities' durations, that will inevitably increase the project indirect costs. On the other hand, to improve the quality of an activity or a project, it is required to apply additional quality assurance and quality control procedures, by which the duration and cost of such an activity or a project may be increased.

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- The large search space associated with finding optimum or near optimum solutions for large-scale problems. If the number of activities is n and there are k execution options for each activity to choose from, then there are $(k)^n$ solution series (Pour et al., 2010). For instance, a project with twenty activities and three execution options for each activity has 3^{20} (3,486,784,401) possible combinations to complete its work.

- Estimates of cost, duration, and quality of activities within construction projects usually depend on the experience of planners, managers, or decision makers. In addition, these estimates could be affected by many unexpected factors such as weather, resource availability, or productivity. It is impractical to set precise values for performance of activities' execution options. Therefore, uncertainty associated with construction projects should be incorporated into the TCT and TCQT analysis.

- There is lack of a commonly accepted methodology to quantify and evaluate quality of construction activities or construction projects. It is needed to propose how to evaluate the quality of each activity, how to aggregate the quality all activities to determine the overall project quality, and how to estimate the quality change due to schedule optimization.

- Recent improvements in the field of optimization approaches such as evolutionary algorithms and the development of advanced optimization tools such as the Evolver Excel add in made it possible to overcome the existing limitations of traditional TCT and TCQT models and approaches.

1.3 Research Scope and Objectives

The main objective of this research is to study the TCT and TCQT approaches and techniques in order to develop innovative and practical optimization models that are appropriate for construction projects. The development of such models supports the efforts of

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construction firms and general contractors to improve projects' performance in terms of time, cost, and quality. The detailed research objectives are as follows:

- Investigating a practical approach for quantifying and evaluating the quality performance of execution options and the whole project.

- Studying the TCQT as a discrete optimization problem, which is more relevant to construction projects. For the discrete TCQT, each project's activity has different modes or options of execution and each mode has its corresponding time, cost and quality value respectively.

- Summarizing recent optimization approaches to propose an appropriate one for TCQT problems. It is required to propose a robust multi-objective optimization approach that is capable of effectively optimizing multiple conflicting objectives of time, cost, and quality within a considered project.

- Incorporating the uncertainty associated with the performance of execution options and the performance of the whole project regarding time, cost, and quality.

- Developing a robust, easy to use, Excel based TCQT models in order to generate execution scenarios that achieve the objectives of a considered project.

1.4 Research Methodology

In order to achieve the aforementioned objectives, the methodology is as follows:

- **An extensive literature review:** General overviews of schedule, cost, quality, and optimization are illustrated. The literature review of the latest research developments is then conducted in order to investigate and analyze relevant research studies and practices in both two-dimensional time-cost trade-off (TCT) analysis and three dimensional time-cost-quality trade-off (TCQT) analysis in order to identify their limitations and drawbacks.

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- **Development of three TCQT models:** Based on the literature review of potential improvements, three TCQT models are developed. The main purpose of these three models is to obtain an optimal or near optimal combination of construction options with the objective of simultaneously minimizing the total project duration, total cost, while maximizing its total quality. The three proposed models are developed and implemented in Microsoft Excel to benefit from the advanced optimization add-in tools and Excel features and capabilities.

- **Validation of the developed models:** The developed models are applied to simple case studies in order to illustrate their capabilities, validate their results, and demonstrate their efficiency. Results of the developed models are compared with results of the literature models. Three case studies are analyzed by the developed models as follows:

  o A case study to demonstrate the ability of the simplified model to obtain satisfactory results compared to those obtained by the literature.

  o A case study to illustrate the ability of the stochastic model to consider uncertainty associated with execution options and to study the stochastic trade-off among time, cost, and quality of the project.

  o A case study to demonstrate the ability of the advanced model to efficiently analyze TCT problems in addition to TCQT problems.

- **Conclusions:** A comprehensive analysis of the developed models and their results is conducted. Limitations and capabilities of the developed models are illustrated and their contributions and significance are discussed.

1.5 Thesis Organization

The reminder of this thesis report is organized as follows:

Chapter 2 presents general overviews of the topics related to the proposed research. These overviews are sub-categorized into four main sections as follows:

1) Schedule overview with the purpose of introducing commonly utilized scheduling techniques.

2) Cost overview with the purpose of identifying cost types and cost estimate procedures for construction projects.

3) Quality overview with the purpose of defining construction quality and investigating various quality evaluation approaches.

4) Optimization overview with the purpose of exploring and elaborating various optimization techniques so that most appropriate ones are incorporated into the proposed research.

Chapter 3 presents a comprehensive literature review that investigates available TCT and TCQT studies and models. The investigation includes a review of traditional and innovative approaches, methodologies, and tools for solving both TCT and TCQT problems in order to identify their strengths and weaknesses. This chapter is sub-categorized into four main sections as follows:

1) Deterministic time-cost trade-off analysis.

2) Stochastic time-cost trade-off analysis.

3) Deterministic time-cost-quality trade-off analysis.

4) Stochastic time-cost-quality trade-off analysis.

Weaknesses and limitations in addition to capabilities and strengths of those models are identified and discussed

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Chapter 4 presents models development and validation, by which three time-cost-quality models are developed as follows:

1) A simplified TCQ model.

2) A stochastic TCQ model.

3) An advanced TCQ model.

The main purpose of these models is to select an appropriate execution option for each activity within a considered project in order to complete the project by a planned deadline or with a minimum total duration, and to satisfy a desired quality level or maximum overall quality with an estimated or minimum total cost.

Chapter 5 summarizes the research, presents its contributions, and lists recommendations for future research.

Chapter II: General Overviews

2.1 Introduction

This chapter is sub-categorized into four main sections: (1) schedule overview with the purpose of introducing widely utilized scheduling techniques: (2) cost overview with the purpose of identifying cost types and cost estimate in construction projects; (3) quality overview with the purpose of defining construction quality and investigating various quality measurement approaches; and (4) optimization overview with the purpose of exploring and elaborating different optimization techniques so that most appropriate ones are incorporated into the proposed model.

2.2 Schedule Overview

Scheduling is an essential management tool in the construction industry. According to PMI (2008), project scheduling or project time management includes the processes required to manage timely completion of projects. These processes include:

1. Define activities, by which a project is divided into smaller actions using the work breakdown structure technique (WBS).

2. Sequence activities, by which relationships among activities are defined.

3. Estimate activity's resources, by which types and quantity of resources required to finish each activity are estimated.

4. Estimate activities' durations, by which work periods required to finish each activity using the estimated resources are estimated.

5. Develop schedule, by which sequences, relationships, resources, durations, and constraints are integrated to develop a project's schedule utilizing an appropriate scheduling technique.

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6. Control schedule, which is updating a project's progress and managing changes to its baseline schedule.

There are several methods and techniques, which are widely utilized in scheduling construction projects. The following are instances of such techniques:

2.2.1 Bar Chart

Gantt chart was independently adapted by Henry Gantt in 1917 to illustrate a project schedule (Hinze, 2004). It is a representation of project activities on a vertical column on the left-hand side of the chart, with a horizontal bar for each activity plotted against a timescale. Advantages and drawbacks of Gantt chart are summarized in Table 2.1.

Table 2.1: Advantages and drawbacks of Bar Chart method

Bar Chart (Gantt Chart)	
Advantages	Disadvantages
Widely used in the construction industry	Increased complexity for larger projects
Simplicity and ease of use	Relationships among activities are not obvious
Suitable for presentation to non-professional and top management	Difficulty of updating
Resources requirement could be linked with activities on the chart	Difficulty of critical paths identification

2.2.2 Critical Path Method

Critical path method (CPM) was developed in the late 1950s by Morgan R. Walker and James E. Kelley (Hinze, 2004). It is an efficient method for scheduling projects, calculating the shortest completion time for a project, activities' early and late start and finish times (ES, EF, LS, LF), activities' total and free floats (TF, ff), and identifying critical activities and path(s). CPM networks could be represented by Activity on Arrow diagrams (AOA), or Activity on Node diagrams (AON). AON, which may be referred to as Precedence Diagram Method (PDM), has more flexibility regarding activity relationships and more simplicity regarding computation efforts. In addition to finish-to-start (FS) relationships among

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activities available by AOA, PDM method allows the incorporation of three additional relationships among projects' activities, which are start-to-start (SS), finish-to-finish (FF), and start-to-finish(SF). Furthermore, times between activities, referred to as leads and lags, may be also applied.

Despite several capabilities and advantages of CPM method, it has some drawbacks as illustrated by Adeli and Karim (1997), Hinze (2004), and Hegazy and Menesi (2010). Table 2.2 summarizes those advantages and drawbacks.

Table 2.2: Advantages and drawbacks of CPM method

Critical Path Method (CPM)	
Advantages	Disadvantages
Widely used in the construction industry	Does not guarantee continuity of work
Displayed dependencies among the project activities	Not suitable for multiple-crew strategies
Multiple, equally critical paths could be defined	Progress of a project is hard to be monitored
Start and finish dates and float times for each activity could be determined	No difference in representation between repetitive and non-repetitive activities
Activities which can run parallel to each other could be evaluated	Difficult to take corrective actions for recovering delays

2.2.3 Program Evaluation and Review Technique

The program evaluation and review technique (PERT) is a statistical scheduling tool developed by the United States Navy in the late 1950s (Hegazy, 2002). It is utilized for planning and scheduling complex, uncertain, or innovative projects, when details and durations of all activities are not defined precisely. It is commonly used in conjunction with CPM by assigning three time estimates for each activity within a project: the optimistic time estimate (T_o); the most likely or normal time estimate (T_m); and the pessimistic time estimate (Tp). According to Hinze (2004) and Hegazy (2002), the expected time (Te) is computed as follows:

$$Te = (To + 4*Tm + Tp) / 6$$

Equation 2. 1

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Standard deviation and variance for each activity, a measure to describe the extent to which the actual duration is expected to vary from the computed expected time, is computed as follows:

$$S = (Tp\text{-}To)/6$$

Equation 2. 2

$$\text{Variance} = S^2$$

Equation 2. 3

Variance of a project is calculated as the sum of all variances on the critical path. The normal probability distribution is then used for calculating the project completion time with a desired probability. Advantages and limitations of PERT are summarized in Table 2.3.

Table 2.3: Advantages and drawbacks of PERT method

Program Evaluation and Review Technique (PERT)	
Advantages	Disadvantages
It is mathematically simple	It needs a higher degree of planning skill and greater amount of details
It provides a weighted estimate of the completion time	Time estimates are subjective
It provides a probability of completion before a given date	The three points formula or beta distribution is not valid for all activities

2.2.4 Critical Path Segments (CPS)

This critical path segments (CPS) scheduling technique was proposed by Hegazy and Menesi (2010) in order to avoid drawbacks associated with using the traditional CPM for decision support purposes. The main innovative features of the CPS technique are as follows:

1. Decomposing durations of each activity into separate time segments that add up to the total duration of such an activity.

2. Transforming complex non-finish to start relationships (i.e., start to start, finish to finish, and start to finish relationships) into simple equivalent finish to start relationships with zero lag as shown in Figure 2.1.

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3. Possibility of defining logical relationships among activities as production based in addition to traditional time based relationships.

4. New representation of activity progress by showing work progress in percentage on associated time segments. Work percentages could be obtained by averaging 100 % over a number of segments of the activity as shown in Figure 2.1.

5. Additional time segments are inserted to represent unscheduled events such as delays and the party who is responsible for them (i.e., contractor, owner, or neither party)
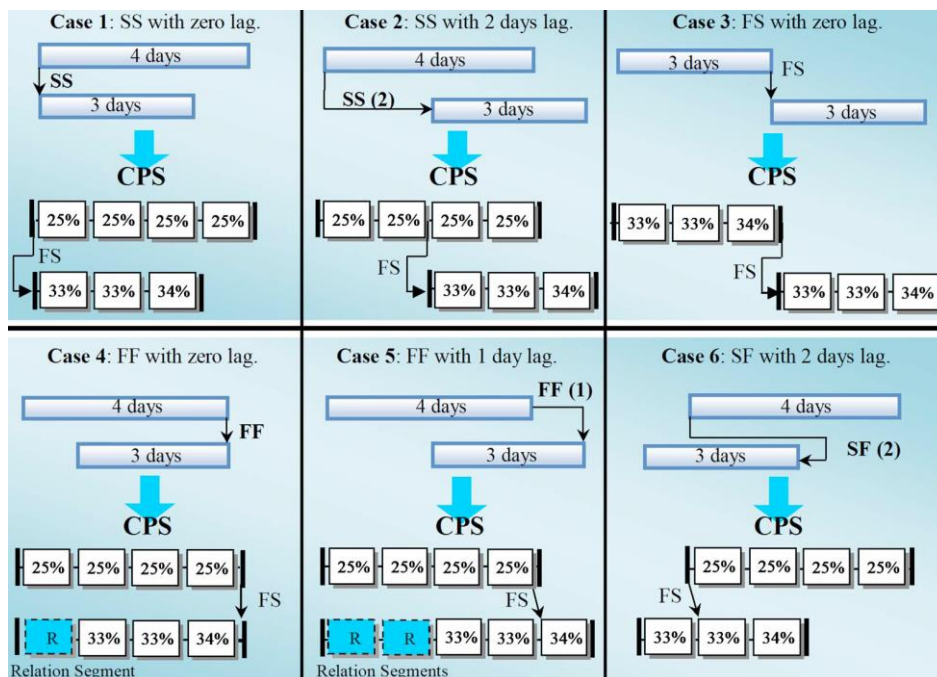
Figure 2.1: Sample CPS relationships transformation (Hegazy & Menesi, 2010)

6. Incorporating project constraints such as deadlines, resource limits, and total cost constraints, into the CPS analysis. This incorporation mechanism is powerful for scheduling in the planning stage and it is utilized to take corrective actions during the execution stage.

The advantages and disadvantages of the CPS method as illustrated by Hegazy and Menesi (2010) are summarized in Table 2.4.

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Table 2.4: Advantages and drawbacks of CPS method

Critical Path Segments	
Advantages	Disadvantages
Avoiding complex network relationships	Not popular for most planning and scheduling practitioners
Identifying all critical path fluctuations	Not applied in commercial scheduling software used in construction projects
Better allocation of limited resources	Converting activities into time segments , is not practical for large-scale construction projects
Better representation of activity progress	More suitable for research purposes rather than practical projects
Possible defining of relationships among activities as time based or production based	
Avoiding multiple calendar problems	
Accurate analysis of project delays since it is more advanced and detailed in documenting as built schedules	

2.3 Cost Overview

Cost is one of the three main attributes associated with executing an activity within a project, which are time or schedule, cost or price, and quality or performance. Cost of an activity or a process is generally determined by the cost of resources that are expended to complete such an activity. Utilized resources are usually categorized as material, labor, equipment, and sub-contractors in the construction industry (AACE International, 2004).

2.3.1 Types of Cost in Construction

Costs in construction projects are mainly classified into two types:

1. Direct costs: expenses of resources that are expended solely to perform work of an activity within a project. Direct costs for a project may include costs of materials, labor, equipment, and subcontractors. A project's total direct cost is equal to the sum of direct costs of all activities that make up the project (Que, 2002). Direct cost of an activity depends on site conditions, utilized resource productivity, and the

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construction method. Usually, total direct costs represent from 70 to 90 percent of total costs in construction projects (Hegazy, 2002).

2. Indirect costs: expenses of resources needed to support the execution and management of a project; however, they cannot be charged to a single activity. According to relation with time, they may be classified into two categories:

   - Time dependent: depends upon the project duration, i.e. the longer the duration, the higher the indirect cost. Electricity and other utilities, rent, and salaries are instances of such a type.

   - Time independent: does not depend upon the project duration. Taxes and insurance expenses are instance of such a type.

Indirect costs are of two categories; project overhead and general overhead. Project overhead costs are those costs that can be charged to a single project. Salaries of staff personnel, supplies, engineering tests, permits, consultants, and drawings are instances of project overhead costs. On the other hand, general overhead costs are a share of costs incurred at the general office of the company but not chargeable to a specific single project. Salaries, office rent, supplies, and costs incurred in operating all projects constructed by the company are instances of general overhead. Figure 2.2 summarizes different types of construction costs.
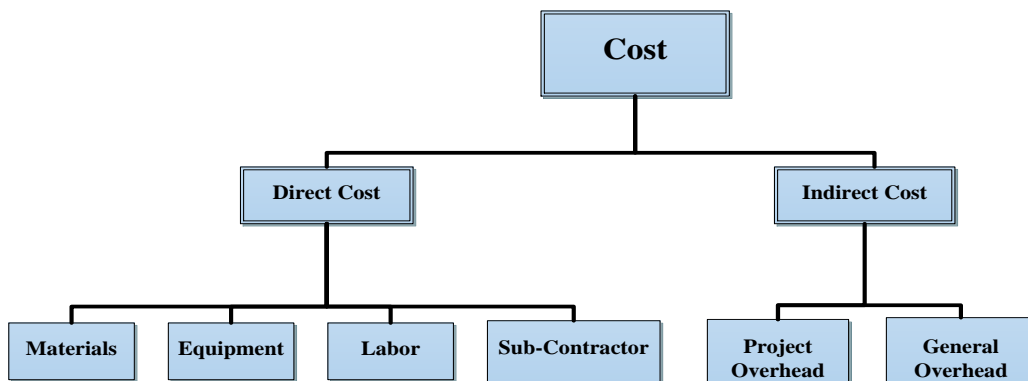
Figure 2.2: Types of cost in construction projects (Hegazy, 2002)

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Price is the cost at which a bid is submitted or an asset is bought. It is the summation of total costs, direct and indirect, and markup, as shown in Figure 2.3. Markup is divided into two parts, which are risk contingency and profit. Risk contingency is an added value to compensate for circumstances that may affect the project such as weather and soil conditions. Profit, which is considered the contactor's added fees, is a percentage that ranges from 0 to 20 percent of the total costs depending on the level of competition and need for winning the bid (Hegazy, 2002).
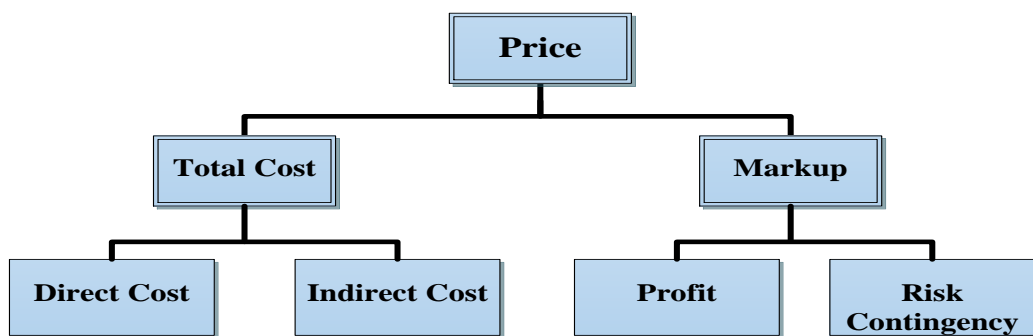
Figure 2.3: Price components (Hegazy, 2002)

For the purpose of this research, direct cost is of a paramount concern. According to Hegazy (2002), the steps needed to estimate the direct cost of a project's activities are as follows:

1. Analyze contract documents and site conditions;

2. Perform a detailed work breakdown structure for the project;

3. Take off the quantities of WBS elements;

4. Analyze quotes from suppliers and the subcontractor;

5. Estimate the resources' production rate;

6. Assess of the project schedule; and

7. Compile the direct cost.

2.4 Quality Overview

Quality in general is defined as "the degree to which a set of inherent characteristics of a product, system, or process fulfills requirements" (O'Braien, 1989). Quality in the construction industry can be defined as meeting the requirements of all parties that are involved in the construction process: the designer; the constructor; regulatory agencies; and the owner (Attalla et al., 2003).

2.4.1 Quality Management Processes

According to (PMI, 2008), quality management incorporates three main processes, which are defined as follows:

1. Quality planning, which is defined as "the process of identifying requirements and standards for the project and the product, and documenting how the project will demonstrate compliance" (PMI, 2008).

2. Quality assurance (QA), which can be defined as "the process of auditing the quality requirements and the results from quality control measurements to ensure appropriate quality standards and operational definitions are used" (PMI, 2008).

3. Quality control (QC), which can be defined as "the process of monitoring and recording results of executing the quality activities to assess performance and necessary changes" (PMI, 2008). With regard to the construction industry, QC is a group of procedures and steps to ensure that the final products, which are structures and buildings, are without any defaults or defects (Attalla et al., 2003).

2.4.2 Quality Measurement

Quality measurement is considered an extremely complicated process in the construction industry since it is unrealistic to quantify the concept. Quality measurement is a qualitative process so most techniques used to measure construction quality are approximate.

The analytic hierarchy process (AHP) has been extensively utilized to evaluate quality. This approach, developed by Saaty in 1977, was used as a decision-making method for prioritizing alternatives when multiple criteria must be considered (Pollack-Johnson & Liberatore, 2006). The main procedures of the AHP approach are as follows:

1. A considered decision problem is deconstructed into a hierarchy of sub-problems, each of which can be analyzed independently.

2. Pair-wise comparisons are conducted to measure the impact of items on one level of the hierarchy on the next level.

3. A numerical weight or priority is defined for each element of the hierarchy.

4. A weighted averaging approach is applied to combine the results across levels of the hierarchy to compute a final weight for the considered decision problem.

AHP is applied to evaluate the anticipated quality of an activity or a task based on available information about subcontractors, contractors, or methods of construction so that a measurable value for quality is determined. The quality values of all activities are then aggregated to estimate the overall quality of the project.

Based on the AHP, El-Rayes and Kandil (2005) developed a quality breakdown structure (QBS) for quantifying construction quality and measuring quality performance of highway construction projects. This QBS technique was utilized to predict quality performance of various resource utilization options based on their average historical performance in standardized quality tests, referred to as quality indicators. The results of quality tests in various indicators are transformed to a value that ranges from zero to 100% to represent quality performance in each indicator. Based on each of the activity's weight within a considered project, quality performance at activities' level is aggregated to provide an overall quality at the project's level. To estimate the overall quality performance at the project level, Equation 2.4 is applied:

$$\mathbf{Q} = \sum_{i=1}^{l} \mathbf{Wt_i} \sum_{k=1}^{K} \mathbf{Wt_{i,k}} * \mathbf{Q_{i,k}^n} \text{ (El-Rayes \& Kandil, 2005)}$$

<div align="right">**Equation 2. 4**</div>

Where Wt_i is the weight of activity (i) to represent its importance and contribution of its quality to the overall project quality. $Wt_{i,k}$ is the weight of the quality indicator (k) to indicate its relative importance to other indicators being used to measure the quality of this activity (i). $Q_{i,k}^n$ is the performance or result of the quality indicator (k) in activity (i) using resource utilization option (n). $Q_{i,k}^n$ represents the average historical performance in quality indicator (k) utilization option (n).

2.5 Optimization Overview

Generally, optimization is the process of finding the best available values of an objective function given a defined domain or optimization variables, and subjected to optimization constraints (Ng & Zhang, 2008). Optimization tries to find the best solution of a problem that has many alternative solutions. Most common optimization techniques utilized for TCT problems and TCQT problems are categorized as follows:

1. Heuristic Methods

2. Mathematical Methods

3. Evolutionary Algorithms

2.5.1 Heuristic Methods

Heuristic methods are non-computer approaches that rely on the rule of thumb of decision makers to find an optimal or near optimal solution (Zheng et al., 2004). Heuristic methods are divided into:

1. Serial heuristic: "in which processes are first prioritized and retain their values throughout the scheduling procedure" (Feng et al., 2000).

2. Parallel heuristic: "in which process priorities are updated each time a process is scheduled" (Feng et al., 2000).

Despite the simplicity, the ease of application, and the small computational efforts, there are difficulties and disadvantages associated with utilizing heuristic methods. For instance, they do not guarantee optimality, and they are effective only for linear relationships.

2.5.2 Mathematical Methods

Mathematical methods demonstrated computational efficiency, accuracy, and robustness compared to heuristic methods. They convert optimization problems into mathematical models containing objective functions, decision variables, solution domains, and constraints. Mathematical methods include linear programming, integer programming, and dynamic programming.

2.5.2.1 Linear Programming

Linear programming (LP) is a special case of mathematical optimization appropriate for problems whose requirements are represented by linear relationships. It assumes that the optimum solution can be obtained at any point.

2.5.2.2 Integer Programming

Integer programming (IP) is an optimization technique in which some or all of the variables must be an integer. It is appropriate for problems with both linear and discrete relationships. It requires excessive computational efforts, particularly for problems containing a large number of variables or a large searching space.

2.5.2.3 Dynamic Programming

Dynamic programming (DP) is a technique for optimizing complex problems by breaking them down into simpler sub-problems. It starts with a small part of the problem to find its

optimal solution; such a solution is then utilized to find an optimal solution for a larger part of the problem until the whole issue is solved (Ezeldin & Soliman, 2009). Dynamic programming is appropriate for networks that can be divided into series or parallel sub-networks. Despite its efficiency, complexity of formulation and lack of a general algorithm are disadvantages of the dynamic programming technique.

Generally, mathematical programming techniques cannot obtain optimal solutions for large-scale projects. They do not guarantee an optimum solution and may be trapped in a local optimal solution (Hegazy & Wassef, 2001). Furthermore, the process of formulating constraints and objective functions is prone to errors. They also cannot handle more than one objective.

2.5.3 Evolutionary Algorithms

Evolutionary algorithms (EA) are stochastic search methods that mimic the metaphor of natural biological evolution and the social behavior of the species (Elbeltagi et al., 2005). These algorithms were developed in order to find optimum or near optimum solutions for large-scale problems with a large search space. As shown in Figure 2.4, the most commonly used EA techniques are Memetic Algorithms (MA), Particle Swarm Optimization (PSO), Ant-Colony Optimization (ACO), Shuffled Frog Leaping Algorithms (SFL), and Genetic Algorithms (GA).
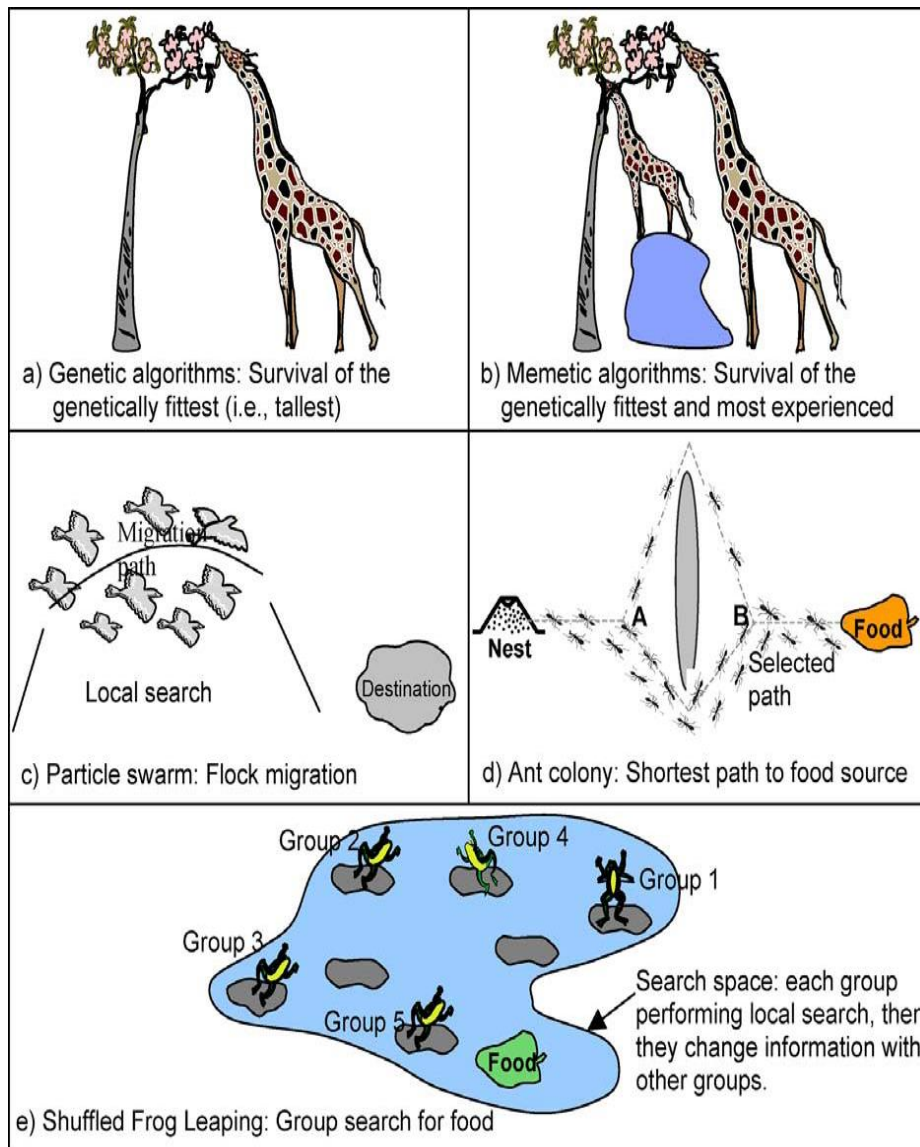
Figure 2.4: Natural evolutionary algorithms (Elbeltagi et al., 2005)

2.5.3.1 Genetic Algorithm

The genetic algorithm (GA) was first proposed by John Holland based on principles inspired by natural genetics (Deb, 2001). It is a computerized search method that was developed based on the principle of "the survival of the fittest" and the natural process of evolution through reproduction (Elbeltagi et al., 2005). As shown in Figure 2.5, the main phases and operators of GA are as follows:

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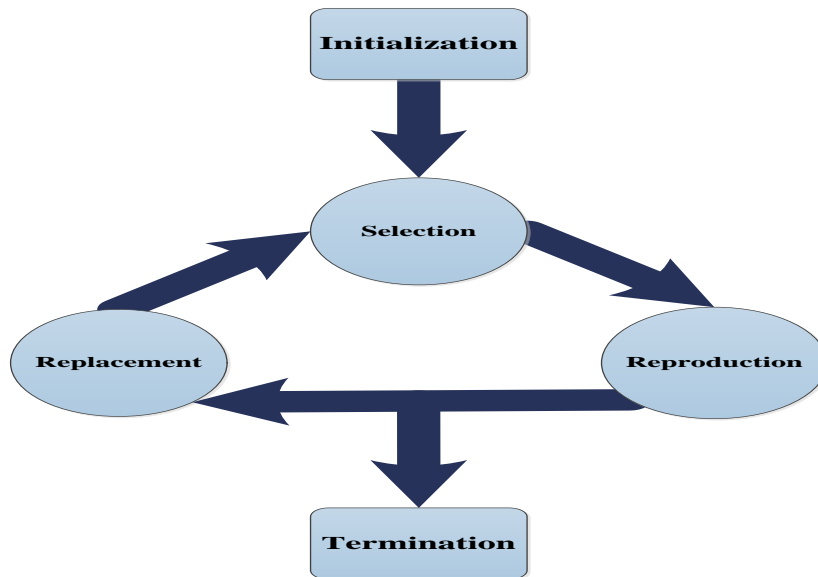
Figure 2.5: Main Phases of GA

- **Initialization**

  The GA works with a population of random individuals (chromosomes). The population is a set of individuals, each representing a possible solution for a given problem. Each individual or solution is represented by a chromosome or a set of genes. Population size (N_{pop}), which is the total number of solutions (individuals) in each generation, depends on the nature of the problem.

  Each chromosome is evaluated by assigning a fitness score. Fitness is an objective function used to evaluate individuals of a population based on the quality of solutions with regard to the required optimization objective. The overall fitness of the population usually improves from one generation to another, which tends to produce better individuals.

- **Selection**

  Selection is to select individuals randomly from a population for recombination to generate a new offspring. For the purpose of the proposed research, three commonly used techniques of selection are discussed as follows:

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1. **Proportional selection**, referred to as roulette wheel, is usually utilized as a selection mechanism to ensure that the less fit individuals would be rejected, and more fit individuals would be selected (Zheng et al., 2005). Typical roulette wheel procedures as described by Deb (2001) are as follows :

   - Sum of fitness function values of all individuals is calculated;

   - Relative fitness for each individual is calculated (relative fitness of (i) = fitness (i)/ sum of fitness values).

   - Cumulative fitness, cumulative distribution function of selection probability, is calculated (cumulative fitness (0) = relative fitness of (0) & total fitness (i) = total fitness (i-1) + relative fitness (i));

   - A random variable r within (0,1) is generated.

   - If total fitness (j-1) ≤ r < total fitness (j), individual j is selected for a new parental generation.

2. **Tournament selection** involves selecting a random subset of (k) solutions from the original population and then the best solution, the one with the best fitness, out of this subset is selected. The winner of each tournament is selected for crossover. Binary tournament selection (k = 2) is most common (Deb, 2001). Typical procedures of tournament selection operation are described in Figure 2.6.

3. **Truncation Selection** involves selecting top N candidate solutions from the population, based on the value of the objective function. Truncation selection is not often used in practice since it is less sophisticated than many other selection methods, and it traps the optimization in local optimal solutions (Deb, 2001).

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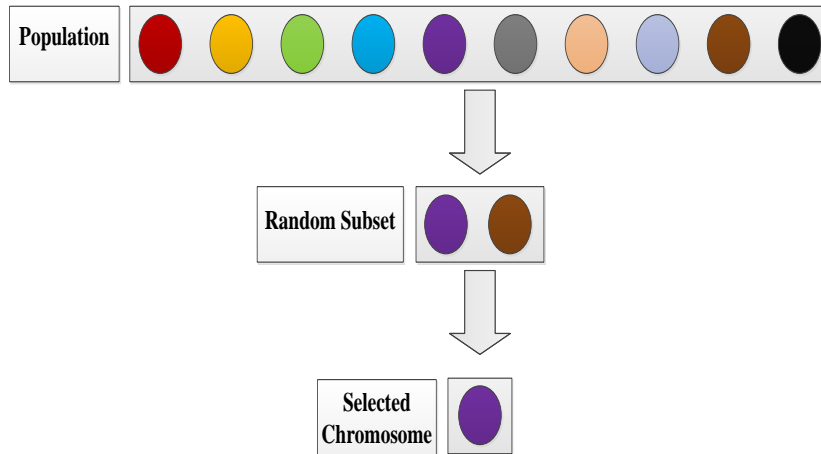
Figure 2.6: Tournament selection (Deb, 2001)

- **Reproduction**

The objective of reproduction is to process selected parent chromosomes to reproduce offspring or child chromosomes that share features with parents but are new in some way. Crossover, mutation, and adaption are three various GA operators commonly utilized for reproduction.

Crossover is a reproduction process, by which two parents are combined to produce two child individuals. It is considered a stochastic operator that allows information exchange between chromosomes. There are three various types of crossover, which are single point, two points, and uniform crossover. For a single point crossover, one random crossing point is selected, and all genes are then exchanged after that point. For the two points' crossover, two random crossing points are selected, and all genes between them are then exchanged. For a uniform crossover, a fixed mixing ratio between two parents is used so that every gene may be exchanged with a probability of such a ratio. Figure 2.7 clarifies differences among the three types of crossover.

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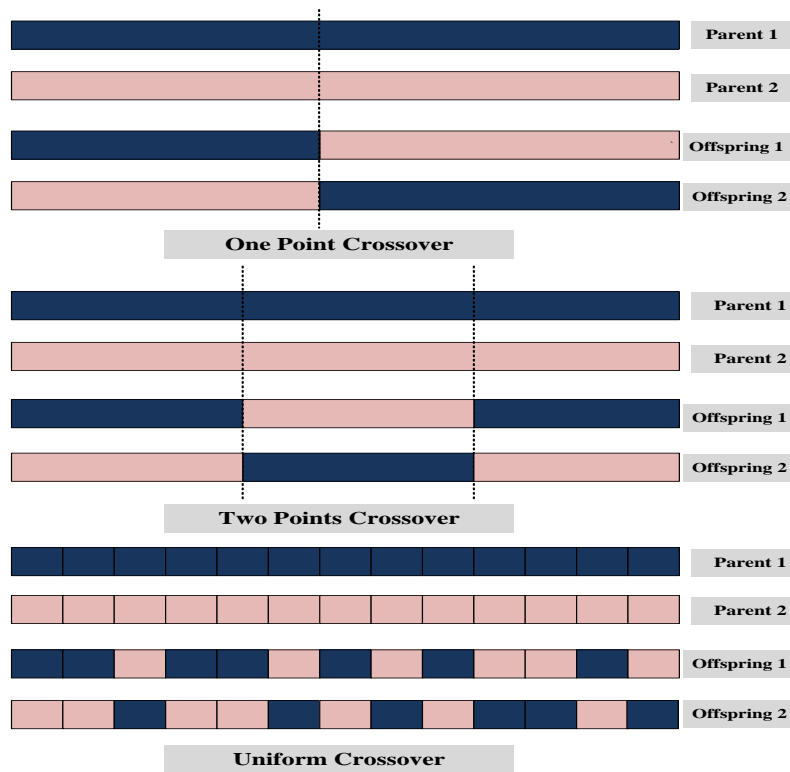
Figure 2.7: Types of crossover in GA (Al-Tabtabai & Alex, 1999)

Mutation is random modifications to maintain diversity within a population in order to avoid premature convergence (Al-Tabtabai & Alex, 1999). Mutation involves random change of one or more genes of a selected chromosome as shown in Figure 2.8. A random variable (z) within (0,1) is generated for each chromosome and each gene in a population. If $z < P_{mutation}$, such a gene is subjected to mutation. P_m value usualy ranges normally within 0.001- 0.05 (Li & Love, 1997).
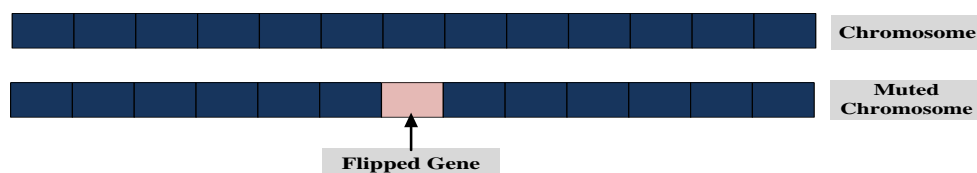
Figure 2.8: Mutation in GA (Al-Tabtabai & Alex, 1999)

Adaption is a random change to the value or order of genes but it retains only improved values. Thus, it is considered a wise mutation that helps to accelerate the search for the optimum solution (Marzouk & Moselhi, 2002)

- **Replacement**

    The main objective of replacement is to incorporate offspring solutions with better fitness instead of the weakest solutions in a population, while keeping the population size constant. Elitist replacement is a replacement approach that preserves best-found solutions for subsequent generations.

- **Termination**

    The evolution process of GA, which means selection, crossover/mutation, and replacement, stops when:

    1. A time limit is reached.

    2. A specified maximum number of generations is reached.

    3. An acceptable error level is achieved which means no improvement in solution.

    4. The highest-ranking solution is obtained.

Advantages and disadvantages of GA are summarized in Table 2.5.

Table 2.5 : Advantages and disadvantages of GA

Genetic Algorithms	
Advantages	Disadvantages
Effective for searching optimal solutions under uncertainties	Excessive computational efforts
Appropriate for problems with multiple objectives	Sophisticated computerized processes are needed
Widely used for engineering and construction management optimization problems	Excessive processing time for large-scale problems
Capable of searching multiple areas simultaneously within a single run	Tendency to converge towards a local optima in some problems
Acceptable balance between exploration and exploitation during the search process	Stop criterion is not clear in every problem

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2.5.3.2 Memetic Algorithm

Memetic algorithm (MA) was proposed by Pablo Moscato in 1989 to simulate the process of Cultural Revolution (Huimin & Zhuofu, 2009). Chromosomes are allowed to gain experience through a local search before they are involved in the evolutionary process. In other words, local search is conducted to obtain a population of local optimum solutions, and then crossover and mutation processes are applied. The main difference between GA and MA is that GA tries to simulate biological evolution where individuals cannot choose, modify and improve their own genes in its natural process, whereas MA tries to mimic cultural evolution where individuals can intentionally acquire, modify, and improve their memes (Huimin & Zhuofu, 2009).

2.5.3.3 Particle Swarm Optimization

The particle swarm optimization (PSO) technique was developed by Eberhard and Kennedy in 1995 (Rahimi & Iranmanesh, 2008) . It is inspired by the social behavior of a flock of migrating birds trying to reach an unknown destination. Each member in a flock of birds determines its velocity based on its personal experience as well as information gained through interaction with other members of the flock. Thus, the birds in the population only evolve their social behavior and accordingly their movement towards a destination (Elbeltagi et al., 2005). The optimization process in PSO includes local search, where birds use intelligence to learn from their own experience, and global search, where birds use social interaction to learn from the experience of other birds in the flock (Elbeltagi et al., 2005). Exploration, which means the ability to check different regions of the space to find the optimum, and exploitation, which means the ability to converge the search promising regions to locate the optimum, should be combined to obtain effective solutions (Bingol & Polat, 2015). Easy calculations and fast convergence are considered instances of PSO advantages.

However, difficulties in maintaining diversity and tendency to be trapped in local optimal solutions are among its disadvantages (Zhang et al., 2014)

2.5.3.4 Ant-Colony Optimization

The ant colony optimization technique (ACO) was first proposed by Colorniin in 1991 (Ng & Zhang, 2008). It is a metaheuristic approach for deriving approximate solutions for computationally sophisticated problems. ACO was developed based on the fact that ants can find the shortest way to food and simulate the use of pheromone trails, which ants deposit whenever they travel as a form of indirect communication (Elbeltagi et al., 2005). Artificial ants however can memorize their paths and include heuristic information for the next node to go. ACO is considered among the best for handling optimization problems in terms of solution quality and processing time (Elbeltagi et al., 2005).

2.5.3.5 Shuffled Frog Leaping Algorithms

The shuffled frog leaping algorithm (SFL), inspired by the process that frogs hunt for food in nature, simulates a set of frogs (solutions) that is partitioned into subsets referred to as memeplexes. Different memeplexes are considered as different cultures of frogs, where each performs a local search. Within each memeplex, individual frogs hold ideas and evolve through a process of memetic evolution. After a defined number of memetic evolutionary steps, ideas are shared among memeplexes in a shuffling process (Elbeltagi et al., 2005).

2.5.4 Multi Objectives Optimization Approaches

Multi objectives optimization (MOO) deals with problems that have more than one objective function which are to be maximized or minimized. Three MOO approaches, which are commonly used for engineering and construction optimization problems, are illustrated hereafter.

2.5.4.1 Goal Programming

Goal programming (GP) was first introduced by Charnes et al. in 1955 (Deb, 2001). It is considered an extension of The LP method, which seeks to simultaneously handle multiple conflicting objectives. Schematic procedures of GP are as follows:

1. An objective function for each objective is formulated

2. A specific numeric target for each objective is set.

3. A weight for each objective is identified to describe its relative importance with respect to other objectives.

4. A combined objective function is formulated to find a solution that minimizes the weighted sum of deviations of these objective functions from their respective numeric target. The objective function is formulated as follow:

$$\text{Min} \sum_{k=1}^{n} \text{W1 d1} + \text{W2 d2} + \cdots \ldots \text{Wn dn} \quad \text{(Deb, 2001)}$$

Equation 2. 5

Where W_1 to W_n are weights corresponding to objective goals and d_1 to d_n are deviations from target goals for each objective. Advantages and disadvantages of the GP are summarized in Table 2.6.

Table 2.6: Advantages and Disadvantages of GP

Goal Programming	
Advantages	Disadvantages
Simplicity, flexibility, and ease of use	Assumptions of weights of objectives are not subjective
Suitable for single and multi-objectives optimization	Difficulty of determining a target value for each objective in some problems
Capability of handling large numbers of variables, constraints and objectives	Tendency for obtaining inefficient solutions (alternative better optimum solutions may be available)

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2.5.4.2 Pareto Optimum

The Pareto optimum or Pareto front was formulated by the Italian economist Vilfredo Pareto (Zheng et al., 2005). Using the concept of dominance, it is commonly used to solve MOO problems, where it is not possible to have a single solution that simultaneously optimizes all objectives. According to the Pareto optimum, a solution (I) dominates another solution (II) if solution (I) is no worse than solution (II) in all objectives, and solution (I) is better than solution (II) in one objective at least (Deb, 2001). For the above mentioned conditions, it is also said that while solution (II) is dominated by solution (I), solution (I) is not dominated by the solution (II), or the solution (I) is non-inferior to solution (II). A Pareto front or Pareto set could be defined as a set of solutions that are not dominated by any member of the entire feasible search space. Therefore, solutions are chosen as optimal if no objective can be improved without deteriorating the performance of at least one other objective (Zheng et al., 2005). The Pareto frontier is a plot of the entire Pareto set in a design objective space. For MOO problems, a Pareto front is established to provide a set of non-dominated solutions, instead of an individual optimum one, for the final selection by decision makers. Since none of the Pareto set solutions is absolutely better than the other non-dominated solutions, all of them are equally acceptable as regards the satisfaction of all the objectives.

There are three approaches to finding the non-dominated set from a given search space or a population of solutions as illustrated by Deb (2001):

- Approach 1: a slow approach that compares each solution with every other solution in the population to check its dominance status. If a solution (i) is dominated by another solution in the population, it cannot belong to the non-dominated set. However, if no solution dominates solution (i), it is a member of the non-dominated set.

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- Approach 2: also called the continuously updated approach in which the first solution of the population (P) is assumed a non-dominated solution and moved to an empty set (p'). Each solution in (P) is then compared with members of (p') to check its dominance status. If a solution (i) dominates any member of (p') that dominated solution is removed from (p'). If a solution (i) is dominated by any member of (p'), the solution (i) cannot belong to the non-dominated set and is ignored. If a solution (i) is not dominated by any member of (p'), it is a member of the non-dominated set and it is moved to (p').

- Approach 3: also called Kung et al.'s efficient method (Deb, 2001). It sorts the population according to the first objective function in a descending order. The population is then halved to top population (T) and bottom population (B). Solutions of (B) are checked for dominance with the top population (T). Solutions of (B) that are not dominated by any solution of (T) are combined with the top population (T), creating a merged set (M). Merging and dominance check processes are continued in a bottom up technique to return (M) as the output Pareto front.

2.5.4.3 Non-dominated Sorting Genetic Algorithm

Non Dominated Sorting Genetic Algorithm (NSGA-II) is a hybrid of non-dominated sorting of Pareto front and genetic algorithm techniques. Non-dominated sorting of a population is classifying solutions into a number of mutually exclusive equivalent non-dominated sets. Such non-dominated sets are sorted in an ascending order, where the best non-dominated solutions are of level 1. Deb (2001) and Deb et al. (2002) suggested an innovative, fast technique to identify an overall non-dominated sorting of a population with less computational complexity. Typical procedures of that technique are as follows:

1. For each solution (i) in a considered population, two entities are calculated, which are domination count (n_i) and dominated set (S_i). (n_i) is the number of solutions

which dominate a solution (i); however (S_i) is a set of solutions dominated by a solution (i).

2. For each solution (i) with a domination count (n_i) = zero, which are solutions of the first non-dominated front, the domination count of each member (j) of its dominated set (S_i) is reduced by 1.

3. If the domination count of any member (j) becomes zero, it is put in another set (p'). After all dominated sets (S_i) for each (i) with (n_i) = zero are modified and members (j) with modified (n_i) of zero are put in (p'), the set (p') represent the second non-dominated front.

4. These processes are continued so that all solutions of the whole population are classified and sorted.

An elite preservation strategy and an explicit diversity mechanism were incorporated to the traditional GA procedures and operators (Deb, 2001). Schematic procedures of that approach, as shown in Figure 2.9, are as follows:

1. The offspring population Q_t is created from the parent population P_t utilizing traditional genetic algorithms' operators.

2. The offspring population is then added to the parent population in order to form a new combined population R_t of size 2N.

3. A non-dominated sorting is then applied to sort the entire combined population R_t, which allows a global non-domination check among parent and child solutions (Deb, 2001).

4. Crowding distance, which is an estimate of the density of solutions surrounding a particular solution (i) in the population, is calculated. It is assumed to be the average distance of two solutions on either sides of solution (i), of its front, along each of the objectives. Crowding distance is calculated by Equation 2.6 as follows:

$$\mathbf{dI_j^m} = \mathbf{dI_j^m} + \{[\ \mathbf{f_m^{I_{(j+1)}^m}} - \mathbf{f_m^{I_{(j-1)}^m}}\ ] / [\ \mathbf{f_m^{max}} - \mathbf{f_m^{min}}]\}\ \ \text{(Deb, 2001)}$$

Equation 2. 6

Where $f_m^{I_{(j-1)}^m}$ and $f_m^{I_{(j+1)}^m}$ are objective function values for two neighboring solutions on either side of solution (i), while f_m^{max} and f_m^{min} are the population maximum and minimum values of the mth objective function.

5. To form a new parent population of size N for a next generation Pt+1, crowded tournament selection operator is applied. Solutions with a better Pareto non-domination rank are selected. To break ties among solutions with same Pareto rank, solutions with a less crowded area or a larger crowding distance are selected.
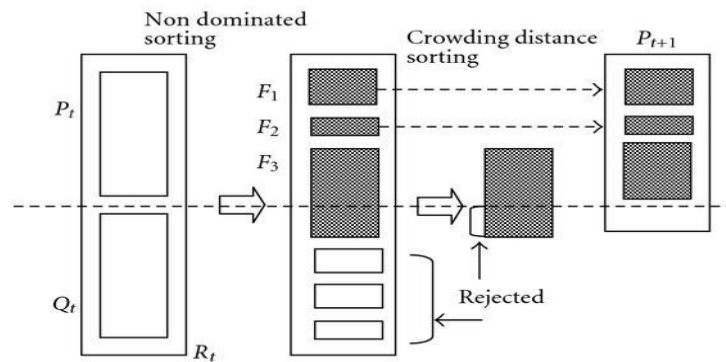
Figure 2.9: NSGA-II methodology (Deb, 2001)

Table 2.7 summarizes advantages and disadvantages of the NSGAII.

Table 2.7: Advantages and disadvantages of NSGAII

Elitist Non-dominated Sorting Genetic Algorithm (NSGA II)	
Advantages	Disadvantages
Global non-domination check among offspring and parent solutions	The non-dominated sorting needs to be performed on a population of size 2N instead of N
Diversity preserving mechanism	Long processing time
Better distribution of solution	Computational complexity for large population size problems
No loss of good solutions once they have been found	Not effective for Problems with a large number of objectives
Better convergence near the true Pareto-optimal	

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2.6 Summary

A review of four distinct sections has been discussed. The first section was dedicated to schedule and time management. Four methods and techniques of scheduling have been discussed, which are bar chart, CPM, PERT, and CPS. Procedures, advantages, and disadvantages of each method have been included.

The second section provided a cost overview. Types of cost in construction have been classified and described and cost estimate procedures have been illustrated.

The third section was dedicated to quality. Quality definitions and quality management processes have been discussed. The analytic hierarchy process was introduced as an effective quality measurement approach.

The fourth section provided an overview of existing optimization techniques. As shown in Figure 2.10, three main categories of optimization techniques have been discussed, which are heuristic methods, mathematical methods, and evolutionary algorithms. EA techniques are preferable and commonly used because they can deal with more than one objective, easily achieve diverse solutions, and they are more effective when applied to large-scale problems. Amongst various EA techniques, GA has been extensively utilized for optimization problems in general and construction management problems in particular. Multi-objectives optimization approaches have been also reviewed. Three approaches of MOO techniques have been discussed, which are goal programming, Pareto optimum, and non-dominated sorting genetic algorithm. NSGA-II has demonstrated to be one of the most robust algorithms for MOO problems.
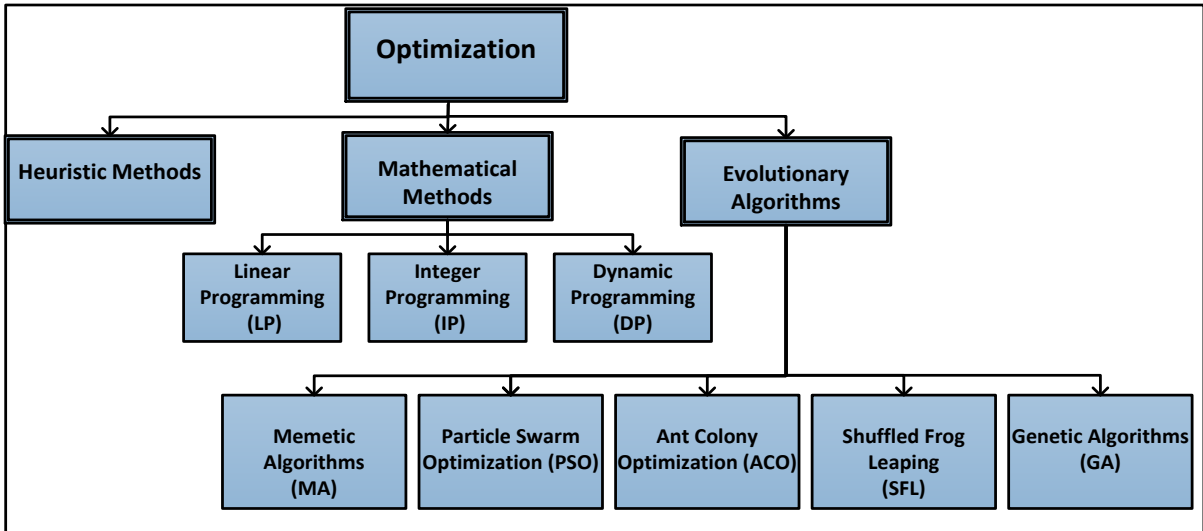
Figure 2.10: Reviewed optimization techniques

Chapter III: Literature Review

3.1 Introduction

An extensive literature review is conducted to establish a distinct starting point for the proposed research. The main purpose of the literature review is to investigate and analyze relevant research studies and practices in both two-dimensional time-cost trade-off (TCT) analysis and three dimensional time-cost-quality trade-off (TCQT) analysis. The investigation includes a review of traditional and innovative approaches for solving TCT and TCQT problems. This literature review focused on methodologies, models development, and optimization techniques in order to ensure that the most appropriate ones are incorporated into the proposed research. Furthermore, strengths and weaknesses of the reviewed research are mentioned.

The reviewed literature is organized in four main sections: (1) deterministic time-cost trade-off analysis; (2) stochastic time-cost trade-off analysis; (3) deterministic time-cost-quality trade-off analysis; and (4) stochastic time-cost-quality trade-off analysis.

3.2 Deterministic Time Cost Trade-Off

The time and cost of an activity or a project are interrelated and have impacts on each other. Usually, the direct cost of an activity increases when its duration is reduced. There is a relationship between the direct cost and duration to complete an activity within a project. Such relationship has various functions as shown in Figure 3.1 introduced by Yang (2005). It could be: (a) piecewise linear; (b) convex; (c) concave; (d) a combination of convex and concave; and (e) discrete. The discrete time-cost relationships are preferred for two main reasons: (1) it is more relevant to practical construction projects; and (2) it is appropriate for modeling any general time-cost relationship (Tareghian & Taheri, 2007).
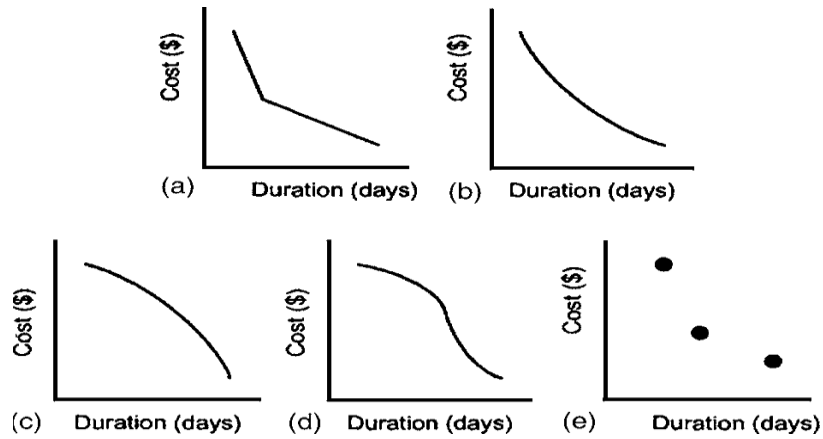
Figure 3.1: Types of time cost relationships (Yang, 2005)

As shown in Figure 3.2, when a project's duration is compressed, an increase in its direct costs occurs, in addition to a decrease in its indirect costs as a function of the project duration. The objective of TCT is to attain a balance between total cost and total duration of projects. By such a balance, the duration of some activities should be reduced by utilizing high productive resources or alternative construction methods in order to minimize the project's duration, while on the other hand, other activities could be executed with less expensive resources and a longer duration so that the project total cost is minimized. TCT analysis involves selecting activities that could be relaxed to bring down the project cost, and activities that could be accelerated to shorten the project duration.
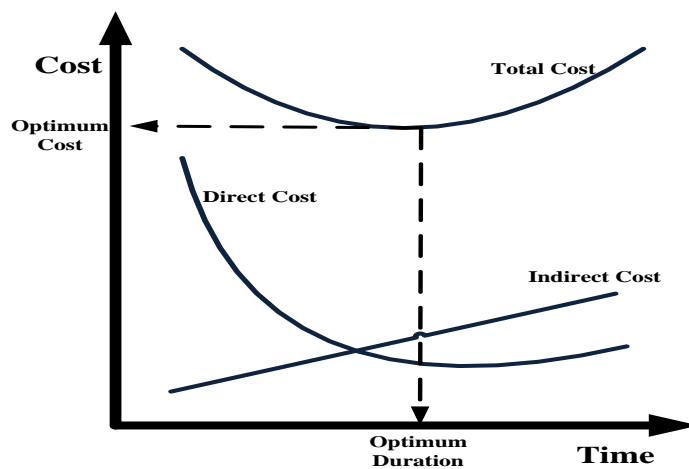
Figure 3.2: Project time-cost relationship (Hegazy, 2002)

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Liu et al. (1995) utilized a hybrid of linear Programming (LP) and integer programming (IP) for the TCT problem. LP was utilized to reach a lower bound of the trade-off curve and IP was then applied to obtain an exact solution. The objective function of the LP model is to minimize the total cost of the project, subject to two sets of constraints. The first set is related to precedence relationships of the network and the second set is related to the convex hull or cost slope of each activity. Time-cost curves for activities were assumed linear and continuous with integer durations. Optimal solutions were obtained using LP software such as *Lindo*. The IP was then applied to find optimal solutions. The objective function of the IP model is to minimize the total project cost subject to two sets of constraints. The first set of constraints is related to precedence relationships between activities and the second is used to make sure that only one option is selected as an optimal solution for each activity. Optimal solutions were obtained using IP software like *Gamas* or *Excel Solver*. This approach as proposed by Liu et al. (1995) has some drawbacks. For instance, linearity of relationships between the cost and duration of activities was assumed, which is not practical for most construction projects. Formulating the equations of objective functions and constraints is time consuming, and prone to errors. In addition, the approach requires excessive computational efforts for large-scale projects.

Feng et al. (1997) proposed a GA based technique for TCT optimization. Pareto front was utilized to obtain a non-dominated set of solutions having least objective conflicts. A convex hull was then applied to enclose all members of the population from below. For each individual within a generation, the closer to the convex hull, the better the fit. This results in moving new populations toward the convex hull. As shown in Figure 3.3, the solution is found when the convex hull can no longer move closer to the coordinate axes. A computer model was developed to execute the algorithm efficiently. Results of a case study that was analyzed by the proposed model demonstrated its effectiveness. In addition, discrete

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relationships between time and cost of activities were considered, which is more appropriate for construction projects. Utilizing the Pareto front with convex hull approach improved the efficiency of the algorithm by searching only a small fraction of the total searching space. On the other hand, the model was not applied to a construction project with a large number of activities. In addition, data entry would be time consuming and prone to errors for large-scale projects.
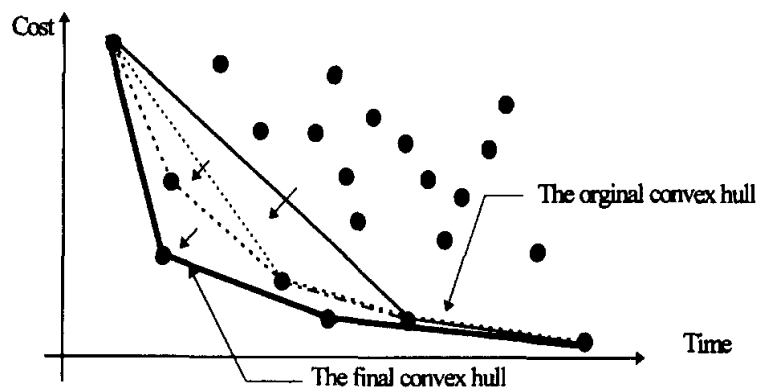
Figure 3. 3: The convex hull approach (Feng et al., 1997)

Li and Love (1997) proposed some modifications to the traditional GA in order to reduce the computational time and increase the reliability of results. The objective of the proposed approach was to minimize total costs incurred by speeding up some activities in order to shorten the total duration of a project to a targeted limit. Two additional operations, improved crossover and improved mutation, were incorporated to the basic GA's operations in order to ensure that offspring chromosomes are still feasible solutions with regard to the objective function and constraints. Improved crossover is calculating the difference between the required expected total reduced time and the total reduced time in the offspring then distributing the difference over the genes. Improved mutation is changing the value of a gene at the symmetric position of the gene changed by ordinary mutation. Compared to the traditional GA, better results with less number of generations were obtained by the proposed approach when applied to a case study. Despite efficiency of the proposed approach, linear relationships between cost and duration of the activities were assumed, which is not relevant

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to all activities in construction projects. In addition, the optimization process was only applied to critical activates, which is not accurate since accelerating activities' on the critical path may result in creating other critical paths. Another drawback is that the crashed times were treated as continuous variable, which results in small fractional durations. Such durations are impractical since the minimum time fraction is usually a half day in construction projects.

Sipos (1998) utilized both LP and IP methods in TCT analysis. The LP method was utilized to compute the cost slope of activities, which is defined as the rate of increase in direct cost of an activity for a required decrease in its duration.

$$\textbf{Cost slope} = \frac{\textbf{crash cost} - \textbf{normal cost}}{\textbf{normal time} - \textbf{crash time}} \quad \text{(Sipos, 1998)}$$

Equation 3. 1

Where crash cost is the estimated cost of doing the activity work in an accelerated rate and normal cost is the estimated cost of doing the work in a normal rate. Normal time is the estimated normal activity duration and crash time is the estimated accelerated time to carry out the activity work. The cost slope was computed for all critical activities. Critical activities with minimum cost slope were then selected to be crashed. Reducing durations of critical activities would be continued until no crash time on the critical path was available or a required deadline was achieved. The purchase time method (P.T.M) was then utilized as an example for integer models, which is suitable for discrete time cost relationships. The input data was the duration and associated cost for several options for completing the work of an activity. Then critical activities were determined to select an option that would reduce the project duration with minimum direct cost. The indirect cost for each trial was calculated and summed with direct costs so that the optimum project schedule was determined based on minimum total costs. This step was repeated until no more options for time reduction of critical activities were available. This technique proposed by Sipos (1998) has some

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drawbacks and weaknesses. For instance, it was not obvious if the schedule and cost calculations were determined manually or by computer software. In addition, it would be time consuming and complicated to use this approach for large-scale construction projects.

Hegazy and Ayed (1999) developed a simplified Excel-based TCT model. The objective of this model was to minimize the total project cost subject to a deadline duration constraint. The decision variables for such a model were the method index representing a resource utilization option to execute the work of each activity within a project. Gene-Hunter software, which is a Microsoft Excel add in tool using the GA approach, was utilized as an optimization tool. An illustrative example was analyzed using the model in order to illustrate its capabilities and demonstrate its efficiency. Ease of use and simplicity are considered the most innovative advantage for this model developed by Hegazy and Ayed (1999). In addition, the model considered several fundamental issues in construction projects such as indirect cost, delay penalty, and early completion incentive. On the other hand, it is complex to use this model for construction projects with a large number of activities, execution options, and different types of dependency relationships among activities.

Hegazy and Ersahin (2001) developed a simplified Excel-based model called *overall schedule optimization*. The objective of this model was to minimize the total project cost considering time, cost, and resources constraints. The Evolver software, which is a Microsoft Excel add in tool using the GA approach, was utilized as an optimization tool. Results of the model when applied to an illustrative case study demonstrated its efficiency. This model is easy to be used, and does not require specific training. In addition, resource allocation, resource leveling, cash flow analyses, schedule optimization, and TCT analysis were incorporated into the model. Furthermore, this model also allowed for what if analysis with regard to time, cost, and construction method of the project's activities.

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Que (2002) proposed a GA-based TCT model utilizing the *Primavera Project Planner* (P3) software as a scheduling tool. Numerous capabilities and advantages associated with the utilization of P3 were acquired. On the other hand, this model has some weaknesses and drawbacks. For instance, the length of the chromosome string is dependent on the size of the network, which affects the performance of the GA for large-scale projects with a large number of activities. The chromosome was assumed a linear string; however, the network is not because of the precedence relationships. The GA representation only included the duration of the activities, although their start times and resources utilization were not considered. The indirect cost of the project was not also incorporated by the model. Furthermore, it was not illustrated if the user has to enter genes' values and activities' durations to P3 manually for each generation either there is an automated link between P3 and the optimization software.

Zheng et al. (2004) proposed a GA based approach for TCT analysis, referred to as MAWA. The main purpose of this approach was to assist decision-makers to obtain optimal projects' total duration and total cost. An adaptive weight approach to assign weights to each objective was introduced in order to decrease the need for decision makers' interaction. For TCT problems, there are two conflicting objectives, which are minimizing the total project cost and duration. According to Zheng et al. (2004), the adaptive weights assigned for those two objectives were formulated as follows:

- For $Z_c^{Max} \neq Z_c^{Min}$ and $Z_t^{Max} \neq Z_t^{Min}$

$$\upsilon_c = Z_c^{Min} / (Z_c^{Max} - Z_c^{Min})$$

Equation 3. 2

$$\upsilon_t = Z_t^{Min} / (Z_t^{Max} - Z_t^{Min})$$

Equation 3. 3

$$\upsilon = \upsilon_c + \upsilon_t, \ Wc = \upsilon_c / \upsilon \ \text{and} \ Wt = \upsilon_t / \upsilon$$

Equation 3. 4

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- For $Z_c^{Max} = Z_c^{Min}$ and $Z_t^{Max} = Z_t^{Min}$

$$W_c = W_t = 0.5$$

- For $Z_c^{Max} \neq Z_c^{Min}$ and $Z_t^{Max} = Z_t^{Min}$

$$W_c = 0.1 \text{ and } W_t = 0.9$$

- For $Z_c^{Max} = Z_c^{Min}$ and $Z_t^{Max} \neq Z_t^{Min}$

$$W_C = 0.9 \text{ and } W_t = 0.1$$

Where Z_c^{Max} and Z_t^{Max} are maximum values of the objective of total cost and time in the current population, respectively. Z_c^{Min} and Z_t^{Min} are minimum values of the objective of total cost and time in the current population, respectively. W_c and Wt are the adaptive weights for total cost and time.

The fitness function of this model is:

$$F(X) = W_t \; \frac{Z_t^{max} - Z_t + \gamma}{Z_t^{max} - Z_t^{min} + \gamma} + Wc \; \frac{Z_c^{max} - Z_c + \gamma}{Z_c^{max} - Z_c^{min} + \gamma} \quad \text{(Zheng et al., 2004)}$$

Where X is the sequence number of a candidate solution within the current generation. Z_c and Z_t are the total cost and time of the Xth solution in the current population. γ is a small random number between 0 and 1.

As shown in Figure (3.4), all Pareto solutions lie within the space Z^-, and the adaptive moving line gradually approaches to the ideal point, when Z^+ and Z^- are renewed along the evolutionary process. Therefore, in each generation, there are new values for W_c, W_t, Z_c^{Max}, Z_c^{Min}, Z_t^{Max}, and Z_t^{Min} till best solutions are obtained. This model is efficient and effective since it optimizes total time and total costs simultaneously. Moreover, utilizing changing adaptive weights for time and cost guides the model to search through a wide searching space

so that the tendency of premature convergence or being trapped in local optimal solutions is reduced. On the other hand, this model may be time consuming and prone to errors when applied to large-scale projects.
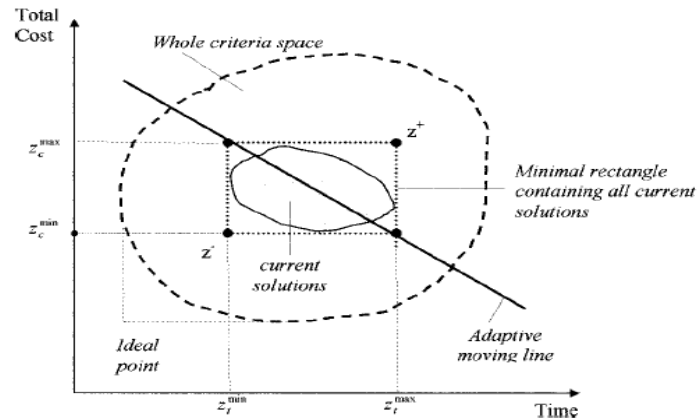
Figure 3.4: Adaptive weight methodology (Zheng et al., 2004)

Zheng et al. (2005) extended their previous research and proposed a modified adaptive weight model, referred to as MAWA, for multi-objective time-cost optimization incorporating Pareto ranking, niche formation, and adaptive mutation rate techniques. The Pareto ranking, which was previously discussed in section 2.5.4, was used to sort the population into equivalent ranks. Ranks were then sorted according to the average fitness of each one. Better Pareto optimal ranks have a greater chance for survival; however, non-dominated solutions on the same level have equal reproductive probability. In other words, the roulette wheel was applied to select a rank, and an individual solution of that rank was then randomly selected for reproduction processes. The niche formation is a mechanism used to promote uniform sampling and maintain appropriate population diversity. This technique is useful for stabilizing multiple subpopulations that arise along the Pareto optimal front. The adaptive mutation rate is a technique used to prevent premature convergence. A higher mutation rate was assigned for early stages in order to maintain diversity; however, a lower mutation rate was assigned for later stages in order not to disrupt good solutions. The adaptive mutation rate equation was formulated as follows:

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$$P_m = P_{mi} - 0.3\,\frac{t}{G} \quad \text{(Zheng et al., 20005)}$$

Equation 3. 9

Where P_m is mutation probability for current generation, P_{mi} is the initial mutation rate, t is current generation number, and G is maximum number of generations.

Compared to the model developed by Zheng et al. (2004), effective techniques such as the niche formation, the adaptive mutation rate, and the Pareto ranking were utilized to avoid premature convergence and to increase the attained robustness of results. On the other hand, the model does not consider resources and it was not applied to large-scale projects.

Elazouni and Metwally (2005) utilized GA to develop finance-based schedule aimed at minimizing financing and indirect costs so that the project's profit is maximized. The optimization problem was formulated to search for a schedule that minimizes the total project duration, to minimize indirect costs, subject to a cash constraint. The optimization variables were the start times of activities; however, the constraints were to maintain the combination of a project's cash out and cash in below an allowed credit limit. In other words, the two objectives of the proposed model were: (1) to maintain the debits below a specific limit using resource leveling and allocating to minimize interest rates and finance costs; and (2) to avoid extension in project durations in order not to increase indirect costs.

Chassiakos and Sakellaropoulos (2005) proposed a hybrid of LP and IP methods to develop a TCT optimization approach. Four advanced scheduling features were incorporated into the proposed approach, which are:

1. Generalized precedence relationships among activities, i.e. SS, FF, and SF in addition to FS relationships.

2. External time constraints due to technical, managerial, or political restrictions. Start no earlier than, or finish no later than a specific date are instance of such constraints.

3. Activity planning constraints such as start as early as possible, or as late as possible.

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4. Bonuses or penalties for early or delayed project completion.

The objective function of the proposed model was to minimize the summation of the project direct cost, the project finish time, the start as soon as possible activities, and the start as late as possible activities with a negative sign. A graph showing the relationship between direct cost and duration of the project was developed. Indirect costs and penalties/bonuses for late/early project completion was then added to the direct cost-time curve to obtain the total project's cost curve as a function of the project's duration. The minimum cost point of such a developed curve was considered the optimum project length. Another alternative to obtain the optimum time-cost point for a project was to consider additional terms in the objective function to account for indirect costs and penalties or bonuses. Although this approach has numerous capabilities, it has some weaknesses. For instance, the objective function was to minimize the summation of time and cost objectives ignoring the effect of different units. In addition, the processing time and complexity would excessively increase for large-scale projects.

Hegazy (2006) developed a powerful computer model called *EasyPlan* used for integrated project management. The *EasyPlan* has several unique features such as managing resources, schedule optimization, cash flow analysis, estimating markup, site layout optimization, recording progress, and delay analysis. GA was utilized to optimize schedule by changing two decision variables. One of them was an index to the selected resource utilization option for each activity, while the other was a start delay value applied to each activity in order to ensure the proper allocation of limited resources. The *EasyPlan* model is simple, easy to use, generalized, and capable of managing several project management issues. Nevertheless, it is more appropriate for educational and training purposes rather than practical purposes since construction projects usually include a large number of activities, various dependency relationships, and complicated resource utilization constraints.

Elazouni and Metwally (2007) incorporated resource management tools into their finance based scheduling approach developed in 2005. The purpose of the proposed incorporation was to balance great fluctuations in daily resource requirements caused by mixing activities with reduced durations, which require high daily resource demand, with others of low daily resource demand. Therefore, resource allocation and leveling techniques was utilized to schedule projects under resource limitation conditions and to ensure the efficient use of resources. The objective of optimization was to minimize the total project cost subject to constraints of resource availability and credit limit.

Ng and Zhang (2008) proposed an ACO-based model for TCT optimization, referred to as ACS-TCO. The main purpose of this model was to determine an optimum set of construction methods, used to perform the work of the project's activities, so that the total cost and total duration of the project would be minimized. The MAWA approach, developed by Zheng et al. (2004), was applied to evaluate the fitness of solutions derived from the ACS-TCO model. Compared to the ACO-based TCT model developed by Elbeltagi et al. (2005), the proposed ACS-TCO model developed by Ng and Zhang (2008) provided better solutions with lower number of iterations and less computation time. In addition, the ACS-TCO model was more effective than GA-based models in terms of the population size and number of iterations. On the other hand, it has a tendency of premature convergence, as its results may converge towards a set of locally optimal values. Another weakness is that ACO models are sensitive to assumed optimization parameters such as the number of ants in each iteration, pheromone reward factor, and the number of iterations. Such parameters may affect the convergence speed and the quality of solutions.

Huimin and Zhuofu (2009) proposed a MA-based approach for the TCT problem. The MAWA approach, developed by Zheng et al. (2004), was utilized as a MOO tool to solve the problem. As previously discussed in section 2.5.3.2, local search was utilized to improve

results. In addition, crossover and mutation were applied to generate better chromosomes by exchanging information. A case study problem was analyzed by the proposed model and results obtained by the proposed MA-based model demonstrated its effectiveness and its efficiency compared to ACO and GA models.

Kandil et al. (2010) developed a NSGAII based model in order to identify optimal resource utilization plans that provide optimal trade-offs between construction time and cost. For each construction activity within a project, one decision variable, referred to as resource utilization option, was considered. Such a variable included construction method, crew formation, and crew overtime policy. The two main objectives of the proposed model were minimizing the total project cost and time. The parallel and distributed computing technique was utilized in order to increase the robustness of the algorithm and its efficiency in analyzing large complex construction projects. Two approaches of parallel computing, which are global parallelization and coarse-grained parallelization, were applied to three case studies. Results of the analyzed case studies demonstrated that coarse-grained parallelization provided better results in terms of less processing time and quality of obtained non-dominated optimal solutions. It was also evident that higher increases in efficiency could be achieved as the number of utilized processors increased. This approach of parallel computing is innovative and advantageous for large-scale projects with a large number of activities since it saves a lot of processing time compared to other optimization approaches. On the other hand, the parallel computing approach is complicated and hard to be used by many practitioners in the construction industry. In addition, it requires several processors, which may not be available in construction sites.

3.3 Stochastic Time Cost Trade-Off

Most TCT analysis methodologies depend on historical data or knowledge of experts to estimate the duration and the cost of various execution options of the projects' activities.

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Even if reliable historical records of past projects are available, it would be imprecise to describe such performances, i.e. time and cost performance, by certain numbers due to the uniqueness associated with construction projects. There are always uncertain factors that may affect the performance of projects and values of the duration and cost of execution options. Weather conditions, site conditions, labor efficiency, productivity of equipment, availability of resources, and economical risks are instances of such factors. That is why stochastic analysis is more appropriate for the analysis of TCT in construction projects. Uncertainties should be incorporated into TCT analysis, which means that the duration and cost of various execution options of activities are not deterministic values. Usually, time and cost of activities follow a certain kind of probabilistic distribution (Feng et al., 2000). Usually, mean values of time and cost of activities are used in time-cost trade-off analysis. This would be acceptable when there is no or a slight overlap between distributions of options as shown in Figure 3.5. On the other hand, this would be inaccurate when there are overlaps between distributions of options as shown in Figure 3.6.
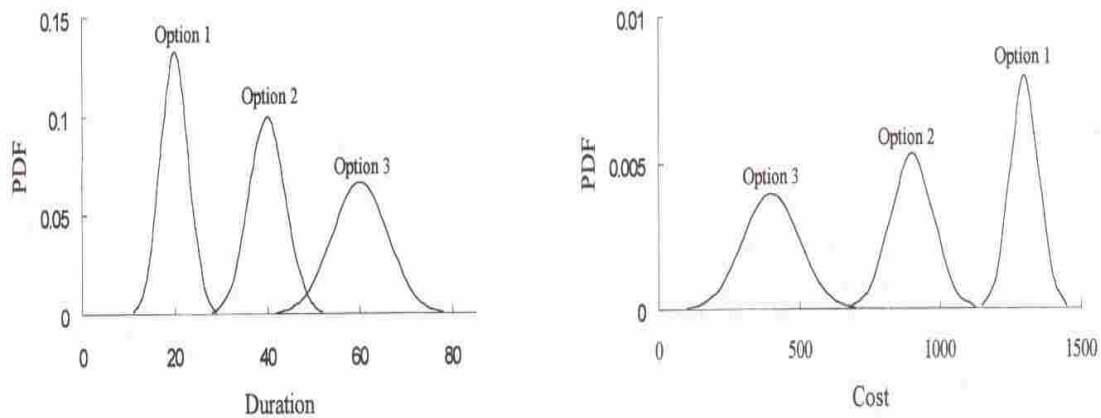
Figure 3. 5: Options without significant overlap (Feng et al., 2000)

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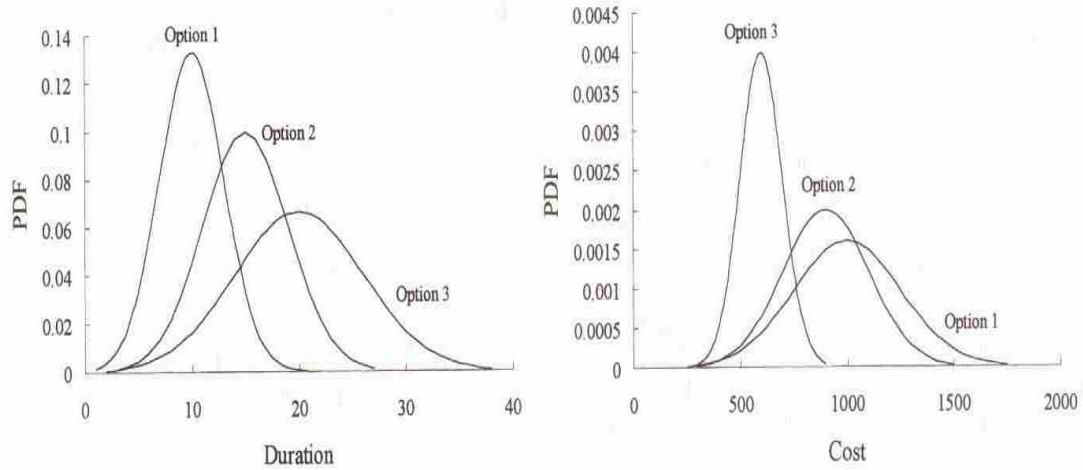
Figure 3. 6: Options with significant overlap (Feng et al., 2000)

Considering uncertainty associated with construction projects, Zheng and Ng (2005) developed a stochastic TCT model incorporating fuzzy sets theory and non-replaceable front. The main three innovative features of the proposed model were as follows:

1. Fuzzy sets theory, which was applied to simulate uncertainties associated with estimating the cost and duration of each option within an activity.

2. Fuzzy niche formation GA, which was utilized to improve the robustness of GA in global searching in order to obtain optimal TCT under different risk levels.

3. Non-replaceable front approach, which was applied to facilitate selecting solutions from the Pareto front obtained by GA. The non-replaceable front was defined as a segment on the Pareto front containing the most superior solutions, which cannot be replaced by all other solutions.

A case study was analyzed utilizing the developed model in order to demonstrate its effectiveness and capabilities. For deterministic scenarios, satisfactory results were acquired compared to other GA-based models. For stochastic scenarios, robust results were obtained, particularly as the risk increased. It was also demonstrated that adequate risk level to cover unexpected events would result in efficient GA's exploration to obtain global optimal solutions. This model developed by Zheng and Ng (2005) has several

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capabilities and advantages. For instance, modifying time and cost estimates during the evolution process was allowable. Therefore, rough estimated values of activities' time and cost would be sufficient to initiate the model. Besides stochastic scenarios, the developed model could be also applied deterministic scenarios by setting the risk level to one, which means that there would be no risk. The number of generated solutions was reduced to facilitate selecting a solution by decision makers. On the other hand, it was assumed that there is a relationship between direct cost and completion time of activities, which is usually true but the discrete relationship is practically more appropriate in construction projects. In addition, the model would be less effective and efficient when applied to large-scale projects due to the wide searching space associated with large number of activities and execution options.

3.4 Deterministic Time-Cost-Quality Trade-Off

Traditional TCT analysis assumed that quality is uniform for all resource utilization options of each activity, which is not accurate. Each resource utilization option would affect the quality performance of the activity and the quality performance of the whole project in case that option is selected for executing the activity. Time, cost, and quality of an activity or a project are interrelated and have impacts on each other. Therefore, quality should be incorporated into the traditional TCT analysis. Advanced three-dimensional time, cost, and quality trade-off analysis (TCQT) would be more effective to make accurate decisions related to projects performance. Therefore, each execution option for each task or activity should be evaluated for its duration, cost, and quality as well. The main purpose of TCQT analysis is to obtain an optimal combination of construction execution options with the objective of minimizing the total project cost and the total project duration, while maximizing the overall project quality.

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Babu and Suresh (1996) were of the first who considered quality impact on total cost and duration of projects. It was assumed that reducing the activity duration would save its duration, but may increase its cost, although the quality of the considered project may be affected. The overall project quality was considered the average of quality levels of activities. It was calculated in three different ways: (1) the arithmetic mean function; (2) the geometric mean function; and (3) the minimum function. Three separate models were developed to analyze cost, time, and quality of projects. Each of the three models was utilized to optimize only one of the three entities, while the other two were constrained by desired levels or bounds. The first model was applied to minimize the total project duration subject to a lower boundary constraint of its average quality and an upper boundary constraint of its direct cost. The second model was applied to minimize the total project direct cost subject to an upper boundary constraint of its completion duration and a lower boundary constraint of its average quality. The third model was applied to maximize the overall project average quality subject to an upper boundary constraint of its direct cost and an upper boundary constraint for its completion duration.

Those three models were applied to a numerical example and their results were represented numerically and graphically in order to investigate relationships and trends among different values of the project's average quality, direct cost, and completion time. Although results of the proposed models demonstrated the inter-relationship among quality, cost and duration of projects, they have some drawbacks and weaknesses. For instance, linearity of relationships among performance of execution options of the project's activities was assumed. This means that the relationship between quality or cost of activities and their duration was assumed linear, which is not practical in most cases in construction projects. It was also assumed that any reduction in activity duration would result in a decrease in its quality, which is not always the case in construction projects. For instance, utilizing new

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technologies in construction may save time and improve the quality of execution; however, cost may increase. Another weakness is that activity on arrow (A.O.A) was used as a scheduling tool, which is not appropriate for large-scale projects. Moreover, the indirect cost was not considered by the developed models.

Khang and Myint (1999) applied approaches and models developed by Babu and Suresh (1996) to an actual construction project in Thailand to evaluate its practical applicability. Results of the trade-off between the optimal direct cost and the project completion time for different average levels were graphically represented to provide decision makers with visualized information. Although this research and case project model demonstrated the importance of quality when decisions would be taken with regard to TCT analysis, it has some weaknesses. For instance, it was assumed that cost and quality of each activity would change linearly with activity completion time, which is not accurate for construction projects. All fixed costs of equipment, materials, and overhead were excluded from cost data of all activities. Quality, cost, and time data for the project activities, particularly for the crashed case, were assumed based only on experience of site managers and engineers. The only way for accelerating activities was through using overtime; however, several other alternatives would be available in construction projects such as utilizing more productive equipment, or more advanced construction methods for such activities. Furthermore, a practical measurement for quality performance of activities and the whole project is needed rather than managers' experience.

El-Rayes and Kandil (2005) were of the first who studied the TCQT as a discreet problem. For discrete TCQT problems, each activity within a considered project has different execution modes or options, which are discontinuous or isolated. Each execution option has its corresponding time, cost and quality values respectively. An innovative model was proposed to search for optimal resource utilization plans, which optimize the project's

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performance in terms of time, cost, and quality. For each activity within a project, construction method, crew formation, and overtime policy were combined into one single variable called resource utilization option. Three main objective functions were considered, which are minimizing the project's total duration, minimizing the project's total direct cost, and maximizing the project's overall quality. The NSGAII approach, previously discussed in section 2.5.4, was utilized as a MOO technique. The output of this model was a set of Pareto optimal solutions for the analyzed project. Each solution consisted of a set of resource utilization options for all the project's activities. An application example was analyzed by the developed model to illustrate its capabilities and demonstrate its efficiency. This model numerous strengths and advantages. For instance, it effectively considered quality in transforming the traditional two-dimensional TCT into a three dimensional TCQT. It proposed an efficient and practical technique for quality measurement in construction projects. Another advantage of the developed model was generating and visualizing optimal trade-offs among time, cost, and quality. A set of resource utilization plans was provided so that planners and decision makers would select the most appropriate scenario to execute the project. On the other hand, the processing time for optimizing a large-scale construction project would be unacceptable due to a large search space associated with excessive solution alternatives of execution plans. In addition, the project's indirect cost was not incorporated into the optimization process.

Kandil and El-Rayes (2006[b]) developed a practical multi-objective automated resource optimization system, referred to as MACROS. The main purpose of this system was to generate optimal resource utilization plans so that the total cost and total duration of a considered project are minimized simultaneously with maximizing its quality. This system incorporated four various modules as follows:

- The first module was a GA based MOO module to identify a resource utilization option for each activity in a considered project in order to obtain optimal solutions. This module included two main sections: (1) an optimization engine utilizing the NSGA II approach; and (2) a quality breakdown structure to estimate the construction quality performance at both the activity and the project levels.

- The second module was a relational database module designed to enable the storage and retrieval of necessary the input data such as project activities and available resource utilization options, in addition to the produced output data such as generated optimal tradeoffs among construction time, cost, and quality. This module included six main tables of construction data: (1) project activities; (2) precedence relationships; (3) resource utilization options; (4) importance weights of all activities regarding the quality; (5) optimal resource utilization options all activities; and (6) optimal project time-cost-quality tradeoffs.

- The third module was a middleware module designed to facilitate the integration between the internal modules in MACROS and external commercially available project management software such as Microsoft Project, in order to allow exchange of data.

- The fourth module was a user interface module designed into two phases: (1) an input phase to facilitate the input of all necessary construction planning and optimization data including scheduling data, activity quality weights and GA parameters; and (2) an output phase to visualize and rank the generated optimal tradeoffs among time, cost, and quality.

An application example of 180 activities was analyzed by the developed system illustrate its capabilities and demonstrate its effectiveness. In addition, the system was efficiently utilized for what-if scenarios analysis by changing planner specified ranking weights of time,

cost, and quality objectives. The MACROS system has numerous strengths and capabilities. For instance, it was capable of ranking optimal plans according to pre-specified weights representing the relative importance of time, cost, and quality in the analyzed project. In addition, it provided integration with commercially available project management software. Another advantage was its capability of visualizing generated optimal TCQT graphs. The MACROS system was also demonstrated to be efficient and effective when applied to large-scale projects.

Tareghian and Taheri (2006) proposed an approach to study TCQT utilizing three interrelated IP models. Each model was applied to optimize one of the three entities, which are time, cost, and quality of the project, by assigning desired bounds on the other two. An instance of a project network was analyzed by the proposed approach in order to validate it. The results were graphically shown to illustrate various trade-offs of the project such as (1) the project costs when its quality and deadline are varied, (2) the project deadline when its quality and budget is varied, and (3) the project quality when its deadline and budget is varied. Although, this model provided contributions to the area of TCQT of construction projects, it has some weaknesses. For instance, indirect costs were not considered, which would affect the total cost of the considered project and the accuracy of the acquired results. Moreover, the developed model was not applied to a construction project to investigate its performance with large-scale problems. Another weakness was the lack of a consistent methodology for quantifying quality of execution options for activities.

Pollack-Johnson and Liberatore (2006) illustrated the importance of incorporating quality considerations into traditional discrete TCT analysis. It was proposed that each execution option for each activity within a considered project should be evaluated for its duration, cost, and its quality as well. A mixed IP/LP model was then developed for the discrete TCQT problem in order to help project managers in taking appropriate scheduling decisions. The

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AHP approach was used to quantify the quality of each activity option. Quality values for the selected execution options of activities were then aggregated to form an overall measure of the project's quality. First version of the proposed model assigned upper limits on the total project duration and cost, while maximizing its quality. A construction example was analyzed in order to illustrate the capabilities and demonstrate the efficiency of the proposed model. Quality curves of various quality levels were then generated to represent the relationship between the total project duration and cost for fixed quality levels. A general formulation of the discrete TCQT problem was then derived applying the GP technique. The objective of the proposed model was to minimize the weighted sum of deviations from four goals: (1) the total project time goal ($T^{(G)}$); (2) the total project cost goal ($C^{(G)}$); (3) the minimum quality goal ($Q_{min}^{(G)}$); and (4) the average quality goal ($\overline{Q}^{(G)}$). The objective function of the model was formulated as follows:

Minimize z = $w_1 d_1^+ + w_2 d_2^+ + w_3 d_3^- + w_4 d_4^-$ (Pollack-Johnson & Liberatore, 2006)

Equation 3. 10

Where z is the weighted sum of deviations from the four goals. w_j is the relative weight of objective j. d_j^+ , d_j^- are the over or under deviational variables of the objective j respectively.

The proposed approach was applied to a case study project to illustrate its practicality and demonstrate its effectiveness. Quality level curves generated by the model provided a summary of the relationship among time, cost, and quality, which facilitates the selection of an appropriate execution scenario. Another advantage of the developed model was using the GP approach as a MOO technique, which was used to optimize the three objectives simultaneously. On the other hand, that model has some drawbacks and weaknesses. For instance, the data entry process is extremely complicated and time consuming, particularly for large-scale projects with a large number of activities and a large number of resource utilization options. Another disadvantage was the subjectivity in defining weights of the

model objectives, which was assumed based on knowledge and experience of the model user or decision maker. Furthermore, weights of activities within the project, which reflect the importance and contribution of each activity's performance to the overall quality of the project, were not considered.

Afshar et al. (2007) introduced a model for the TCQT optimization problem utilizing a metaheuristic multi-colony ant algorithm. The main purpose of the proposed model was selecting an appropriate option for each activity within a considered project to achieve the objectives of time, cost, and quality of such a project. The total project duration was considered the sum of durations of activities on the critical path of the project. Sum of direct costs of all activities and indirect costs represented the total project cost. To quantify the activities quality, quality-based contractor prequalification systems developed by Anderson and Russell (2001) were applied. The overall quality at the project level was considered the weighted average of quality performance of all activities of the project. The main procedures of the developed model as proposed by Afshar et al. (2007) were as follows:

1. A colony of ants was assigned for each of time, cost, and quality objectives.

2. Each colony of ants would try to search for a solution according to its objective. Each solution represents a set of execution options for the considered project's activities.

3. Each set of produced solutions found by a colony of ants was moved to another colony for updating according to each colony's objective.

4. Non-dominated solutions according to the values of the three objectives were moved to an external set called Archive.

5. Iterations would continue until all produced solutions could satisfy desired constraints or a pre-specified number of iterations would be met.

A case study was analyzed by the developed model to illustrate its capabilities and demonstrate its effectiveness in solving TCQT problems. Furthermore, the model was used to

optimize a TCT example that was analyzed by the MAWA approach (Zheng et al., 2005) and the generated solutions were more satisfactory with less number of generations. Afshar et al. (2007) demonstrated the efficiency of the ACO based model for considering quality and generating efficient Pareto optimal solutions. Compared to the traditional GA, effective results with less number of generations were obtained by the developed model when applied to TCT problems. On the other hand, this model has some weakness. For instance, the input of data for large sized projects is extremely complicated and time consuming. Moreover, the ACO technique is considered more complicated than GA for most project managers and decision makers.

Tareghian and Taheri (2007) proposed a meta-heuristic approach for the discrete TCQT problem. The objective of such an approach was to minimize the total cost of a project while maximizing its quality and meeting a pre-specified completion deadline. Electromagnetic scatter search was utilized to solve that problem utilizing attraction–repulsion mechanisms of the electromagnetism theory. The main procedures of this approach as illustrated by Tareghian and Taheri (2007) are as follows:

1. A population of random solutions P was generated.

2. b1, which are high quality solutions according to their values of objective functions, were selected and transferred to a reference set R. b2, which are diverse solutions that have maximum distances, were selected from the current P–R solutions and transferred to set R, where R = b1 U b2.

3. Solutions in set R were combined utilizing the Electromagnetism Mechanism (EM) global optimization algorithm to obtain new improved solutions.

4. The new updated reference set R was built with the best solutions in the union of combined new improved solutions and the initial solutions that were in set R. Good solutions in set R are updated and maintained.

This model developed by Tareghian and Taheri (2007) has some strengths and advantages. For instance, it was effectively applied to complex and large-scale projects with a large number of activities. Moreover, convergence to optimal solutions was reasonable with regard to the large searching space. On the other hand, this model has some weaknesses and drawbacks. For instance, it was assumed that the quality of each activity within the project would decrease and its cost would increase, when its duration was reduced, which is not always the case in construction projects. Another weakness is that geometric mean of activities' quality was applied to aggregate the overall quality of the project, which ignored weights of activities and their relative importance within the whole project. In addition, the indirect cost of the project was not considered when calculating the total project cost.

Rahimi and Iranmanesh (2008) proposed a PSO based model for the discrete TCQT problem. The main purpose of that model was constructing a complete and efficient time, cost and quality profile for a considered project in order to minimize its total duration, total cost while maximizing its total quality. The main procedures of the proposed model were as follows:

1. A number of solutions from initial population were selected for local improvement.
2. Improved solutions were then combined to generate a new set of solutions.
3. The process stopped when no improvements in solutions acquired.

A comparison between using PSO and GA for the discrete TCQT problem was conducted to demonstrate the efficiency and advanced performance of the PSO model when they were applied in the same conditions. This model developed demonstrated its efficiency for large size and small size problems; however, it has some weaknesses. For instance, the weight of each activity and its importance within the whole project was not considered when optimizing the total quality of projects. The total quality of a project was calculated as the

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arithmetic mean of quality of its activities. In addition, a consistent measurement approach for quality of alternatives for executing activities of a project was not proposed.

Iranmanesh et al. (2008) developed a model for the TCQT problem utilizing a version of GA adapted for multi-objective problems called Fast Pareto Genetic Algorithm (FPGA). It was proposed that activities of a considered project could be executed by various execution modes, where each execution mode has triple characteristics of time, cost, and quality. To keep diversity of population, an advanced ranking strategy, which was based on the dominance and crowding distance approaches previously discussed in section 2.5.4, was deployed for evaluating the fitness of solutions for the reproduction process. A regulation operator to adjust the population size until it reaches a user-specified maximum population size was used to avoid premature convergence or slow down convergence. A case study project of 30 activities was analyzed by the developed model and results demonstrated its efficiency and effectiveness. This model could produce a set of optimal non-dominated solutions rather than a single optimal one, which helps decision makers to select the most appropriate scenario to run the project. Another advantage of that model was the efficiency associated with the utilization of a new ranking strategy, adaptive population sizing, and conservative solution evaluation. On the other hand, the weight of each activity and its importance within the whole project while optimizing its total quality was not considered since the overall quality of a project is calculated as the arithmetic mean of quality of its activities. Another weakness is that a quality measurement approach for the project's activities was not proposed.

Ghodsi et al. (2009) proposed a mathematical model to identify an appropriate relation function among time, cost, and quality of activities of construction projects. To define such a relationship, it was assumed that the quality of an activity would reduce by reducing its duration, the cost of an activity would increase by improving its quality, and the cost of an

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activity would increase by reducing its time. Considering such assumptions and utilizing mathematical approaches, a general equation for the total cost of an activity was formulated as follows:

$$\text{TC } (t,q) = C_{norm} + \Delta C_T (t - t_{norm}) + [\frac{\Delta C_Q^{norm} - \Delta C_Q^{crash}}{t_{norm} - t_{crash}} (t - t_{norm}) + \Delta C_Q^{norm}] (q - q_{norm} - \Delta Q_T(t - t_{norm}))$$ (Ghodsi et al., 2009)

Equation 3. 11

Where C_{norm} is the cost of executing an activity in the normal duration and C_{crash} is the cost of executing an activity in the crashed duration. t_{norm} is the normal duration of an activity, t_{crash} is the crashed duration of an activity, and t is the duration of an activity. q_{norm} is the quality of executing an activity in the normal duration, q_{crash} is the quality of executing an activity in the crashed duration, and q is the quality of an activity. $\Delta C_T = (C_{norm} - C_{crash}) / (t_{norm} - t_{crash})$ and

$\Delta Q_T = (q_{norm} - q_{crash}) / (t_{norm} - t_{crash})$. ΔC_Q^{norm} is the cost of increasing one percent of quality

in the normal time of an activity and ΔC_Q^{crash} is the cost of increasing one percent of quality in the crashed time of an activity.

Based on the proposed relation function among time, cost, and quality of each activity, a three dimensional TCQT model was developed for the whole project. The main three objectives of the developed model were minimizing the total duration of the project, minimizing the total cost of the project, and maximizing the overall quality of the project. The Pareto front approach was applied to obtain a set of efficient solutions for that TCQT problem. Quality, cost, and time contours, which could be identified by optimizing one objective while bounding the two remaining objectives, were also generated to help managers in the trade-off decisions. Although this model is efficient, easy to be used by decision makers, and practical to be applied to construction projects, it has some weaknesses and drawbacks. For instance, the total quality of a project was calculated as the arithmetic mean

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of quality of its activities, which does not consider the importance and weight of each activity within the whole project. Linearity of time-cost and time-quality functions were assumed for simplification purposes, which is not appropriate for all activities in construction projects. Moreover, indirect costs were not considered while optimizing the total project cost.

Cristóbal (2009) proposed three alternative IP based models for optimizing time, cost, and quality simultaneously. The first model was applied to minimize the time objective subject to quality and cost limits, the second was used to minimize the cost objective subject to quality and time limits, and the third model was applied to maximize the quality objective subject to time and cost constraints. The first model was applied to a construction project and results demonstrated its efficiency. On the other hand, the optimization process was only conducted on critical activities, which would save the processing time but the accuracy of results might be affected. In addition, reducing the durations of activities on the critical path would create other critical paths. Another drawback of the developed model was that indirect costs of the project were not considered when optimizing the total project cost.

Madany et al. (2009) developed a four-dimensional optimization approach for optimizing the objectives of time, cost, quality, and total air pollution in construction projects. The main purpose of the proposed approach was to provide decision makers with a set of non-dominated solutions that minimize total cost, duration, and air pollution, while maximizing the overall quality of a considered project. The developed model incorporated two distinct modules: a fitness evaluation module in order to calculate time, cost, quality and construction emissions; and an optimization module utilizing the biased sharing non-dominated sorting genetic algorithm (NSGA) to optimize the trade-off objectives. Microsoft Project 2003 was utilized to estimate projects' total cost and total duration; however, the QBS approach proposed by El-Rayes and Kandil (2005) was applied to evaluate the overall quality. The overall pollution was quantified by estimating the amount of dust, harmful gases, and noise

associated with construction activities. An illustrative example was analyzed by the developed model and satisfactory results were obtained.

Abd El Razek et al. (2010) developed a GA based computer system called "Automatic Multi-objective Typical Construction Resource Optimization System", referred to as AMTCROS. The purpose of that system was to optimize resource utilization in order to minimize the total project cost and the total project duration while maximizing its quality. This system was developed in four main modules:

1. A relational database module to store and retrieve the input and output data;

2. A logical module to enable the integration of the relational database module with other modules;

3. A modifying module to modify activities' durations and relations from one stage to all stages; and

4. A user interface module to facilitate the input of construction planning data and the output of ranked optimal solutions and their resource utilization options.

A construction case study was analyzed by the AMTCROS system to demonstrate its capabilities. A number of what-if scenarios were created for the analyzed project by changing the three objective's importance weights in order to facilitate the selection of an optimal scenario for executing the project. Generated optimal plans were sorted according to those weights. Visualizing optimal trade-offs among time, cost, and was another capability of this software. In addition to considering generalized dependency relationships among activities, this software provides integration with commercial project management software to benefit from their scheduling and control features. On the other hand, this software is considered a re-production copy of the MACROS system proposed by Kandil and El-Rayes (2006[b]). Both are similar in all features, capabilities, and modules. The main difference is that the system of Abd El Razek et al. (2010) was developed utilizing the *JAVA* programming language;

however, the model of Kandil and El-Rayes (2006[b]) was developed utilizing the *Microsoft Visual C[++]*. Another difference is that the MACROS utilized *Microsoft Project* as a scheduling tool; however, the AMTCROS is considered a scheduling tool itself.

Pour et al. (2010) proposed a model for the discrete TCQT problem utilizing a new meta-heuristic algorithm called the Novel Hybrid Genetic Algorithm (NHGA). The main purpose of that model was to obtain an optimal combination of duration-cost-quality for each activity within a considered project in order to minimize its total cost and its total duration, although its overall quality would not decrease than a specified limit. The main difference between the traditional GA and the NHGA was the utilization of the hill climbing approach, which means transferring a small number of the best parents directly to the next generation before applying the crossover and mutation processes. Compared to the traditional GA, high speed of the algorithm, high accuracy, and quick convergence of solutions were of the advantages and strengths of that model. Discrete time-cost and time-quality relationships were considered, which is more appropriate to construction projects. On the other hand, data entry would take excessive time for large projects with a large number of activities. Moreover, the accuracy of solutions depends on the experience of mangers or engineers who provide the input data, particularly the quality data.

Diao et al. (2011) proposed a computer-based Pareto approach for solving the TCQT problem. The NSGAII was utilized as a MOO technique to provide decision makers with a set of optimal or near optimal solutions. An illustrative example was analyzed by the developed model and Pareto optimal solutions were visualized in a 3-D decision space chart. Quadratic time-cost relationships and linear time-quality relationships were assumed for all activities, which is not practical for construction projects. It was also assumed that reducing the duration of activities would definitely increase their costs and decrease their qualities. This assumption is not accurate for several activities that might require advanced, high

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productive equipment. Another weakness was that weights and relative importance of activities were not considered when the overall project quality was calculated.

Shrivastava et al. (2012) proposed a metaheuristic multi-colony ant algorithm for the optimization of four objectives, which are time, cost, quality, and quantity of goods or products. The main purpose of that model was to obtain a vector of the options of resource utilization for all activities of a considered project in order to minimize its total cost and its total duration while maximizing its overall quality. As shown in Figure 3.7, a project with N activities and K resource utilization options for each activity was represented by a graph. The horizontal axis represented the project activities, and the vertical one represented resource utilization options. The ACO procedures, previously discussed in section 2.5.3, and the Pareto front approach, previously discussed in section 2.5.4, were utilized to obtain a set of non-dominated solutions to the analyzed project. The model was also applied to time-cost-quality-quantity optimization problems and TCT problems in order to demonstrate its efficiency over some existing approaches. Nevertheless, the purpose and benefit of incorporating quantity as an optimization objective was not properly illustrated. It was not also obvious how the model was applied or how results were obtained for the analyzed case study.
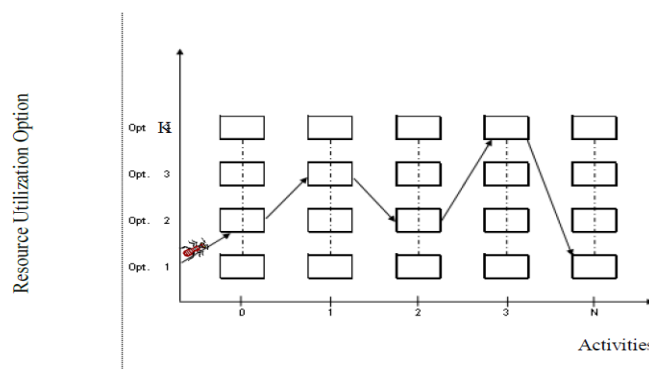
Figure 3. 7: Representation of a project with N activities and K resource utilization options (Shrivastava et al., 2012)

Zhang et al. (2014) proposed an integrated optimization approach to solve the problem of TCQT in construction projects. The main purpose of the proposed approach was to provide decision makers with various Pareto optimal solutions with the objective of minimizing the total project cost, minimizing the total project duration, and maximizing the overall project quality. The PERT method was utilized as a scheduling tool to calculate the total project duration. Direct costs, indirect costs, and tardiness costs were included in the total project cost. Quality performance index approach (QPI) was introduced to evaluate the quality of construction methods of activities and the overall project quality as well. A hybrid combination of GA, PSO and immune algorithm was developed to benefit the advantages of most promising characteristics of each algorithm. The crossover and mutation from GA were applied to increase the diversity of the population, while immune selection from immune algorithm was incorporated to accelerate the converging speed. When applied to a practical example, results of the developed approach demonstrated its effectiveness and efficiency. On the other hand, QPI was assumed a function of duration of activity, which is not always accurate in construction projects. The values of best duration, shortest duration, longest duration of construction methods was estimated by the project engineer, which depends on his experience and knowledge. Another weakness of that model was the subjectivity associated with assigning relative importance weights of the problem objectives. There was no evidence that the relationship between time and cost or between time and quality of activities is quadratic as assumed by the author. Complexity and excessive calculations associated with large construction projects was another disadvantage of the developed model.

Suad Awadallah (2014) developed a framework for optimizing time, cost, quality, and environmental impact objectives in highway construction projects. The purpose of that framework was to provide decision makers with a set of optimal solutions that simultaneously minimize the total duration and cost, maximize the overall quality, and

minimize the resulted pollution. To evaluate the quality of activities and the whole project, an index referred to as "The Highway Quality Performance Index" was proposed. To evaluate the pollution generated by each activity and the whole project, an index referred to as "The Highway Environmental Pollution Index" was introduced. GA was utilized as a MOO approach to optimize the four objectives simultaneously. The developed framework was applied to a construction project to demonstrate the efficiency of the proposed indices and the effectiveness of the optimization approach.

Bingol and Polat (2015) introduced the process of subcontractors' selection as a discrete TCQT problem. The main purpose of the proposed research was to select an optimal combination of subcontractors that would execute work packages of a considered project with the objective of simultaneously minimizing its time and cost, while maximizing its quality. The PSO method was adopted as a MOO technique to generate a set of optimal solutions to decision makers. Indirect costs, an incentive reward for early completion, and a penalty for late completion were included in the total cost of the project. The total duration of the project was the sum of durations of work packages on the critical path. The overall quality of the project was the sum of weights of work packages multiplied by the quality percentage of the selected subcontractor option for that work packages. When applied to a case study, The developed model demonstrated various capabilities and advantages. On the other hand, the quality performance of subcontractors was subjectively evaluated based on the experience of general contractors' top managers. Furthermore, weights of work packages with regard to quality were inaccurately assumed equal. Durations of activities' execution options were taken from subcontractors' bids, which might be inaccurate or somehow optimistic values.

3.5 Stochastic Time-Cost-Quality Trade-Off

Similar to stochastic TCT analysis, it is more appropriate to consider uncertainty while studying TCQT problems in construction projects. Time, cost, and quality performance of an

execution option or a construction method may be affected by several uncertain factors such as weather conditions, labor productivity, equipment efficiency, and materials availability. That is why it is impractical to describe time, cost, and quality of execution options by precise numbers.

Zhang and Xing (2010) proposed a fuzzy-multi-objective PSO approach to solve the stochastic TCQT problem. The main purpose of this approach was to obtain an optimal combination of construction methods in order to minimize the total cost and duration of the project while maximizing the total quality. Fuzzy numbers were considered to describe time, cost, and quality associated with each construction method for the project's activities. Quality associated with construction methods of activities were described by linguistic terms such as very high, high, medium, and low and each term could be then represented by a triangle fuzzy number. A fuzzy multi-attribute utility methodology based on constrained fuzzy arithmetic was utilized to evaluate the project's fuzzy performance regarding time, cost, and quality. The proposed fuzzy multi-objective PSO approach was then implemented in visual C^{++} to develop an effective computer model. A simple construction project was analyzed by the developed model to illustrate its capabilities. Results of the case study project demonstrated its effectiveness and its efficiency in analyzing TCQT problems considering uncertainty and imprecision associated with construction projects. On the other hand, indirect costs were not considered in computing the total cost of the project. In addition, subjectivity in assuming weights of the project's objectives was another drawback of the proposed methodology.

Shankar et al. (2011) proposed a hybrid of IP and LP approach for the problem of scheduling construction projects considering TCQT. The main purpose of this approach was to obtain a set of efficient execution scenarios for a considered project. Stochastic dominance rules were applied to evaluate the project with regard to time, cost, and quality performances.

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Projects that satisfied restrictions specified by decision makers were then generated in order to select a final execution scenario. This model has some weaknesses and drawbacks. For instance, it was not obvious how the model generated different scenarios and how their schedules and network times were obtained. It was not also illustrated how resources are allocated on different activities. In addition, It was not shown how a project's total duration, cost, and quality are calculated for those huge number of execution scenarios.

Pour et al. (2012) developed a model for the stochastic discrete TCQT problem utilizing a metaheuristic algorithm called the new hybrid genetic algorithm (NHGA). The main purpose of this model is to obtain an optimal combination of execution modes for all activities of a considered project in order to minimize the total project cost, and reduce the total project duration, while the overall project fuzzy quality would not decrease than the desired level. Quality of each mode was considered a linguistic variable, i.e. it was evaluated by words or sentences not numbers. The fuzzy logic theory was utilized to simulate the uncertainty associated with the project quality. Triangular fuzzy numbers were assumed for any activity's quality and the weighted sum of activities' quality was then compared with a lower acceptable bound for fuzzy quality of the project. The proposed model was applied to a case study in order to illustrate its capabilities. The statistical analysis of variance (ANOVA) method was then utilized to compare the performance of the NHGA and the traditional GA. Results of the ANOVA demonstrated the efficiency and effectiveness of the developed model and the NHGA approach. In addition, the robustness of the algorithm and effective convergence of solutions made that model capable of analyzing construction projects with a large number of activities. On the other hand, uncertainty associated with the duration and cost of activities was not considered. It was assumed that any reduction in the duration of activities would decrease their quality, which is not always accurate in construction projects.

In addition, the activity on arrow (A.O.A) was utilized as scheduling tool, which is complicated and impractical for large-scale projects.

Heravi and Faeghi (2014) proposed a group decision-making framework for stochastic optimization of TCQT in construction projects. The purpose of that framework was to seek the optimal resource utilization plan, considering time, cost, and quality simultaneously, that would acquire desirable project performance. Monte Carlo Simulation (MSC) was incorporated for the stochastic measurement of time and cost. Three points estimation, which are the most likely, the worst, and the best conditions, was applied to estimate duration and cost for each activity to drive a triangle distribution. Linguistic terms and their corresponding triangular fuzzy numbers were introduced to determine weights of activities within the project, importance weights of quality indicators, and quality levels of activities as well. Fuzzy simple additive weighting system was then utilized for the stochastic estimation of the total project quality. Three main modules were incorporated in the developed framework: (1) an information establishment module to read project information and decision making parameters; (2) an alternatives evaluation module to compute time, cost, and quality for each alternative; and (3) a decision-making module in order to aggregate the decision makers' preference to make the final decision and select the best solution. A project application example was analyzed by the framework demonstrated that it is efficient and capable of analyzing stochastic TCQT problems in construction projects. The decision makers' risk, confidence levels, and the power of individual decision makers were considered. Various weights of the project objectives, time, cost, and quality, could be analyzed. Another advantage is that different levels of uncertainty could be addressed depending on the source of the data and the nature of the construction project. On the other hand, huge computations, complexity of the input process, and excessive processing time for large-scale projects are considered instances of drawbacks and weaknesses of the developed framework.

MA et al. (2014) proposed a stochastic TCQT model capable of considering uncertain factors existing in construction projects. A hybrid of stochastic simulations and GA was utilized by the proposed model. The main objective of the proposed model was to minimize the total project cost subject to deadline and minimum quality constraints. The duration of various execution options for each activity within a project was considered a random variable normally distributed, although cost and quality were assumed deterministic. Although the methodology of that model is effective, it has several weaknesses. For instance, the uncertainty associated with the cost and quality values were not considered. The indirect cost was not included in the total project cost calculations, which has an impact on the accuracy of results obtained by the developed model. In addition, only finish to start precedence relationships among activities were considered in scheduling computations.

Fang and Zhang (2014) introduced a new approach to solve the discrete TCQT problem in construction projects. The main objective of that approach was to minimize the expectation of total quality cost. The total quality cost included: (1) prevention costs, which were assumed a percentage of direct cost of each activity based on the executed mode; and (2) failure costs categorized into: (a) internal failure costs or repair costs during construction; and (b) external failure costs or accident loss after closeout. The relationship among time, cost, and quality of each activity was assumed to be normally distributed. The SFL algorithm was utilized to develop a non-linear stochastic programming model. The application of the developed model to a construction project demonstrated that the proposed algorithm could converge fast to satisfactory solutions. Despite being innovative, it would be impractical to apply that model to construction projects due to huge computations and complicated equations associated with it. Another weakness was that the total cost, total duration, and total quality were not optimized simultaneously. The model only focused on minimizing the total quality cost.

Moreover, large number of assumptions associated with the model development made it inaccurate for construction projects.

3.6 Summary

A review of four distinct sections: deterministic TCT; stochastic TCT; deterministic TCQT; and stochastic TCQT was conducted. Tables 3.1 to 3.4 summarize and organize the discussed studies and the utilized approaches with regard to the four sections.

Table 3.1: A summary of deterministic TCT reviewed literature

Deterministic Time Cost Trade-Off Analysis (TCT)		
Author	**Year**	**Utilized Technique**
Liu et al.	1995	LP and IP
Feng et al.	1997	GA and Pareto front
Li and Love	1997	Improved GA
Sipos	1998	LP and IP
Hegazy and Ayed	1999	GA (Gene Hunter Excel add in)
Hegazy and Ersahin	2001	GA (Evolver Excel add in)
Que	2002	GA
Zheng et al.	2004	GA (MAWA)
Zheng et al.	2005	GA and Pareto ranking (MAWA)
Elazouni and Metwally	2005	GA
Chassiakos and Sakellaropoulos	2005	LP and IP
Hegazy	2006	GA
Elazouni and Metwally	2007	GA
Ng and Zhang	2008	ACO
Huimin and Zhuofu	2009	MA
Kandil et al.	2010	NSGAII

Table 3.2: A summary of stochastic TCT reviewed literature

Stochastic Time Cost Trade-Off Analysis (TCT)		
Feng et al.	2000	MCS and GA
Zheng & Ng	2005	Fuzzy Sets and GA

Table 3.3: A summary of deterministic TCQT reviewed literature

Deterministic Time Cost Quality Trade-Off Analysis (TCQT)		
Author	**Year**	**Utilized Technique**
Babu and Suresh	1996	LP
Khang and Myint	1999	LP
El-Rayes and Kandil	2005	NSGAII
Kandil and El-Rayes	2006	NSGAII
Tareghian and Taheri	2006	IP
Pollack-Johnson and Liberatore	2006	GP, LP and IP
Afshar et al.	2007	ACO and Pareto front
Tareghian and Taheri	2007	Electromagnetic scatter
Rahimi and Iranmanesh	2008	PSO
Iranmanesh et al.	2008	GA and Fast Pareto
Ghodsi et al.	2009	LP and Pareto Front
Cristóbal	2009	IP
Madany et al.	2009	NSGA
Abd El Razek et al.	2010	GA
Pour et al.	2010	Novel Hybrid Genetic Algorithm
Diao et al.	2011	NSGA
Shrivastava et al.	2012	ACO
Zhang et al.	2014	Immune Genetic PSO
Awadallah S.	2014	GA
Bingol and Polat	2015	PSO

Table 3.4: A summary of stochastic TCQT reviewed literature

Stochastic Time Cost Quality Trade-Off Analysis (TCQT)		
Author	**Year**	**Utilized Technique**
Zhang and Xing	2010	Fuzzy-PSO
Shankar et al.	2011	Stochastic dominance rules and LP/IP
Pour et al.	2012	NHGA and Fuzzy Sets
Heravi and Faeghi	2014	MCS, Fuzzy Simple Adaptive Weight, and Group Decision Making
MA et al.	2014	Stochastic Simulations and GA
Fang and Zhang	2014	SFL

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Throughout the reviewed literature, the following conclusions were reached:

- Compared to TCT research, less reported research focused on TCQT of construction projects

- Compared to deterministic TCT and TCQT, less reported research incorporated uncertainty into analyzing TCT and TCQT of construction projects.

- EA algorithms in general and the GA technique in particular have been extensively applied to both TCT and TCQT models.

- There are two categories of trade-off problems, which are continuous and discrete. The discrete relationships are more relevant to construction projects since they can appropriately describe relationships among time, cost, and quality of execution options. The discrete relationships could be also applied to other continuous relationships.

- Three main approaches were commonly utilized to analyze MOO models which are:

1. The weighted objective function approach, the MAWA and the GP are instances of such an approach.

2. The single objective function approach, in which a single objective is optimized and the other remaining objectives are restricted by limiting constraints.

3. The dominance approach, the Pareto optimal and the NSGAII techniques are examples of that approach.

Chapter IV: Models Development and Validation

4.1 Introduction

The main objective of this chapter is to present and illustrate the development of three TCQT models. The main purpose of these models is to select an appropriate execution option for each activity within a considered project in order to complete the project by a desired deadline or with a minimum duration, satisfy a desired quality level or maximum quality within an estimated budget or minimum cost. In other words, it is required to acquire an optimal or near optimal combination of construction options with the objective of simultaneously minimizing the total project duration, total cost, while maximizing its total quality. The proposed models are developed and implemented in Microsoft Excel to benefit its features and capabilities in addition to advanced optimization add-in tools. The three developed models are as follows:

1. A simplified time-cost-quality optimization model.

2. A stochastic time-cost-quality optimization model.

3. An advanced time-cost-quality optimization model.

4.2 Simplified Time-Cost-Quality Trade off Analysis Model

The purpose of this model is to obtain an optimal or near optimal execution scenario for simple construction projects. It is required to select a resource utilization option or execution option for each activity within a considered project in order to achieve decision makers' objectives regarding the total project time, cost, and quality.

4.2.1 The Proposed Approach and Methodology

4.2.1.1 Decision Variables

Decision variables are variables or construction factors that may affect a considered activity or project performance in terms of time, cost, or quality. Those variables may include used materials, equipment, construction methods, crews' formation, or crews' overtime policy. For simplification purposes, all of the aforementioned decision variables are combined into a single variable per activity, referred to as an execution option or a resource utilization option. Each activity within a project may have several execution options to execute that activity. Each execution option has an expected cost rate and production rate, which result in a completion duration and direct cost for that activity when constructed using this execution option. Each resource utilization option will result in a different performance of the activity and a different performance of the whole project in case this option is selected for executing that activity. In other words, the total project cost, duration, and quality are changed when a selected option index is changed. It is required to select an index for each activity in order to achieve the optimization objectives.

4.2.1.2 Optimization Constraints

Optimization constraints are conditions that must be satisfied for a solution to be valid. Depending on the optimization approach, the optimization constraints may be one of the following:

- The minimum acceptable overall quality of the project.

- The maximum acceptable total project duration, referred to as the project deadline.

- The maximum acceptable total project cost.

- The selected method index value for each activity must be an integer number, more than zero, and within the available number of options for executing that activity.

4.2.1.3 Total Project Cost

As previously illustrated in section 2.3, the total cost of a project includes both direct and indirect costs. The direct cost of the project is the sum of direct costs of all project's activities for selected execution options. Since the indirect cost is proportional to the duration of the project, it is assumed a fixed value per time unit. According to contract documents, there may be a penalty cost for completion delay after a specified deadline. There may also be a bonus incentive reward for early completion before a specified deadline. Both penalties and bonuses are considered in calculating the total project cost. To calculate the total project cost, Equation 4.1 is used.

$$C = \sum DC + IC * D + Pen* (D\text{-deadline}) – Bon* (\text{deadline-} D)$$

Equation 4.1

Where C is the total project cost, $\sum Dc$ is the summation of direct costs of all activities, and IC * D is indirect cost per time unit multiplied by total duration. Pen* (D-deadline) is the penalty of delay per time unit multiplied by the number of delay units and Bon* (deadline- D) is bonus per time unit multiplied by no of early units.

4.2.1.4 Total Project Duration

To calculate the total project duration, the CPM approach previously discussed in section 2.2.2 is applied. A forward path is applied to determine early start times of activities. An ES time of zero is assigned to the first node. The EF time of any activity is calculated using Equation 4.2. The ES time of a successor activity is the largest EF value of its predecessors. The EF value of the end node or the finish activity, which is considered the total project duration, is transferred to be its LF value. A backward path is applied to determine late finish times of activities. The LS time of any activity is calculated using Equation 4.3. The LF time of a predecessor activity is the smallest LS value of its successors. The TF value is calculated for each activity using Equation 4.4 in order to identify critical activities with zero total float.

$$\textbf{Early Finish (EF) = Early Start (ES) + Dur}$$

<div align="right">**Equation 4.2**</div>

$$\textbf{Late Start (LS) = Late Finish (LF) – Dur}$$

<div align="right">**Equation 4.3**</div>

$$\textbf{Total Float (TF) = LS – ES = LF – EF}$$

<div align="right">**Equation 4.4**</div>

Where Dur is the duration of the activity for a selected execution option.

4.2.1.5 Overall Project Quality

To evaluate the quality of a considered project, the QBS approach, proposed by El-Rayes and Kandil (2005), is applied. For each activity within a considered project, an activity weight is assigned to represent its importance and the contribution of its quality to the overall quality of the project. Activities' weights are not affected by the utilized execution option. These weights are defined before starting the optimization process and their sum should be equal to 100. A set of quality indicators, which are assumed three for the proposed model, are incorporated to evaluate the quality of each activity. Weights of such indicators are assigned to indicate the relative importance of each one its effect on the activity's quality compared to other indicators. The sum of such indicators' weights should be equal to 100. The performance or result of quality with regard to each indicator for each available alternative execution option is determined based on the average historical performance of that option. Equation 4.5 and Equation 4.6, proposed by El-Rayes and Kandil (2005), are applied to evaluate the quality of each execution option and the overall project quality respectively.

$$\mathbf{q_i} = \sum_{k=1}^{k} Wt_{i,k} * q_{i,k}^{l}$$

<div align="right">**Equation 4.5**</div>

$$\mathbf{Q_T} = \sum_{i}^{n} Wt_i * q_i = \sum_{i=1}^{n} Wt_i \sum_{k=1}^{k} Wt_{i,k} * q_{i,k}^l$$

<div align="right">**Equation 4.6**</div>

Where $Wt_{i,k}$ is the weight of quality indicator (k) of activity (i) and $q_{i,k}^l$ is the performance or result of quality indicator (k) in activity (i) using resource utilization option (l). Wt_i is the weight of activity (i) and the term q_i or $\sum_{k=1}^{k} Wt_{i,k} * q_{i,k}^l$ is the quality of each activity when executed by a specific execution option (l). Figure 4.1 shows an instance of quality quantifying and aggregation for a typical construction project.
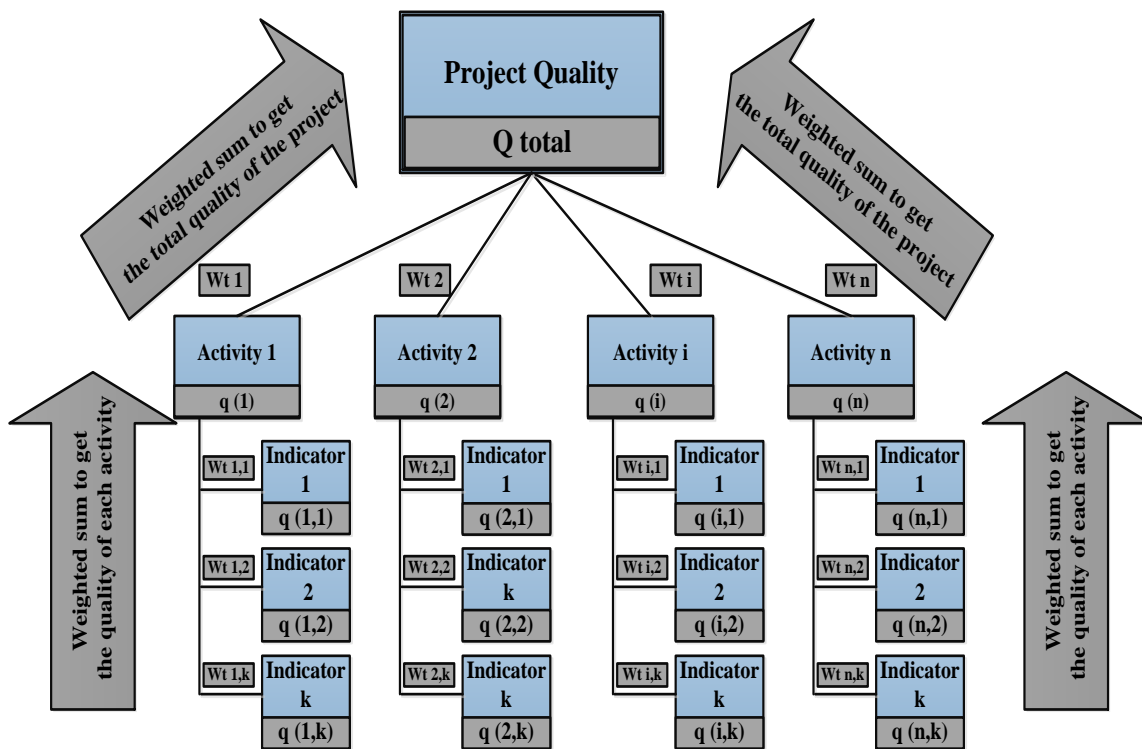
Figure 4.1: Quality breakdown structure

4.2.1.6 Optimization Approach

According to the model user's preference and depending on the project conditions, the optimization process may be conducted as follows:

- Minimizing the total project cost subject to a deadline constraint and a minimum overall quality constraint.

- Minimizing the total project duration subject to a maximum total cost constraint and a minimum overall quality constraint.

- Maximizing the overall project quality subject to a maximum total cost constraint and a deadline constraint.

- Simultaneously optimizing the three project objectives by minimizing the term T*C/Q, which would minimize the project total cost and duration while maximizing the project overall quality.

4.2.1.7 Optimization Tool

The GA based modeling and optimization tool Evolver is utilized to solve the model. Evolver is considered one of the most powerful optimization software packages. It is a Microsoft Excel add-in developed by Palisade Corporation to find the best global solution of complicated, nonlinear problems. Finding better solutions, ease of use, dealing with large numbers of variables and constraints, and accuracy are instances of the strengths of the Evolver (Palisade Corporation, 2010).

To define the model on Evolver, the Model Definition button on the Evolver toolbar is pressed. As shown in Figure 4.2, the objective function or Optimization Goal is specified and set to maximum or minimum. The decision variables or Adjustable Cell Ranges and constraints are added and described. Figure 4.3 shows the Evolver settings, which include the stopping conditions, population size, crossover and mutation rates, and other Evolver options. To run the optimization process, the Start button is pressed.
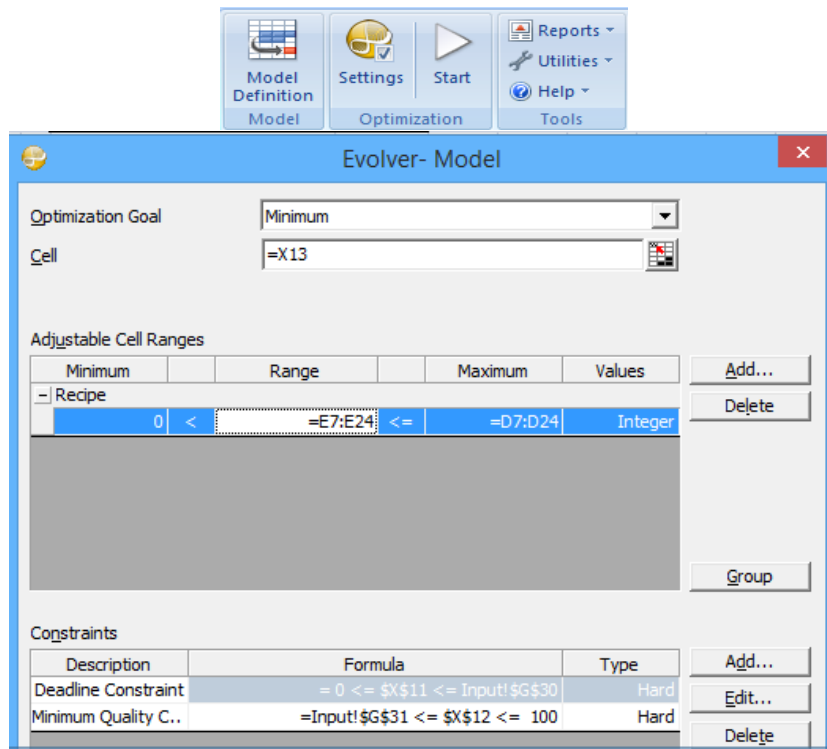
Figure 4.2: The Evolver model definition
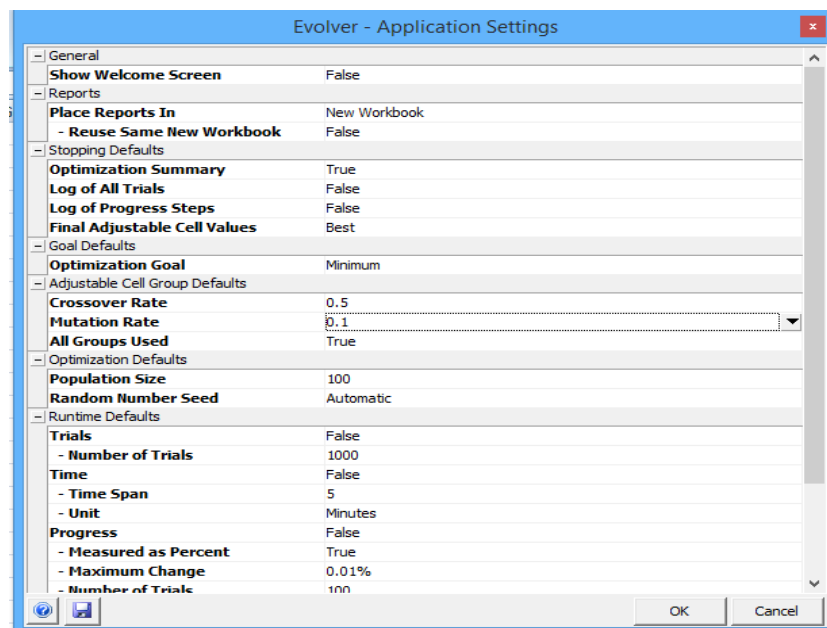
Figure 4.3: The Evolver settings

4.2.2 Model Description and Organization

As shown in Figure 4.4, the proposed simplified model incorporates two distinct modules, which are the input and the output modules.

4.2.2.1 Input Module

The main objective of this module is to facilitate the input of all necessary construction planning and optimization data as follows:

- General activities data, including ID and description of each activity.

- Scheduling data, including predecessors and successors of each activity.

- Quality data, including activities' weights and quality indicators' weights for each activity.

- Execution options data, including duration, direct cost, and performance in quality indicator for each execution option. Quality of each option is computed based on indicators' weights of the activity and their quality performances in such indicators.

- Project constraints and contractual data, including the project deadline, the minimum acceptable overall quality, the indirect cost, a penalty of late completion, and a bonus of early completion.

4.2.2.2 Output Module

The main objective of this module is to present the TCQT results. These results include the following:

- The selected optimal scenario for executing the project by providing a set of execution options for the project's activities.

- CPM calculations for the selected scenario, including ES, EF, LS, LF, and TF for all the project activities, and critical activities identification.

- Early bar chart schedule representation for the selected scenario.

- The project performances for the selected scenario, including the total duration, the total direct and indirect cost, and the overall quality performance of the project.
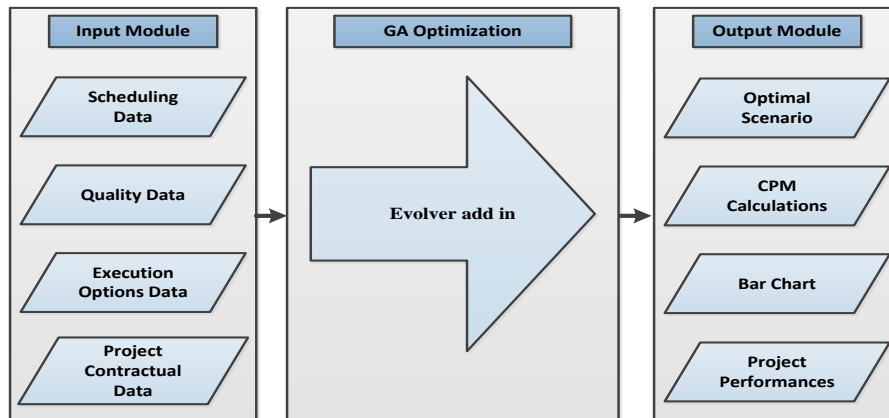
Figure 4.4: The simplified TCQ model description

4.2.3 Model Implementation and Validation

In order to validate the developed model and demonstrate its efficiency, the model was applied to a case study. This case study was originally introduced by Feng et al. (1997) and used by many researchers in studying TCT analysis such as Hegazy and Ayed (1999), Hegazy and Ersahin (2001), and Ng and Zhang (2008). Data of the original example was then expanded to illustrate the impact of each resource utilization option on construction quality in addition to its time and cost by El-Rayes and Kandil (2005), and Afshar et al. (2007). The case study project consists of 18 construction activities, where each one has a number of possible resource utilization options to execute that activity. Precedence relationships among activities of the project are shown in Figure 4.5. Duration, cost, and quality data of different execution options as presented by El-Rayes and Kandil (2005) are shown in Table 4.1.
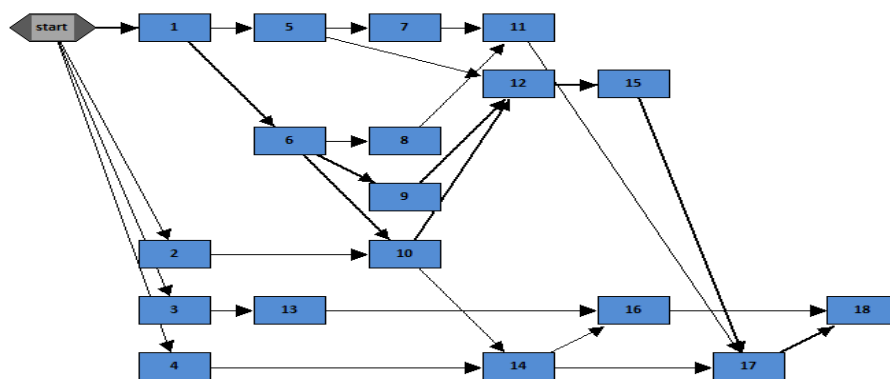
Figure 4.5: The simplified model case study network

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Table 4.1: The Original data of the application example (El-Rayes & Kandil, 2005)

Activity	Resource Options	Duration	Cost	Activity Weight (Wt_i)	Quality Indicator K=1		Quality Indicator K=2		Quality Indicator K=3	
					Indicator Weight ($Wt_{i,k}$)	Quality Performance ($Q_{i,k}^n$)	Indicator Weight ($Wt_{i,k}$)	Quality Performance ($Q_{i,k}^n$)	Indicator Weight ($Wt_{i,k}$)	Quality Performance ($Q_{i,k}^n$)
1	1	14	2,400	3	50	100	30	96	20	98
	2	15	2,150			90		89		89
	3	16	1,900			86		77		84
	4	21	1,500			75		72		73
	5	24	1,200			63		60		65
2	1	15	3,000	5	40	98	40	94	20	99
	2	18	2,400			87		94		95
	3	20	1,800			81		92		85
	4	23	1,500			77		72		70
	5	25	1,000			60		66		59
3	1	15	4,500	8	70	100	15	97	15	98
	2	22	4,000			80		82		81
	3	33	3,200			62		60		63
4	1	12	45,000	11	50	99	35	95	15	94
	2	16	35,000			74		71		76
	3	20	30,000			59		63		64
5	1	22	20,000	10	60	100	20	97	20	99
	2	24	17,500			93		89		89
	3	28	15,000			77		71		72
	4	30	10,000			61		64		61
6	1	14	40,000	11	50	95	25	95	25	100
	2	18	32,000			76		74		79
	3	24	18,000			59		62		68
7	1	9	30,000	10	30	97	30	99	40	93
	2	15	24,000			70		73		71
	3	18	22,000			61		62		67
8	1	14	220	1	100	95	0		0	
	2	15	215			83				
	3	16	200			75				
	4	21	208			68				
	5	24	120			61				
9	1	15	300	1	50	100	50	99	0	
	2	18	240			97		92		
	3	20	180			81		88		
	4	23	150			71		75		
	5	25	100			63		64		
10	1	15	450	1	60	94	40	97	0	
	2	22	400			79		83		
	3	33	320			63		69		
11	1	12	450	2	70	96	30	95	0	
	2	16	350			72		75		
	3	20	300			61		66		
12	1	22	2,000	3	50	99	35	98	15	95
	2	24	1,750			89		85		87
	3	28	1,500			70		71		79
	4	30	1,000			62		61		63
13	1	14	4,000	7	40	99	40	96	20	97
	2	18	3,200			73		71		76
	3	24	1,800			60		62		63
14	1	9	3,000	6	80	100	10	95	10	98
	2	15	2,400			79		82		81
	3	18	2,200			63		67		66
15	1	16	3,500	7	70	100	30	98	0	
16	1	20	3,000	3	30	97	30	96	40	98
	2	22	2,000			89		85		87
	3	24	1,750			81		79		78
	4	28	1,500			72		73		74
	5	30	1,000			67		60		62
17	1	14	4,000	6	70	98	20	97	10	99
	2	18	3,200			73		75		72
	3	24	1,800			62		65		61
18	1	9	3,000	5	30	98	45	99	25	94
	2	15	2,400			75		77		71
	3	18	2,200			63		66		67

Original data of the example was re-organized and tabulated in order to represent each activity in one row as shown in the input spreadsheet of Figure 4.6. Columns C and D are used to identify the activity, columns E to J are used to characterize dependency relationships among activities, column K is used to define each activity's weight within the whole project, and columns L to N are used to specify weights of the three quality indicators for each activity. It is obvious that the sum of weights of all activities equals 100% and the sum of quality indicators for each activity equals 100%. The indirect cost of the project is assumed a fixed value of 1500 $ per day. A late completion penalty of 20,000 $ per day is assumed and no incentive for early completion is considered. The minimum acceptable quality of the project and its deadline are set 70% and 130 days respectively.

	Activity ID	Activity Description	Predecessors			Successors			Activity Weight (%)	Quality Indicator weight # 1	Quality Indicator weight # 2	Quality Indicator weight # 3
			P1	P2	P3	S1	S2	S3				
1	1	A				5	6		3	50	30	20
2	2	B				10			5	40	40	20
3	3	C				13			8	70	15	15
4	4	D				14			11	50	35	15
5	5	E	1			7	12		10	60	20	20
6	6	F	1			8	9	10	11	50	25	25
7	7	G	5			11			10	30	30	40
8	8	H	6			11			1	100	0	0
9	9	I	6			12			1	50	50	0
10	10	J	2	6		12	14		1	60	40	0
11	11	K	7	8		17			2	70	30	0
12	12	L	5	9	10	15			3	50	35	15
13	13	M	3			16			7	40	40	20
14	14	N	4	10		16	17		6	80	10	10
15	15	O	12			17			7	70	30	0
16	16	P	13	14		18			3	30	30	40
17	17	Q	11	14	15	18			6	70	20	10
18	18	R	16	17					5	30	45	25
									100			

TCQ Model Constraints	
Penalty $/day	20000
Bonus $/day	0
Indirect Cost $/day	1500
Deadline (days)	130
Minimum Acceptable Quality (%)	70

Figure 4.6: The input data of the simplified model

The spreadsheet of Figure 4.7 shows the time, cost, and quality performance in quality indicators corresponding to each execution option (columns O to AM).

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Option #1					Option #2					Option #3					Option #4					Option #5				
Dur. (days)	Cost ($)	Quality Perf. Ind. #1	Quality Perf. Ind. #2	Quality Perf. Ind. #3	Dur. (days)	Cost ($)	Quality Perf. Ind. #1	Quality Perf. Ind. #2	Quality Perf. Ind. #3	Dur. (days)	Cost ($)	Quality Perf. Ind. #1	Quality Perf. Ind. #2	Quality Perf. Ind. #3	Dur. (days)	Cost ($)	Quality Perf. Ind. #1	Quality Perf. Ind. #2	Quality Perf. Ind. #3	Dur. (days)	Cost ($)	Quality Perf. Ind. #1	Quality Perf. Ind. #2	Quality Perf. Ind. #3
14	2400	100	96	98	15	2150	90	89	89	16	1900	86	77	84	21	1500	75	72	73	24	1200	63	60	65
15	3000	98	94	99	18	2400	87	94	95	20	1800	81	92	85	23	1500	77	72	70	25	1000	60	66	59
15	4500	100	97	98	22	4000	80	82	81	33	3200	62	60	63										
12	45000	99	95	94	16	35000	74	71	76	20	30000	59	63	64										
22	20000	100	97	99	24	17500	93	89	89	28	15000	77	71	72	30	10000	61	64	61					
14	40000	95	95	100	18	32000	76	74	79	24	18000	59	62	68										
9	30000	97	99	93	15	24000	70	73	71	18	22000	61	62	67										
14	220	95			15	215	83			16	200	75			21	208	68			24	120	61		
15	300	100	99		18	240	97	92		20	180	81	88		23	150	71	75		25	100	63	64	
15	450	94	97		22	400	79	83		33	320	63	69											
12	450	96	95		16	350	72	75		20	300	61	66											
22	2000	99	98	95	24	1750	89	85	87	28	1500	70	71	79	30	1000	62	61	63					
14	4000	99	96	97	18	3200	73	71	76	24	1800	60	62	63										
9	3000	100	95	98	15	2400	79	82	81	18	2200	63	67	66										
16	3500	100	98																					
20	3000	97	96	98	22	2000	89	85	87	24	1750	81	79	78	28	1500	72	73	74	30	1000	67	60	62
14	4000	98	97	99	18	3200	73	75	72	24	1800	62	65	61										
9	3000	98	99	94	15	2400	75	77	71	18	2200	63	66	67										

Figure 4.7: The performance of execution options of activities of the simplified model

For the output spreadsheet of Figure 4.8, column C identifies the activity ID and column D determines the number of available execution options for each activity. Columns E to G are used to show the selected execution option for each activity and to specify the duration and cost associated with such an option. The quality of the selected option is calculated based on Equation 4.5 (column H). The total project cost, duration, and quality are computed as previously discussed in section 4.2.1. The model is designed to modify the total project cost, duration, and quality when a selected option index is changed. It is required to obtain a combination of execution options in order to achieve the desired objectives.

Activating the Evolver add-in, the optimization goal is to minimize the total project cost. The optimization variables or the adjustable cell ranges are the values of option indices (column E). It is noticeable that such indices should be integer numbers, greater than zero, and within the available number of options for each activity (column D). The first optimization constraint is to restrict the total duration of the project less than the project deadline. The second optimization constraint is to restrict the overall project quality more than the minimum acceptable quality. Three additional optimization scenarios are applied as follows:

- The optimization goal is minimizing the total project duration, while restricting the total project cost and quality.

- The optimization goal is maximizing the overall project quality, while restricting the total project duration and cost.

- The optimization goal is minimizing the value of T*C/Q in order to simultaneously minimize the total project cost and duration while maximizing the overall project quality.

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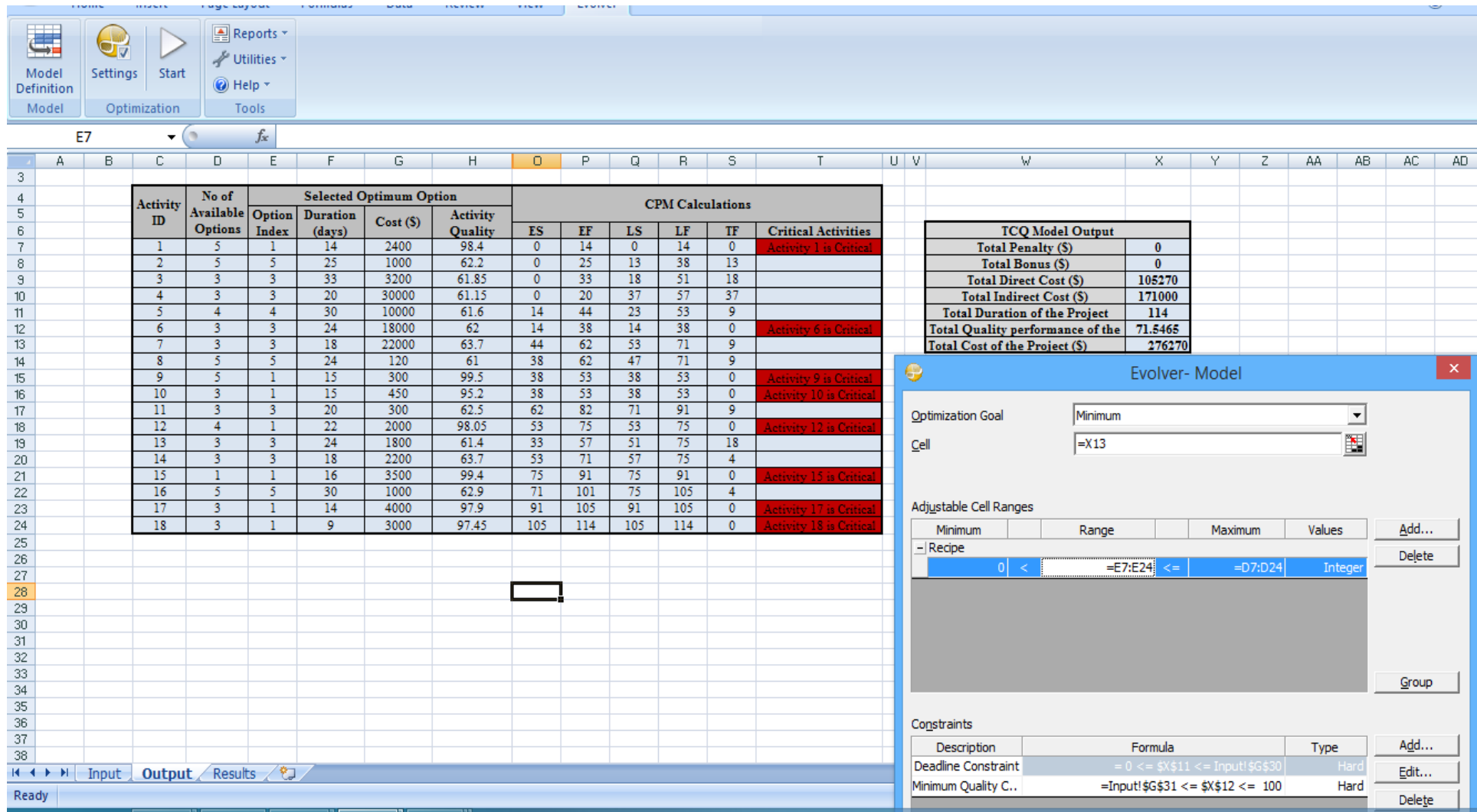
Figure 4.8: The simplified model optimization formulation

After the Evolver optimization stops, the output optimum or near optimum scenario is obtained. As shown in Figure 4.9, columns O to R determine the early and late times of each activity, column S determines the total float of each activity, and column T identifies the critical and non-critical activities. The total project duration, direct cost, indirect cost, and quality are computed. In addition, an early bar chart of the selected scenario is developed.

Results of the four optimization scenarios are summarized in Table 4.2. To examine the quality of results of the simplified model, they were compared with results of Table 4.3, which were obtained by El-Rayes and Kandil (2005). It is obvious that the results of the simplified model are comparable with the results of El-Rayes and Kandil (2005). For instance, the second solution of the simplified model dominates the second one of El-Rayes and Kandil (2005). For the simultaneous optimization scenario, the direct cost is 153,820 by the simplified model; however, it was 166,320 by the literature model for the same total duration (104 day) and a slight decrease in overall quality (95% and 93.7%). In addition, the maximum quality and minimum direct cost obtained by the simplified model are better. For instance, the minimum direct cost obtained by the simplified TCQ model is 103,700; however, it was 104,620 by the literature model. The maximum quality obtained by the simplified TCQ model is 97.63%; however, it was 95% by the literature model. Constraints may be also utilized to improve the obtained solutions by increasing the minimum quality constraint and reducing the deadline constraint.

Activity ID	No of Available Options	Selected Optimum Option				CPM Calculations					
		Option Index	Duration (days)	Cost ($)	Activity Quality	ES	EF	LS	LF	TF	Critical Activities
1	5	1	14	2400	98.4	0	14	0	14	0	Activity 1 is Critical
2	5	1	15	3000	96.6	0	15	13	28	13	
3	3	1	15	4500	99.25	0	15	46	61	46	
4	3	3	20	30000	61.15	0	20	46	66	46	
5	4	1	22	20000	99.2	14	36	21	43	7	
6	3	1	14	40000	96.25	14	28	14	28	0	Activity 6 is Critical
7	3	1	9	30000	96	36	45	60	69	24	
8	5	1	14	220	95	28	42	55	69	27	
9	5	1	15	300	99.5	28	43	28	43	0	Activity 9 is Critical
10	3	1	15	450	95.2	28	43	28	43	0	Activity 10 is Critical
11	3	1	12	450	95.7	45	57	69	81	24	
12	4	1	22	2000	98.05	43	65	43	65	0	Activity 12 is Critical
13	3	1	14	4000	97.4	15	29	61	75	46	
14	3	1	9	3000	99.3	43	52	66	75	23	
15	1	1	16	3500	99.4	65	81	65	81	0	Activity 15 is Critical
16	5	1	20	3000	97.1	52	72	75	95	23	
17	3	1	14	4000	97.9	81	95	81	95	0	Activity 17 is Critical
18	3	1	9	3000	97.45	95	104	95	104	0	Activity 18 is Critical

TCQ Model Output	
Total Penalty ($)	0
Total Bonus ($)	0
Total Direct Cost ($)	153820
Total Indirect Cost ($)	156000
Total Duration of the Project	104
Total Quality performance of the	93.702
Total Cost of the Project ($)	309820

Early Bar Chart

Figure 4.9: The simplified model output

Table 4.2: Results of the simplified model

Solution	Act.1	Act.2	Act.3	Act.4	Act.5	Act.6	Act.7	Act.8	Act.9	Act.10	Act.11	Act.12	Act.13	Act.14	Act.15	Act.16	Act.17	Act.18	Time	Direct Cost	Total Cost	Quality
Min. Direct Cost	3	5	3	3	4	3	3	5	3	1	2	4	3	3	1	5	1	1	129	103,700	297,200	70.05%
Min. Total Cost	1	5	3	3	4	3	3	5	1	1	3	1	3	3	1	5	1	1	114	105,270	276,270	71.55%
Min. Duration	1	2	2	1	3	1	3	4	1	1	2	1	3	3	1	3	1	1	104	150,358	306,358	84.28%
Max. Quality	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	104	168,820	324,820	97.63%
Min. (T*C/Q)	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	104	153,820	309,820	93.70%

Table 4.3: Results of El-Rayes and Kandil (2005)

Solution	Optimal resource utilization options[a]	Time (days)	Cost (dollars)	Quality (%)
		Project performance		
1	{1,1,1,1,2,1,1,1,1,1,1,1,1,1,1,1,1,1}	104	166,320	95
2	{1,5,3,3,4,3,3,5,1,1,3,1,3,2,1,5,1,1}	114	105,470	71
3	{2,3,1,1,2,3,1,1,1,1,1,1,1,1,1,3,1,1}	115	141,620	90
4	{2,5,1,3,4,2,3,3,1,1,1,1,3,1,1,5,1,1}	109	121,350	77
5	{1,5,1,3,4,3,3,5,1,1,2,1,3,2,1,5,3,1}	124	104,620	72

4.2.4 Model Capabilities and Limitations

Despite its efficiency and simplicity, the simplified model has some limitations. Table 4.4 summarizes the capabilities and limitations of the simplified model.

Table 4.4: Capabilities and limitations of the Simplified TCQ model

Simplified TCQ Model	
Advantages and Capabilities	Disadvantages and Limitations
Simplicity and ease of use associated with the utilization of MS Excel and the Evolver GA optimization tool	Only three predecessors and three successors are available for each activity
Penalty for late completion and bonus for early completion are considered	Generalized relationships among activities are not considered
Direct and indirect costs of the project are included	Uncertainty is not considered
Early and late start and finish of all activities are determined	Huge data entry for large-scale projects
Critical activities are identified	Subjectivity in quantifying quality of different execution options
Bar chart of the project is developed	

4.3 Stochastic Time-Cost-Quality Trade-Off Model

Actual time, cost, and quality of execution options for various activities within a considered project cannot be determined certainly prior to construction. The objective of this model is to optimize time, cost, and quality of construction projects under uncertainty utilizing the PERT approach. For a desired confidence level, it is required to find a set of execution options for the project's activities in order to minimize the total project cost and duration while its overall quality is maximized.

4.3.1 The Proposed Approach and Methodology

As shown in Figure 4.10, a project with (n) number of activities has different execution options for executing each activity. Each execution option for each activity represents an alternative of different construction methods, equipment, crews' formation, or overtime policy. Each execution option has values of duration, cost, and quality. Such values should not be specified by precise or deterministic values due to uncertainty associated with them. Therefore, each attribute of a considered execution option is characterized by three points: the optimistic; the pessimistic; and the most likely value.
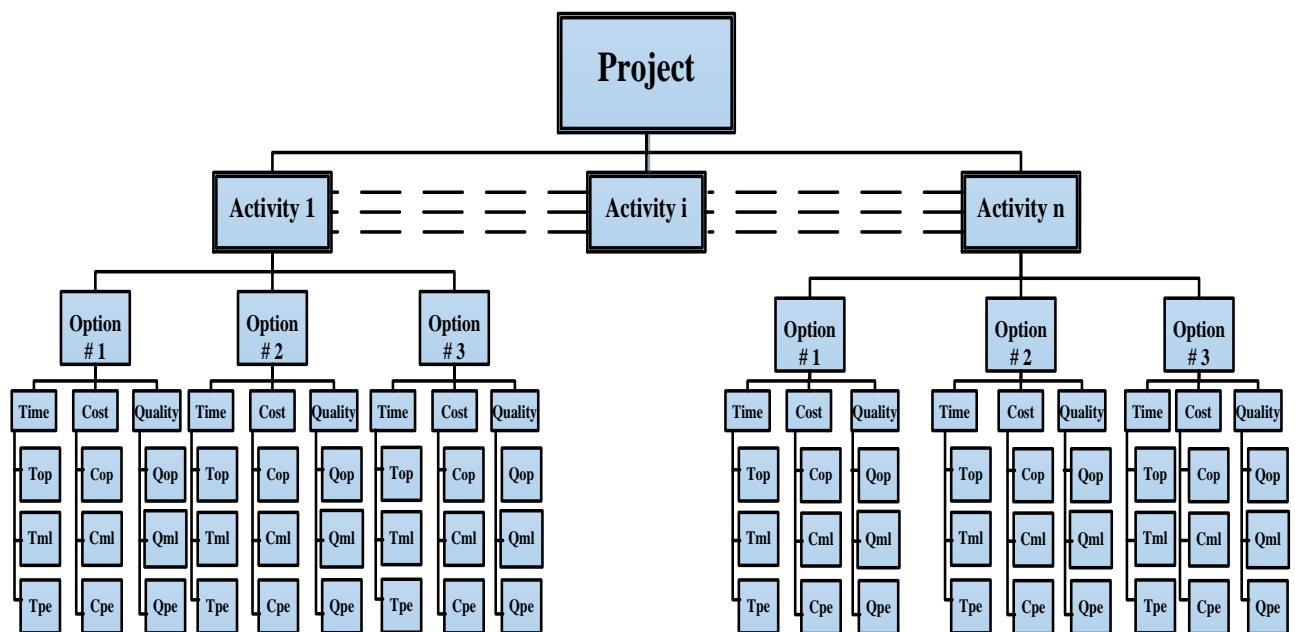
Figure 4.10: The Project structure of the stochastic model

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4.3.1.1 Total Project Duration

For each activity, the expected value or weighted mean of its duration and the variance of duration are computed as previously discussed in section 2.2.3. The expected value of duration is calculated using equation 2.1, and its standard deviation and variance are calculated using Equations 2.1 to 2.3.

To compute the total duration of the project, CPM calculations previously discussed in sections 2.2.2 and 4.2.1.4 are applied to the expected duration values for selected execution options. The EF value of the end node or the finish activity is considered the mean value of the total project duration. On the other hand, the variance of the whole project duration is the sum of duration variance values of activities on the critical path. If there is more than one critical path, the largest variance is considered. As shown in Figure 4.11, the normal probability distribution is then used to estimate an upper bound of the total project duration for a desired confidence level (Montgomery & Runger, 2003).
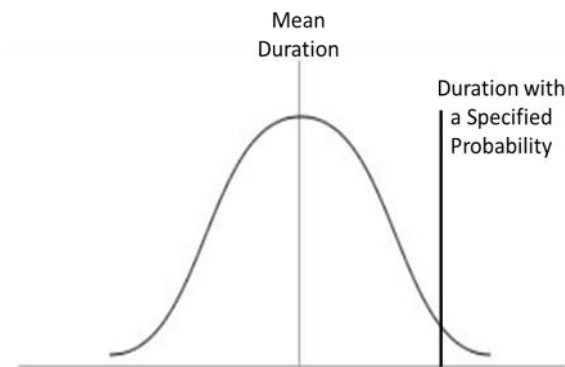
Figure 4.11: Applying the normal distribution to the project duration

4.3.1.2 Total Project Cost

Similar to duration, the expected value or weighted mean of cost of an activity and its cost variance are calculated based on the PERT approach using the following equations:

$$Ce = (Cop + 4*Cml + Cpe) / 6$$

Equation 4. 7

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$$Sc = (Cpe - Cop)/6$$

Where Cop is the optimistic value of activity cost, Cml is its most likely cost value, and Cpe is its pessimistic cost value.

To compute the total cost of the project, the calculated expected values of cost are considered. The total project direct cost is the sum of expected direct costs of all the project's activities for selected execution options. The indirect cost is assumed a fixed value per time unit. There may be a penalty cost and a bonus incentive reward for late and early completion respectively. The mean value of the total project cost is calculated using Equation 4.1 previously illustrated in section 4.2.1.3. The variance of the whole project cost is the sum of cost variance values of all activities of the project. As shown in Figure 4.12, the normal probability distribution is also used to estimate an upper bound of the total project cost for a desired confidence level (Montgomery & Runger, 2003).
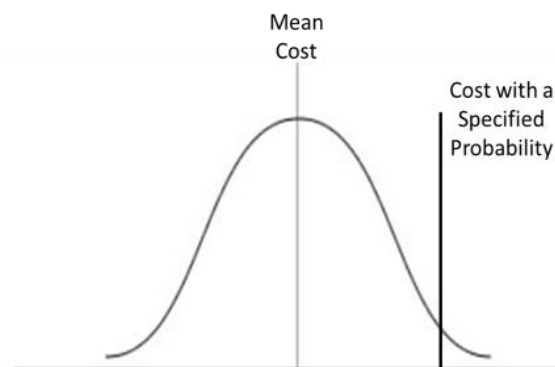
Figure 4.12: Applying the normal distribution to the project cost

4.**3.1.3 Overall Project Quality**

Quality of execution options is described by linguistic terms such as highest, high, and low. Such terms could be then represented by a three values of optimistic, most likely, and pessimistic quality as shown in Table 4.5 originally introduced by Zhang and Xing (2010).

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Table 4.5: Quality values for linguistic terms

Linguistic description	Q_{pe}	Q_{ml}	Q_{op}
The Highest	0.9	1	1
Very High	0.7	0.9	1
High	0.6	0.8	0.9
Medium	0.4	0.6	0.7
Low	0.2	0.4	0.6
Very Low	0	0.2	0.4
The Lowest	0	0	0.2

Similar to cost and duration, the expected value or weighted mean of quality of an activity and its quality variance are calculated based on the PERT approach using the following equations:

$$Qe = (Qop + 4*Qml + Qpe) / 6$$

Equation 4. 9

$$S_Q = (Qop - Qpe)/6$$

Equation 4. 10

Where Qop is the optimistic quality value, Qml is its most likely quality value, and Qpe is the pessimistic quality value.

The mean value of the overall project quality is calculated using Equation 4.6 previously illustrated in sections 4.2.1.5 and 2.4.2.1. The variance of the whole project quality is the sum of quality variance values of all activities of the project. As shown in Figure 4.13, the normal probability distribution is also used to estimate a lower bound of the overall project quality for a desired confidence level (Montgomery & Runger, 2003).
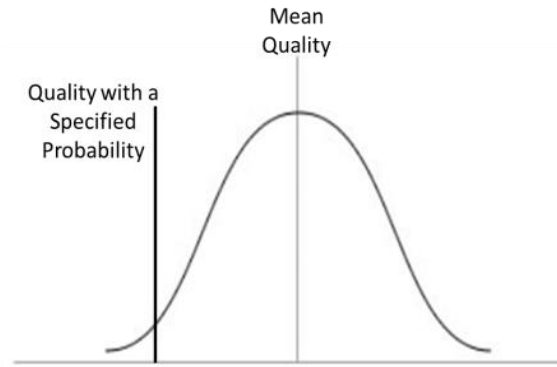
Figure 4.13: Applying the normal distribution to the project quality

4.3.1.4 Decision Variables

As previously discussed in section 4.2.1.1, decision variables of the stochastic model are indices of execution options that can be used to execute each activity within the project. The calculated expected values of duration, cost, and quality for each option are considered.

4.3.1.5 Optimization Constraints

The optimization constraints of the stochastic model are same constraints of the simplified model previously discussed in section 4.2.1.2.

4.3.1.6 Optimization Tool

The GA based modeling and optimization tool, *Evolver,* is utilized to solve the model.

4.3.2   Model Description and Organization

The proposed stochastic model incorporates four distinct modules, which are the input, the PERT calculations, the optimization, and the schedule module as shown in Figure 4.14.

100
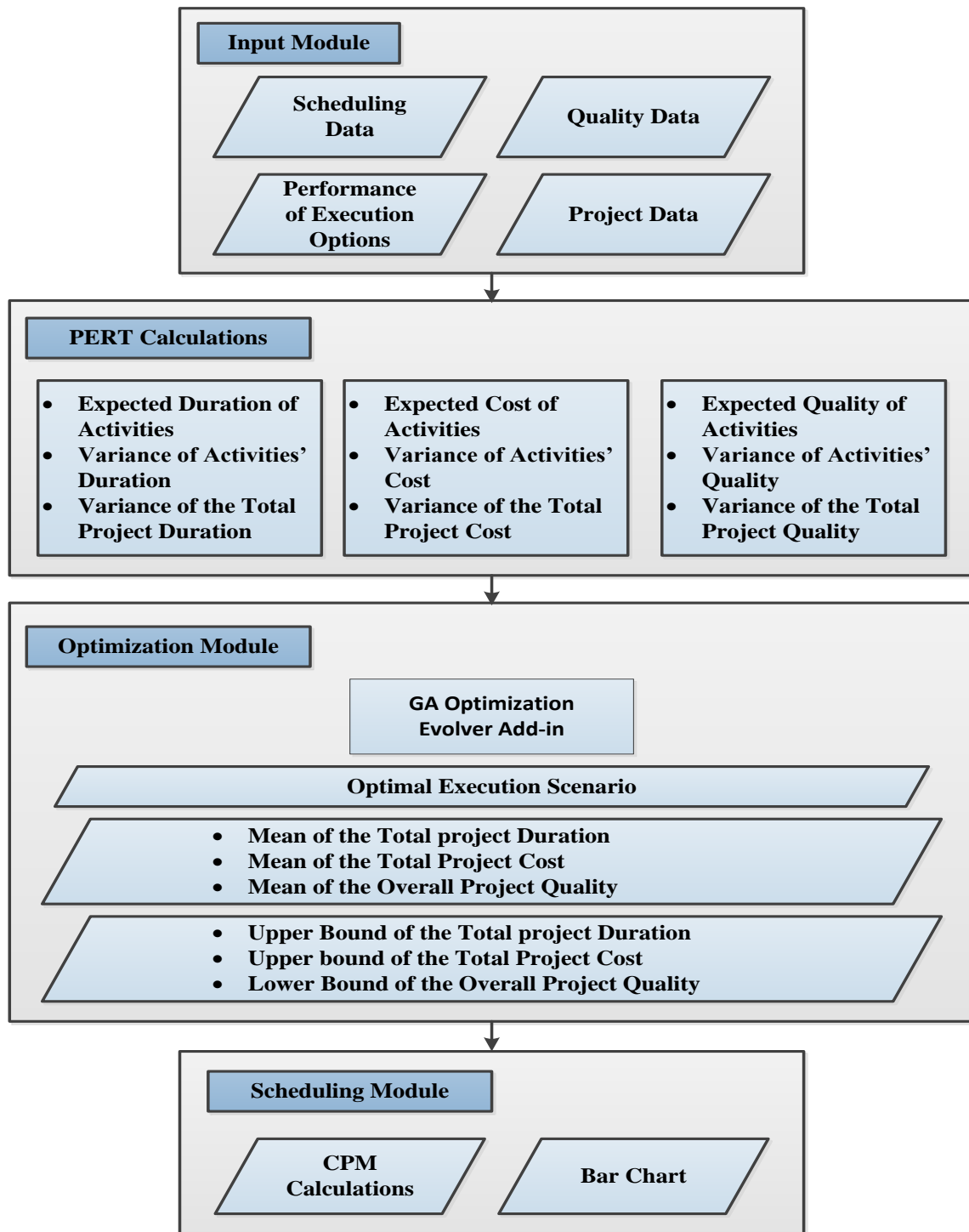
Figure 4. 14: The stochastic TCQ model description

4.3.2.1 Input Module

The first module is the input module, in which the model user specifies activities description, precedence data, and performance of execution options. The activity number from 1 to (n), where (n) is the total number of activities of the project, and the activity

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description are identified. The user then enters the number of predecessors, and number of successors for each activity. Weights of activities in percentage, which represents the relative importance of each activity and its effect on the overall project's quality, are defined. For each of the five available execution options for each activity, the user specifies three duration values and three cost values as previously illustrated in section 4.3.1. Quality of each option is selected from a list of linguistic terms ranging from highest quality to lowest quality performance. The project constraints including the minimum acceptable quality and the project deadline are defined. The indirect cost per unit of time, penalties, and bonus rewards are also specified by the model user.

4.3.2.2 PERT Calculations Module

The second module is the PERT calculations module, in which the expected values and variance of duration, cost, and quality are calculated for all activities. As previously discussed in section 4.3.1, optimistic, pessimistic, and most likely values of cost and duration of each execution option is used to calculate its mean or expected value and its variance regarding cost and duration. On the other hand, linguistic performance of quality for each execution option is transformed to a numerical value of expected quality and quality variance based on the pre-specified fuzzy numbers. Variance of a project's duration is calculated as the sum of variances of activities on the critical path for the selected execution options. A VBA macro is developed to identify the critical path and calculate the sum of variances of activities on it. The variance of the project's cost and quality are the sum of variances of all activities of the projects for the selected execution options.

4.3.2.3 Optimization Module

The third module is the optimization module, in which the selection of execution options for different activities is acquired in order to obtain optimum or near optimum construction scenario for the project with regard to decision makers' preference. Several optimization

approaches may be applied in this module. For instance, it can optimize the mean value of the project cost, duration, or quality. It can also optimize their values for a desired confidence level.

4.3.2.4 Scheduling Module

The fourth module is the scheduling module, by which CPM calculations and visualized early and late bar charts are generated for the optimal solution.

4.3.3 Model Implementation and Validation

An application example is analyzed in order to validate the stochastic TCQ model and demonstrate its capabilities in generating optimal TCQ trade-offs. The example was originally introduced by Zhang and Xing (2010) to study the stochastic TCQT problem. The example consists of 13 construction activities, where each has a number of possible execution options that can be used to execute the activity. Each execution option has three values of time and cost; however, its quality performance is described by a linguistic term. Precedence relationships among activities of the project are shown in Figure 4.15 and time, cost, and quality data of different execution options as presented by Zhang and Xing (2010) are shown in Table 4.6.
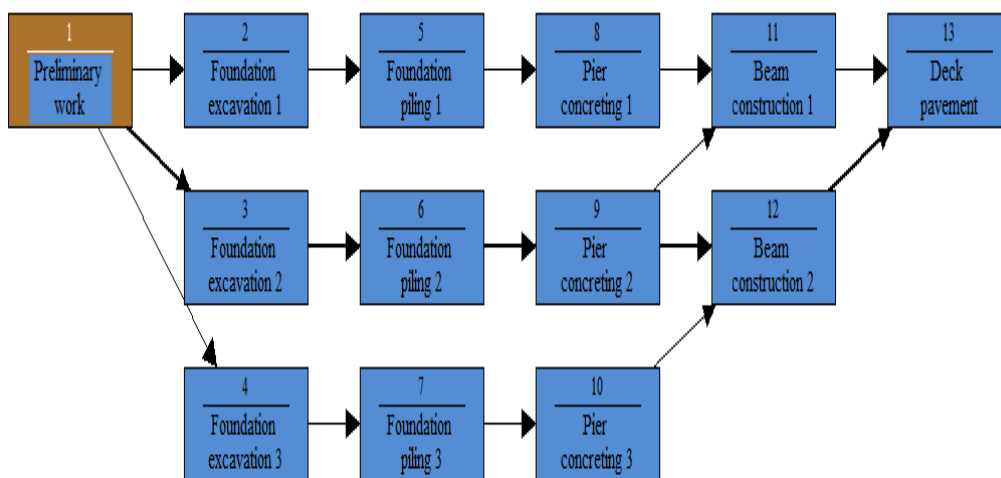
Figure 4.15: The network of the stochastic application example

Table 4.6: The original data of the stochastic application example (Zhang & Xing, 2010)

No	Name	Activity Weight	Method	Time			Cost (10^3)			Quality			
1	Preliminary work	0.01	1	26	28	30	16	18	20	0.9	1	1	Highest
			2	23	25	27	19	20	22	0.7	0.9	1	V. High
			3	17	19	21	20	22	24	0.6	0.8	0.9	High
2	Foundation excavation 1	0.08	1	40	42	46	160	170	180	0.9	1	1	Highest
			2	35	37	39	180	190	200	0.6	0.8	0.9	High
			3	30	33	36	210	220	230	0.2	0.4	0.6	Low
3	Foundation excavation 2	0.09	1	40	45	50	165	175	185	0.9	1	1	Highest
			2	38	40	43	190	200	210	0.4	0.6	0.7	Medium
			3	32	35	38	215	225	235	0.2	0.4	0.6	Low
4	Foundation excavation 3	0.08	1	39	44	49	160	170	180	0.9	1	1	Highest
			2	36	38	42	190	200	210	0.4	0.6	0.7	Medium
			3	30	33	36	210	220	230	0.2	0.4	0.6	Low
5	Foundation piling 1	0.11	1	36	38	40	124	134	144	0.9	1	1	Highest
			2	32	34	36	154	164	174	0.6	0.8	0.9	High
			3	28	30	32	210	220	230	0.2	0.4	0.6	Low
6	Foundation piling 2	0.11	1	46	50	54	180	190	200	0.9	1	1	Highest
			2	40	42	44	220	230	240	0.4	0.6	0.7	Medium
			3	33	36	39	260	270	280	0.2	0.4	0.6	Low
7	Foundation piling 3	0.11	1	38	40	42	130	140	150	0.9	1	1	Highest
			2	33	35	37	160	170	180	0.7	0.9	1	V. High
			3	28	30	32	175	180	185	0.6	0.8	0.9	High
8	Pier concreting 1	0.08	1	83	85	87	210	220	230	0.7	0.9	1	V. High
			2	80	82	84	240	250	250	0.6	0.8	0.9	High
			3	73	75	77	260	275	290	0.4	0.6	0.7	Medium
9	Pier concreting 2	0.08	1	87	90	93	230	240	250	0.7	0.9	1	V. High
			2	82	84	86	250	260	270	0.6	0.8	0.9	High
			3	76	78	80	280	300	320	0.4	0.6	0.7	Medium
10	Pier concreting 3	0.08	1	83	85	87	220	230	240	0.7	0.9	1	V. High
			2	78	80	82	240	250	260	0.6	0.8	0.9	High
			3	74	76	78	270	280	290	0.4	0.6	0.7	Medium
11	Beam construction 1	0.06	1	18	20	22	110	120	130	0.9	1	1	Highest
			2	16	18	20	135	145	155	0.4	0.6	0.7	Medium
			3	14	16	18	150	160	170	0.2	0.4	0.6	Low
12	Beam construction 2	0.06	1	20	22	24	120	130	140	0.9	1	1	Highest
			2	14	17	20	130	140	150	0.4	0.6	0.7	Medium
			3	12	14	16	155	165	175	0.2	0.4	0.6	Low
13	Deck pavement	0.05	1	22	25	28	59	65	71	0.9	1	1	Highest
			2	20	22	24	70	75	80	0.7	0.9	1	V. High
			3	13	15	17	75	80	85	0.6	0.8	0.9	High

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Original data of the example was re-organized and tabulated in order to represent each activity in one row as shown in the input spreadsheet of Figure 4.16. Columns C and D are used to identify the activity, columns E to N are used to characterize dependency relationships among activities, column O is used to define each activity's weight within the whole project, and column P is used to identify the available number of execution options for each activity. The indirect cost of the project is assumed a fixed value of 10 ($*10^3$) Chinese Yuan per day. A late completion penalty of 25 ($*10^3$) Chinese Yuan per day is assumed and no incentive for early completion is considered. The minimum acceptable quality of the project and its deadline are set 60% and 240 days respectively.

As shown in Figures 4.17 to 4.19, the performance of each execution option in terms of duration, cost, and quality is specified for each activity. Three values for cost and duration of each execution option are entered, while its quality performance is selected from a drop list ranging from highest to lowest quality.
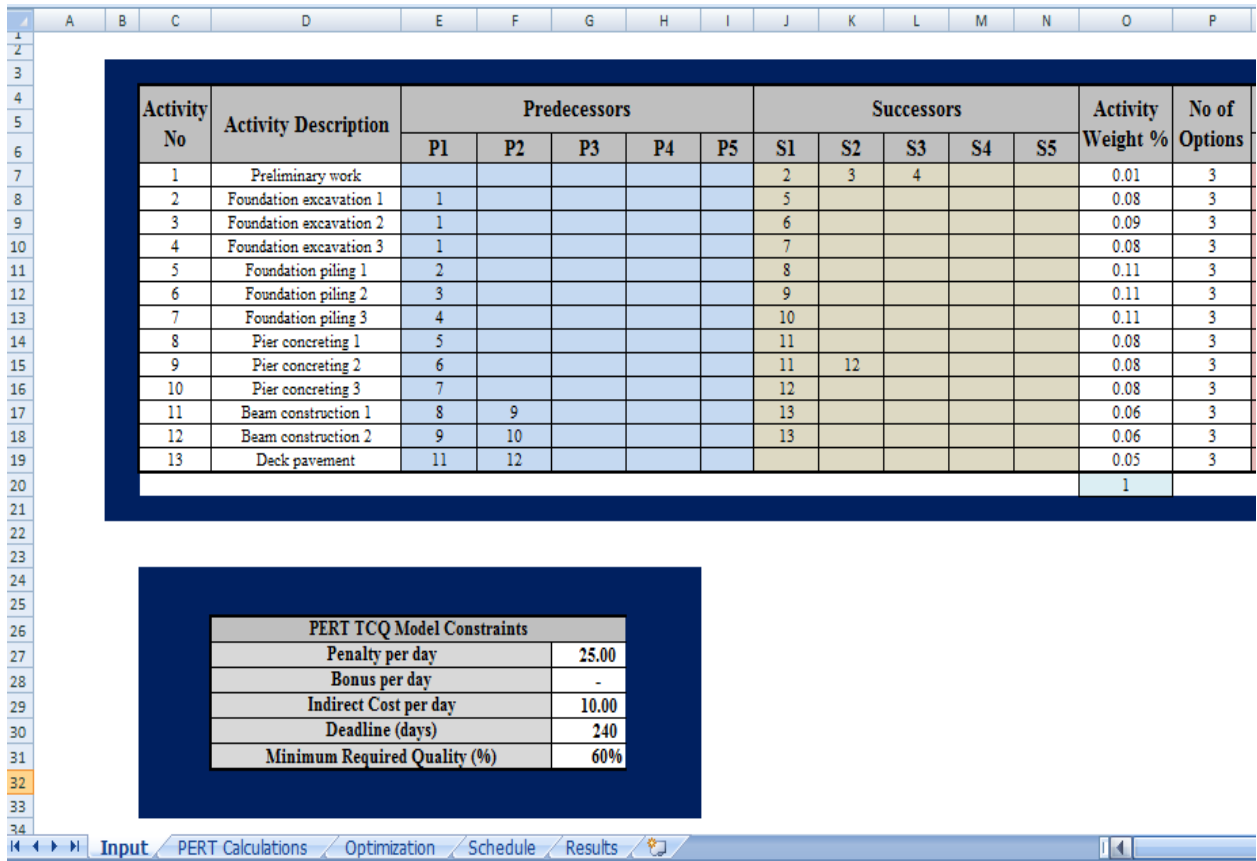
Figure 4.16 The input data of the stochastic model
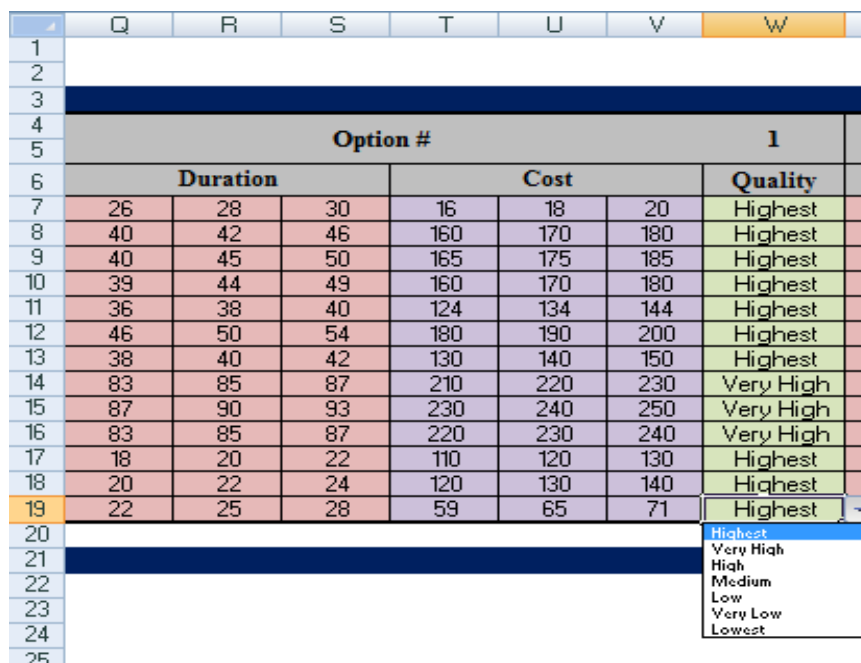
Figure 4.17: The performance of execution option # 1 of the stochastic model

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	Option #					2
	Duration			Cost		Quality
23	25	27	19	20	22	Very High
35	37	39	180	190	200	High
38	40	43	190	200	210	Medium
36	38	42	190	200	210	Medium
32	34	36	154	164	174	High
40	42	44	220	230	240	Medium
33	35	37	160	170	180	Very High
80	82	84	240	250	250	High
82	84	86	250	260	270	High
78	80	82	240	250	260	High
16	18	20	135	145	155	Medium
14	17	20	130	140	150	Medium
20	22	24	70	75	80	Very High

Figure 4.18: The performance of execution option # 2 of the stochastic model

	Option #					3
	Duration			Cost		Quality
17	19	21	20	22	24	High
30	33	36	210	220	230	Low
32	35	38	215	225	235	Low
30	33	36	210	220	230	Low
28	30	32	210	220	230	Low
33	36	39	260	270	280	Low
28	30	32	175	180	185	High
73	75	77	260	275	290	Medium
76	78	80	280	300	320	Medium
74	76	78	270	280	290	Medium
14	16	18	150	160	170	Low
12	14	16	155	165	175	Low
13	15	17	75	80	85	High

Figure 4.19: The performance of execution option # 3 of the stochastic model

As previously discussed in sections 4.3.1 and 4.3.2, the expected value and variance for each activity is calculated as shown in Figure 4.20. Variances of the project cost and quality are summed for all activities; however, the variance of the project duration is calculated for activities on the critical path by a VBA macro called *Critical Variance*.

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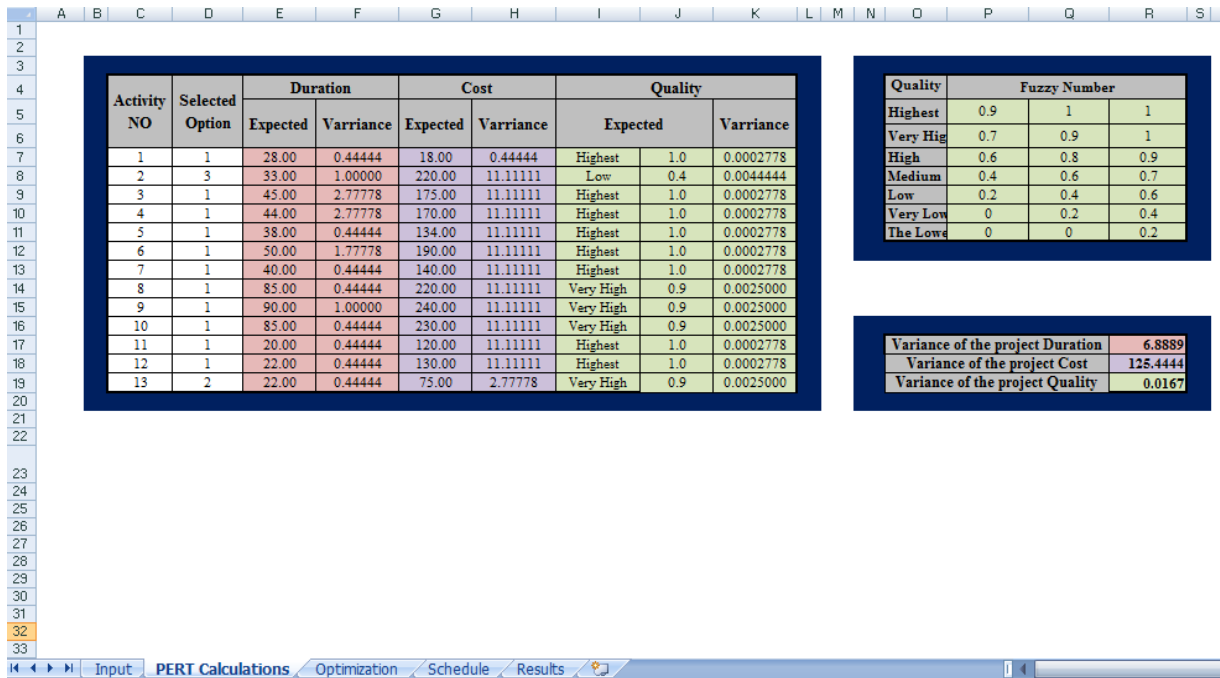
Figure 4.20: PERT calculations for selected execution options of the stochastic model

For the optimization module of Figure 4.21, column C identifies the activity number, column D is used for the activity description, and column E determines the selected number of execution option for each activity. The mean values of the total project duration, direct cost, total cost, and quality are computed as previously illustrated in sections 4.3.1 and 4.3.2. For a selected confidence level, the probabilistic performance values of the project are calculated by applying the normal distribution to the mean and standard deviation of such required values by the following Excel built in function:

$$\text{NORMINV (probability, mean, standard\_dev)}$$

Equation 4. 11

Where NORMINV is the function syntax, probability is the selected confidence level, assumed 90% for this example, mean is the mean value of the total duration, direct cost, total cost, or quality of the project, and standard_dev is the square root of the total variance calculated by the PERT calculations module. The model is designed to modify the values of

mean and probabilistic performance of the whole project when a selected option index is changed.

Activating the Evolver add-in, the optimization variables or the adjustable cell ranges are the values of execution option indices (column E). The optimization constraints are the project deadline and its minimum acceptable overall quality. Several optimization scenarios can be conducted as follows:

- The optimization goal is minimizing the mean total project duration or the upper bound of the total project duration for a desired confidence level.

- The optimization goal is minimizing the mean total project direct cost or the upper bound of the total project direct cost for a desired confidence level.

- The optimization goal is minimizing the mean total project cost or the upper bound of the total project cost for a desired confidence level.

- The optimization goal is maximizing the mean overall project quality or the lower bound of the overall quality for a desired confidence level.

- The optimization goal is minimizing the value of T*C/Q in order to simultaneously minimize the total project cost and duration while maximizing the overall project quality. Where T is the mean total project time, C is the mean total project cost, and Q is the mean overall quality of the project. This scenario may be also conducted for the project performance values for a desired confidence level.

For the schedule module shown in Figure 4.22, the CPM times and floats are calculated, and the early and late bar charts are generated.
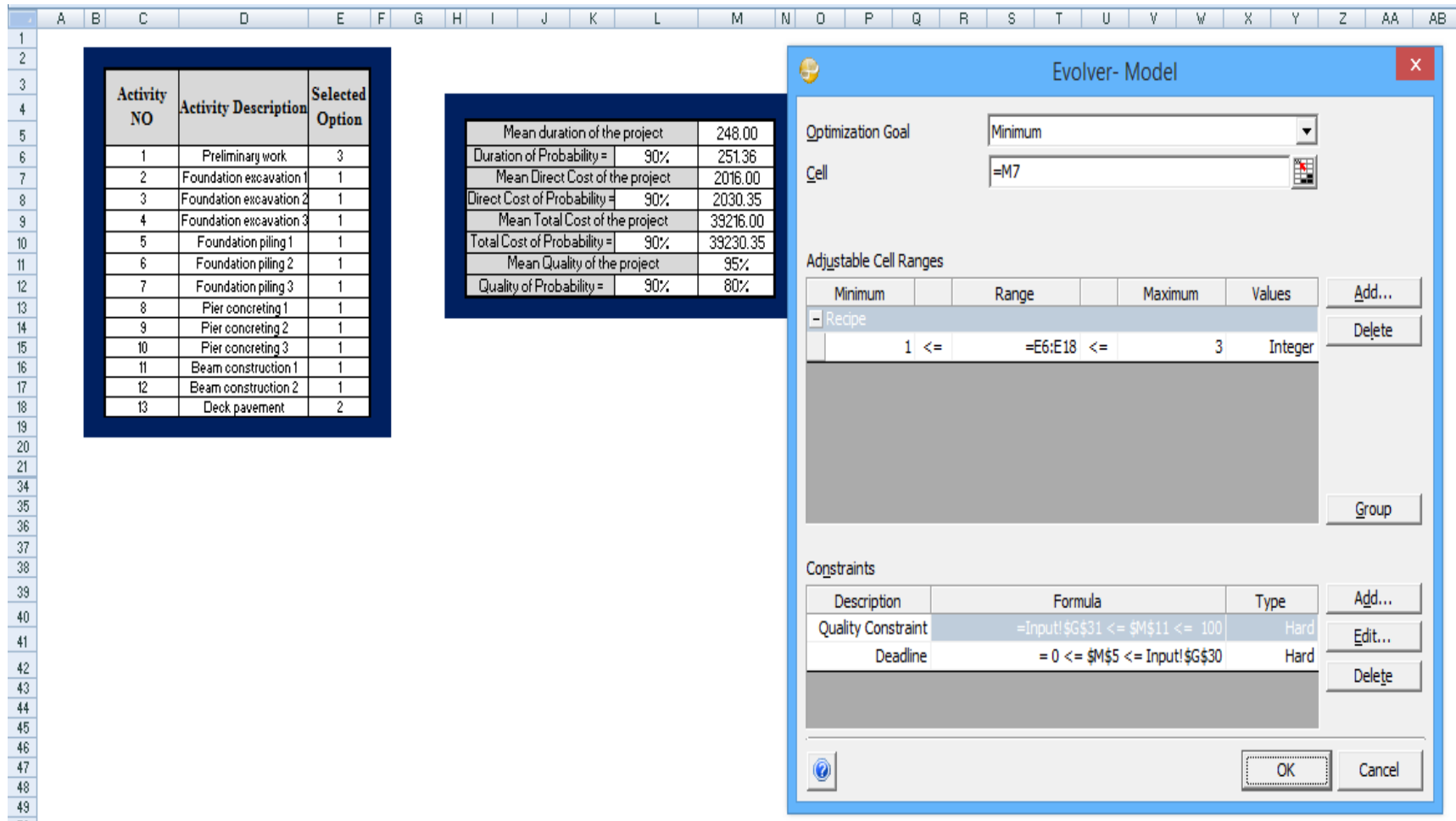
Figure 4.21: The optimization formulation of the stochastic model

Activity NO	Expected Duration	CPM Calculations					
		ES	EF	LS	LF	TF	Critical Activities
1	28.00	0.00	28.00	0.00	28.00	0.00	Activity 1 is Critical
2	33.00	28.00	61.00	51.00	84.00	23.00	
3	45.00	28.00	73.00	28.00	73.00	0.00	Activity 3 is Critical
4	44.00	28.00	72.00	56.00	100.00	28.00	
5	38.00	61.00	99.00	84.00	122.00	23.00	
6	50.00	73.00	123.00	73.00	123.00	0.00	Activity 6 is Critical
7	30.00	72.00	102.00	100.00	130.00	28.00	
8	85.00	99.00	184.00	122.00	207.00	23.00	
9	84.00	123.00	207.00	123.00	207.00	0.00	Activity 9 is Critical
10	80.00	102.00	182.00	130.00	210.00	28.00	
11	20.00	207.00	227.00	207.00	227.00	0.00	Activity 11 is Critical
12	17.00	207.00	224.00	210.00	227.00	3.00	
13	15.00	227.00	242.00	227.00	242.00	0.00	Activity 13 is Critical
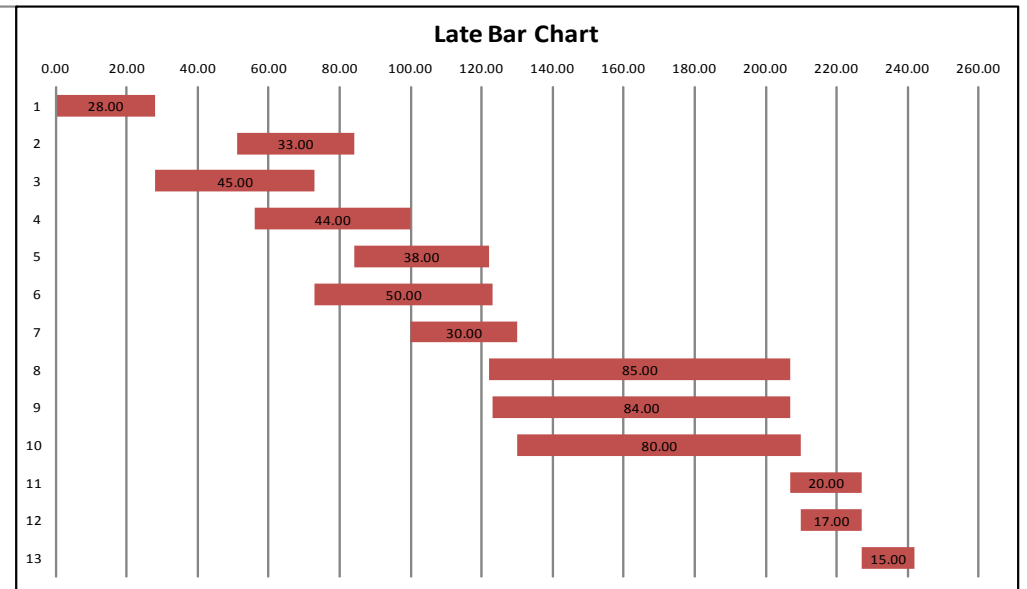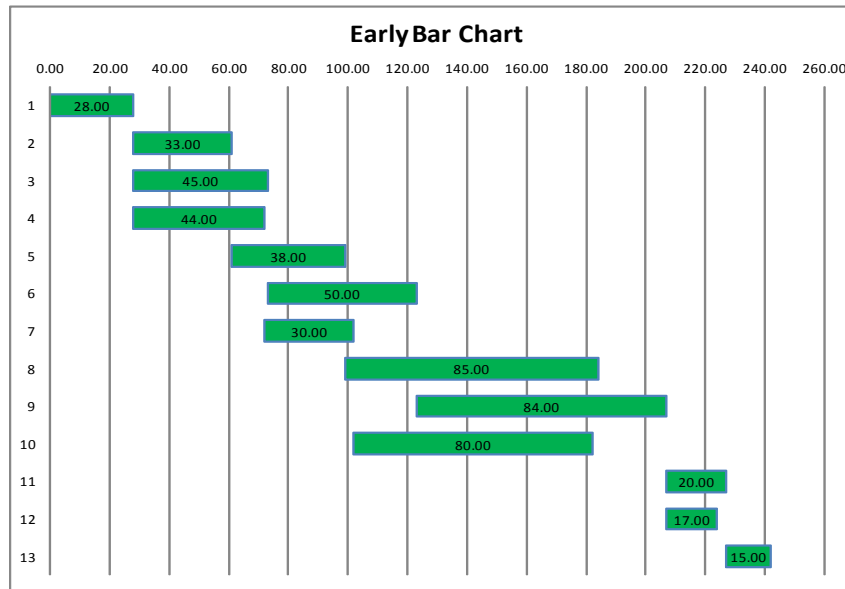
Figure 4.22: The schedule module output of the stochastic model

In order to validate the results provided by the stochastic TCQ model, they were compared to those reported in the literature for the same application example as shown in Tables 4.7 and 4.8. It is obvious that satisfactory results are obtained by the stochastic TCQ model. For instance, the mean performance values of the simultaneous optimization scenario are better than those of the literature results in terms of cost and quality. In addition, the stochastic model generates better results when a single objective optimization approach is conducted. For instance, a maximum value of quality of 92.53% was obtained by the stochastic model, while the quality value of the literature results was 88.6%. Another comment on the literature results is that the generated execution options do not result in the reported performance of the project.

Table 4.7: Results of the stochastic model

Solution	Resource Utilization Options for Activities													Duration	Duration with P=90%	Direct cost	Direct cost with P=90%	Total cost	Total cost with P=90%	Quality	Quality with P=90%
	1	2	3	4	5	6	7	8	9	10	11	12	13								
Min. Direct Cost	3	1	2	1	1	1	1	1	2	1	1	2	3	228.167	230.809	2076	2090.354	4357.667	4372.02	0.8793	0.7019106
Min. Total Cost	3	1	2	1	1	2	1	1	2	1	1	2	3	220.167	222.355	2116	2130.354	4317.667	4332.02	0.8353	0.6479072
Min. Duration	3	3	3	2	1	3	3	3	3	2	3	3	3	199	201.491	2481	2497.429	4471	4487.429	0.604	0.3476897
Max. Quality	1	1	1	1	1	1	1	1	3	1	1	1	3	238	241.225	2077	2093.148	4657	4673.148	0.9253	0.7820515
Min. (T*C/Q)	3	1	1	1	1	1	1	1	3	1	1	1	3	229	232.225	2081.00	2097.15	4371.00	4387.148	0.9233	0.767836

Table 4.8: Results of the literature example (Zhang and Xing, 2010)

Descriptions	Results
TCQT solution $X^G = \{x_1^G, ..., x_N^G\}$	(3, 1, 1, 1, 1, 1, 3, 1, 2, 2, 1, 2, 3)
Fuzzy composite attribute utility (U)	(0.573, 0.839, 0.906)
Optimal fuzzy project duration (T)	(185, 199, 213)
Optimal fuzzy total cost (C)	(1999, 2111, 2223)
Optimal fuzzy project quality (Q)	(0.731, 0.886, 0.941)

4.3.4 Model Capabilities and Limitations

Despite satisfactory results and simple application, the stochastic TCQ model has some limitations. Table 4.9 summarizes such capabilities and limitations.

Table 4.9: Capabilities and limitations of the stochastic TCQ model

Stochastic TCQ Model	
Advantages and Capabilities	Disadvantages and Limitations
Five successors and predecessors are available for each activity	Only finish to start dependency relationships are considered
The bounds total duration, cost, and quality of the project for a desired confidence level is determined	The three points formula or beta distribution is not valid for all activities
Several optimization scenarios can be conducted	Applying the normal distribution to the total cost, duration and quality of all projects is not accurate
Simplicity and ease of use associated with the utilization of MS Excel and the Evolver GA optimization tool	Subjectivity and inaccuracy associated with estimating three values for each attribute of execution options
Generating of CPM times, early and late bar charts	Huge data entry particularly for large-scale projects

4.4 Advanced Time Cost Quality Trade-Off Analysis Model

The main purpose of this model is to obtain an optimal or near optimal execution scenario for a considered project. It is required to select an execution option for each activity within the project in order to achieve the project objectives in terms of time, cost, and quality. The model is developed and implemented in Microsoft Excel utilizing the Visual Basic Application VBA. A self-developed optimization tool utilizing three various optimization approaches is proposed for the aforementioned purpose.

4.4.1 The Proposed Approach and Methodology

4.4.1.1 Decision Variables

Each activity within the project has various discrete execution options to complete its work. As shown in the table of Figure 4.23, decision variables of the proposed model are the indices of execution options for the project activities.

Activity No	Execution Option Index
1	5
2	2
3	3
4	2
5	2
6	3
7	1
8	1
9	2
10	2
11	2
12	4
13	1
14	1
15	1
16	2
17	1
18	3

Figure 4.23: Decision variables of the advanced TCQ model

4.4.1.2 Total Project Duration

To calculate the total duration of a project, the CPM approach is applied. Generalized dependency relationships among activities in addition to lag and lead times previously discussed in section 2.2.2 are incorporated into the proposed model. Figure 4.24 and Table 4.10 summarize various dependency relationships and CPM calculations utilized by the advanced TCQ model.

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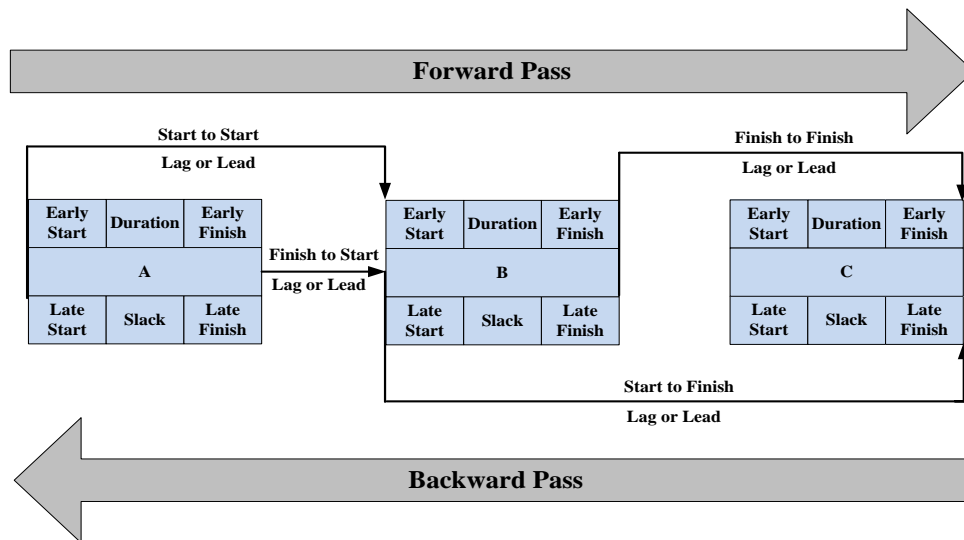
Figure 4.24: Different dependency relationships among activities

Table 4.10: CPM calculations for different dependency relationships

CPM Calculations	
Equation No	Equation
Equation 4.12	EF (A) = ES (A) + Duration (A)
Equation 4.13	ES (B) = Max { EF(A) + lag or lead , ES(A) + lag or lead }
Equation 4.14	EF (B) = ES (B) + Duration (B)
Equation 4.15	EF (C) = Max { EF(B) + lag or lead , ES(B) + lag or lead }
Equation 4.16	ES (C) = EF(C) – Duration (C)
Equation 4.17	LF (C) = EF(C)
Equation 4.18	LS (C) = LF(C) - Duration (C)
Equation 4.19	LF(B) = Min { LF (C) - lag or lead , LF(C) - lag or lead + Duration (B) }
Equation 4.20	LS (B) = LF(B) - Duration (B)
Equation 4.21	LF(A) = Min { LS (B) - lag or lead , LS(B) - lag or lead + Duration (A) }
Equation 4.22	LS (A) = LF(A) - Duration (A)
Equation 4.23	Slack or total float = LF - EF or LS - ES

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4.4.1.3 Total Project Cost

Similar to the simplified TCQ model, the total cost of a project incorporates direct costs, indirect costs, penalties, and bonus incentives if any. To calculate the total cost of the project, Equation 4.1 is used.

4.4.1.4 Overall Project Quality

As previously illustrated in section 2.4.2 and similar to the simplified TCQ model, the QBS approach is applied to evaluate the overall quality of the project. A project is divided into a hierarchy of activities, where activities' weights to represent their effect on the overall project quality are identified. For each activity, five measurable indicators with regard to quality are defined to evaluate its quality. The quality value of an execution option is the summation of each quality indicator weight multiplied by its performance or result percentage regarding such an indicator. The overall project quality is the weighted summation of each activity's weight multiplied by its quality value for a selected execution option. Equation 4.5 and Equation 4.6, proposed by El-Rayes and Kandil (2005), are applied to evaluate the quality of each execution option and the overall project quality respectively.

4.4.1.5 Optimization Approach

Three MOO approaches are utilized by the proposed model:

1. **The non-dominated sorting genetic algorithm (NSGAII),** which was previously illustrated in section 2.5.4.3, is applied as shown in Figure 4.25 as follows:

   - Random parent population of size N is generated. Each random solution represents a set of execution options for the project's activities. The total project cost, duration, and quality are calculated for each solution.

   - Maximum overall quality, minimum total duration, and minimum total cost of the project are computed according to execution options that are available for each activity

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- Based on the non-domination approach previously illustrated in section 2.5.4.3, the parent population is sorted and ranked.

- For the purpose of diversity preservation, the crowding distance is calculated for each solution. It is assumed to be the average distance of two solutions on either sides of solution (i), on its front, along each of the objectives. Crowding distance is calculated based on Equation 2.6 proposed by Deb (2001) as follows:

$$dI_j^m = \{[\ C_m^{I_{(j+1)}^m} - C_m^{I_{(j-1)}^m}\ ]\ /\ [\ C_m^{max} - C_m^{min}]\} + \{[\ T_m^{I_{(j+1)}^m} - T_m^{I_{(j-1)}^m}\ ]\ /\ [\ T_m^{max} - T_m^{min}]\}$$
$$+ \{[\ Q_m^{I_{(j+1)}^m} - Q_m^{I_{(j-1)}^m}\ ]\ /\ [\ Q_m^{max} - Q_m^{min}]\}$$

Equation 4. 24

Where $C_m^{I_{(j-1)}^m}$ and $C_m^{I_{(j+1)}^m}$, $T_m^{I_{(j+1)}^m}$ and $T_m^{I_{(j-1)}^m}$, and $Q_m^{I_{(j+1)}^m}$ and $Q_m^{I_{(j-1)}^m}$ are the total cost, duration, and quality values for two neighboring solutions on either side of solution (i). C_m^{max} and C_m^{min}, T_m^{max} and T_m^{min}, and Q_m^{max} and Q_m^{min} are the maximum and minimum values of the total cost, duration, and quality.

- To form a new parent population for a next generation, tournament selection operator is applied. Solutions with a lower Pareto non-domination rank are selected. If both solutions belong to the same front with same Pareto rank, solutions with less crowded area or a larger crowding distance are selected. Two points' crossover and mutation are employed to create a child population of size N. The adaptive mutation rate technique is used to prevent premature convergence. A higher mutation rate is assigned for early stages in order to maintain diversity; however, a lower mutation rate is assigned for later stages in order not to disrupt good solutions. The adaptive mutation rate is calculated based on Equation 3.9.

- In order to ensure elitism, the child population is added to the parent one to form a combined population of size 2N. The solutions of the combined population are then

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sorted and ranked based on their Pareto non-dominated rank and crowding distance in order to reject solutions more than the original population size N.

- The processes of evolutionary generation and non-domination ranking are repeated until a predefined generation number is reached or the optimization is stopped.

```
                        ┌──────────┐
                        │  Start   │
                        └──────────┘
                             │
              Optimization Data:
              Npop, Ngen, Pmi, and Pcr
                             │
              Determine:
              No of activities
              No of options for each activity
                             │
              Random generation of Npop solutions
                             │
              Determine:
              Max. quality, Min. duration, and Min. cost
                             │
              Non-dominated sorting
              Crowding distance
                             │
        ┌─── Genetic Algorithm ──────────────────┐
        │         Tournament selection           │
        │                  │                      │
        │         Two points' crossover          │
        │                  │                      │
        │         Adaptive mutation              │
        │                  │                      │
        │         Nchild ≥ Npop ──── No ──────────┘
        └────────────────────────────────────────┘
                             │
              Combine:
              Parent population + Offspring population
                             │
              Non-dominated sorting
              Crowding distance
              Discard weakest solutions
              Population size = Npop
                             │
              Last generation ──── No
                             │
              Output of optimal solutions
                             │
                        ┌──────────┐
                        │   End    │
                        └──────────┘
```

Figure 4. 25: The NSGAII optimization approach

2. **The goal programming approach (GP),** which was previously illustrated in section 2.5.4.1, is applied as shown in figure 4.26 as follows:

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- Random parent population of size N is generated. Each random solution represents a set of execution options for the project's activities. The total project cost, duration, and quality are calculated for each solution.

- Maximum overall quality, minimum total duration, and minimum total cost of the project are computed with regard to execution options that are available for each activity. These computed values are considered numeric targets for their corresponding objective.

- For each solution within the parent population, a combined objective function representing the weighted sum of deviations of time, cost, and quality objective functions from their respective numeric target. The GP objective function is formulated based on Equation 2.5 as follows:

Dev_T = [Total Duration (solution) – Min_Dur] / Min_Dur

Equation 4. 25

Dev_C = [Total Cost (solution) – Min_Cost)]/ Min_Cost

Equation 4. 26

Dev_Q = [Max_Qual – Total Quality (solution)] / Max_Qual

Equation 4. 27

GP_Obj_Fn = Wt_C * Dev_C + Wt_T * Dev_T + Wt_Q * Dev_Q

Equation 4. 28

Where Wt_C, Wt_T, and Wt_Q are weights corresponding to objectives of cost, time, and quality as specified by decision makers. Dev_C, Dev_T, and Dev_Q are deviations from target goals for each objective respectively.

- To form a child population, GA operators and processes are applied. Based on the objective function for each solution, tournament selection is conducted to select solutions for recombination. Two points' crossover and adaptive mutation are applied

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to create new modified solutions of size N. the total cost, duration and quality, and the objective function are calculated for the new population.

- The child population is added to the parent one to form a combined population of size 2N. The solutions of the combined population are then sorted based on minimizing the objective function to discard solutions more than the original number of population N.

- The processes of evolutionary generation, evaluation, and replacement repeated until a predefined generation number is reached or the optimization is stopped.
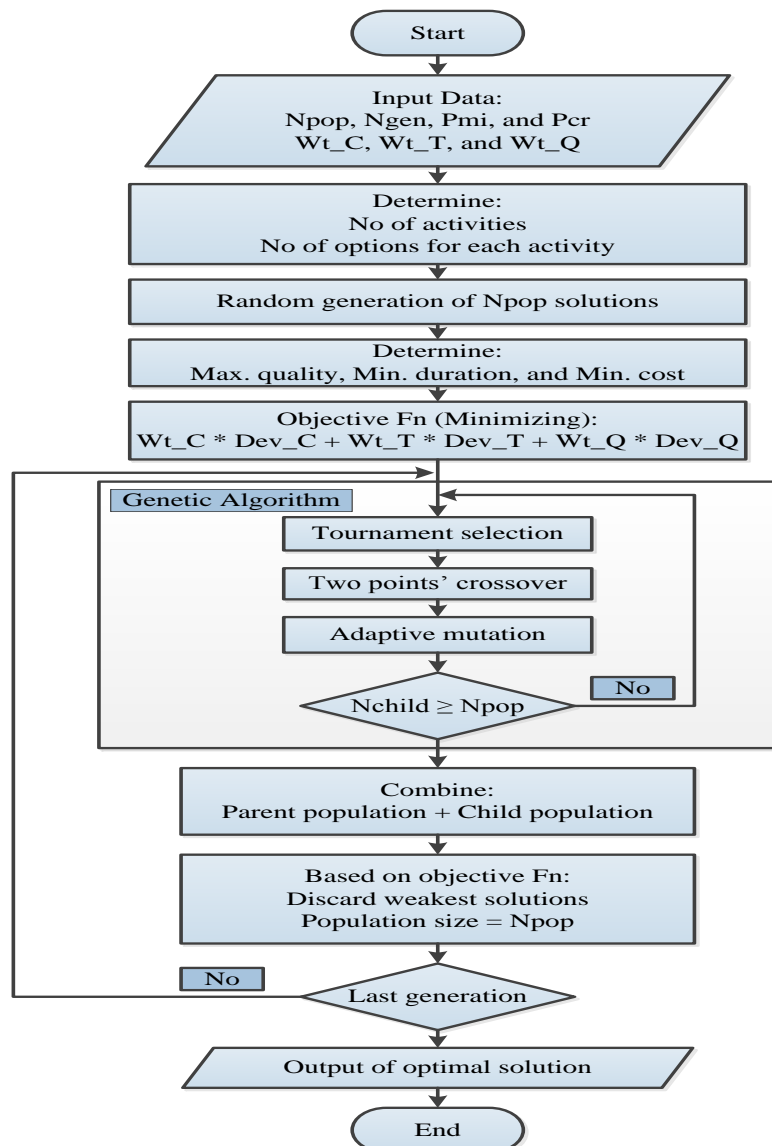
Figure 4. 26: The GP optimization approach

3. **The modified adaptive weight approach (MAWA),** which was introduced by Zheng et al. (2004), is applied as shown in Figure 4.27 as follows:

- Random parent population of size N is generated. Each random solution represents a set of execution options for the project's activities. The total project cost, duration, and quality are calculated for each solution.

- Based on Equations 3.2 to 3.7 introduced by Zheng et al. (2004) and considering the quality objective, new adaptive weights of time, cost, and quality objectives are proposed as follows:

For $Zt^{Max} \neq Zt^{Min}$, $Zc^{Max} \neq Zc^{Min}$, and $Zq^{Max} \neq Zq^{Min}$,

$$Vc = Zc^{Min} / (Zc^{Max} - Zc^{Min}), Vt = Zt^{Min} / (Zt^{Max} - Zt^{Min}), Vq = Zq^{Max} / (Zq^{Max} - Zq^{Min}), V = Vc + Vt + Vq, Wc = Vc / V, Wt = Vt / V, \text{ and } Wq = Vq / V$$

Equation 4. 29

For $Zt^{Max} = Zt^{Min}$, $Zc^{Max} = Zc^{Min}$, and $Zq^{Max} = Zq^{Min}$,

$$Wc = 1 / 3, Wt = 1 / 3, \text{ and } Wq = 1 / 3$$

Equation 4. 30

For $Zt^{Max} = Zt^{Min}$, $Zc^{Max} = Zc^{Min}$, and $Zq^{Max} \neq Zq^{Min}$,

$$Wc = 0.45, Wt = 0.45, \text{ and } Wq = 0.1$$

Equation 4. 31

For $Zt^{Max} = Zt^{Min}$, $Zc^{Max} \neq Zc^{Min}$, and $Zq^{Max} = Zq^{Min}$,

$$Wc = 0.1, Wt = 0.45, \text{ and } Wq = 0.45$$

Equation 4. 32

For $Zt^{Max} = Zt^{Min}$, $Zc^{Max} \neq Zc^{Min}$, and $Zq^{Max} \neq Zq^{Min}$,

$$Wc = 0.1, Wt = 0.8, \text{ and } Wq = 0.1$$

Equation 4. 33

For $Zt^{Max} \neq Zt^{Min}$, $Zc^{Max} = Zc^{Min}$, and $Zq^{Max} = Zq^{Min}$,

$$Wc = 0.45, Wt = 0.1, \text{ and } Wq = 0.45$$

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Equation 4. 34

For $Zt^{Max} \neq Zt^{Min}$, $Zc^{Max} = Zc^{Min}$, and $Zq^{Max} \neq Zq^{Min}$,

Wc = 0.8, Wt = 0.1, and Wq = 0.1

Equation 4. 35

For $Zt^{Max} \neq Zt^{Min}$, $Zc^{Max} \neq Zc^{Min}$ and $Zq^{Max} = Zq^{Min}$,

Wc = 0.1, Wt = 0.1, and Wq = 0.8

Equation 4. 36

Where Z_c^{Max}, Z_t^{Max}, and Zq^{Max} are maximum values of total cost, time, and quality in the current population, respectively. Z_c^{Min}, Zt^{Min}, and Zq^{Min} are minimum values of total cost, time, and quality in the current population respectively. Wc, Wt, and Wq are the adaptive weights for total cost, time, and quality.

- Based on Equation 3.8 introduced by Zheng et al. (2004) and considering the quality objective, The fitness function of this approach is proposed as follows:

$$\text{Maximize } F(X) = W_t \; \frac{Z_t^{max} - Z_t + \gamma}{Z_t^{max} - Z_t^{min} + \gamma} \; + Wc \; \frac{Z_c^{max} - Z_c + \gamma}{Z_c^{max} - Z_c^{min} + \gamma} + Wq \; \frac{Z_q - Z_q^{min} + \gamma}{Z_c^{max} - Z_c^{min} + \gamma}$$

Equation 4. 37

Where X is the sequence number of a candidate solution within the current generation. Z_c, Z_t, and Z_q are the total cost, time, and quality of the Xth solution in the current population and γ is a small random number between 0 and 1.

- The population is sorted and ranked based on the non-domination approach. Ranks were then sorted according to the average fitness of each one. The roulette wheel selection is applied to select a rank and an individual solution of that rank is then randomly selected for reproduction processes. Traditional two points' crossover and adaptive mutation are applied to create offspring solutions. Weakest solutions are discarded to keep N solutions for next generations.

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- The processes of evolutionary generation, evaluation, non-dominated sorting, and replacement repeated until a predefined generation number is reached or the optimization is stopped.
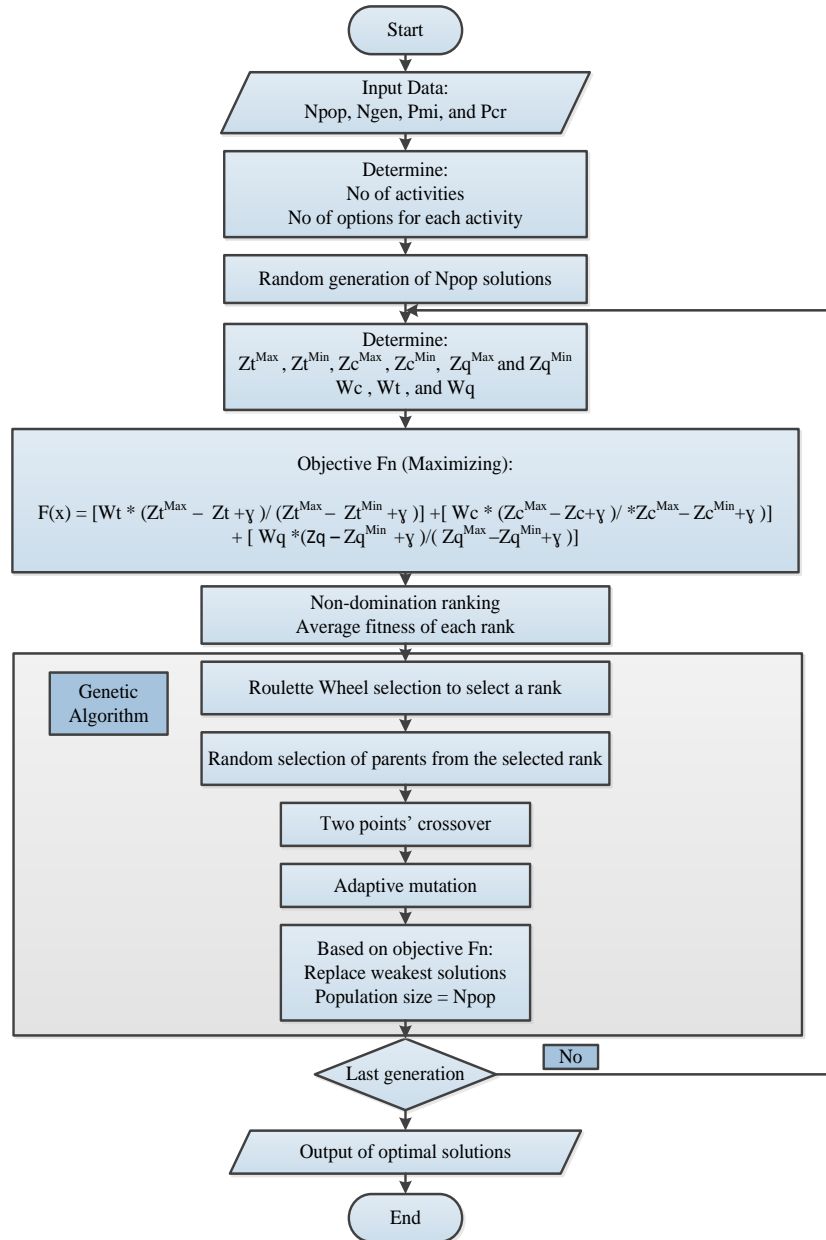
Figure 4. 27: The MAWA optimization approach

4.4.2 Model Description and Organization

As shown in Figure 4.28, the advanced TCQ model incorporates four various modules: initialization module; quality evaluation module; optimization module; and output module.
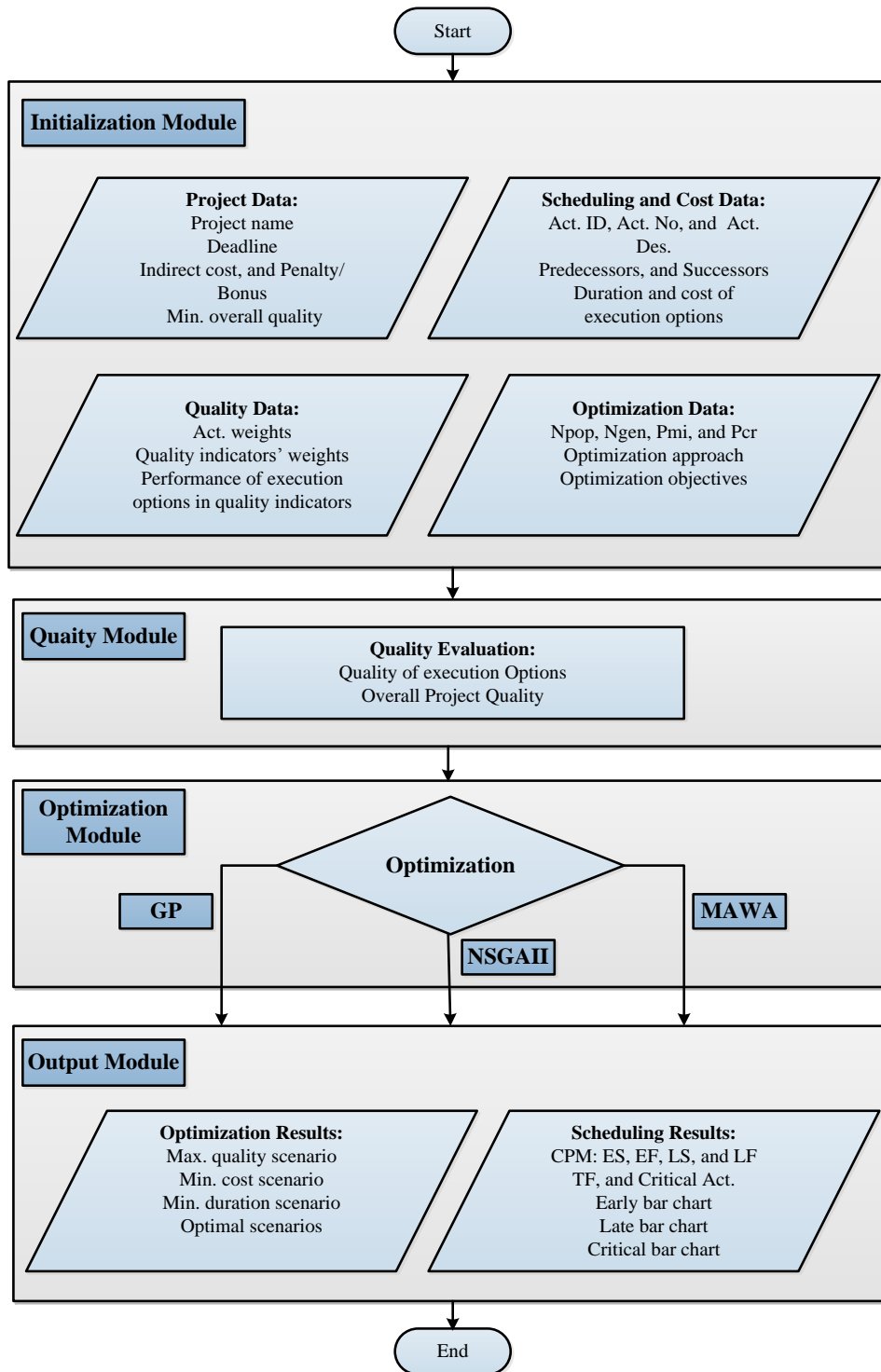
Figure 4. 28: The advanced TCQ model flowchart

4.4.2.1 Initialization Module

As shown in Figure 4.29, this module includes the input of four types of data: project data; schedule and cost data; quality data; and optimization data. It is recommended to clear previous data before initializing a new project.
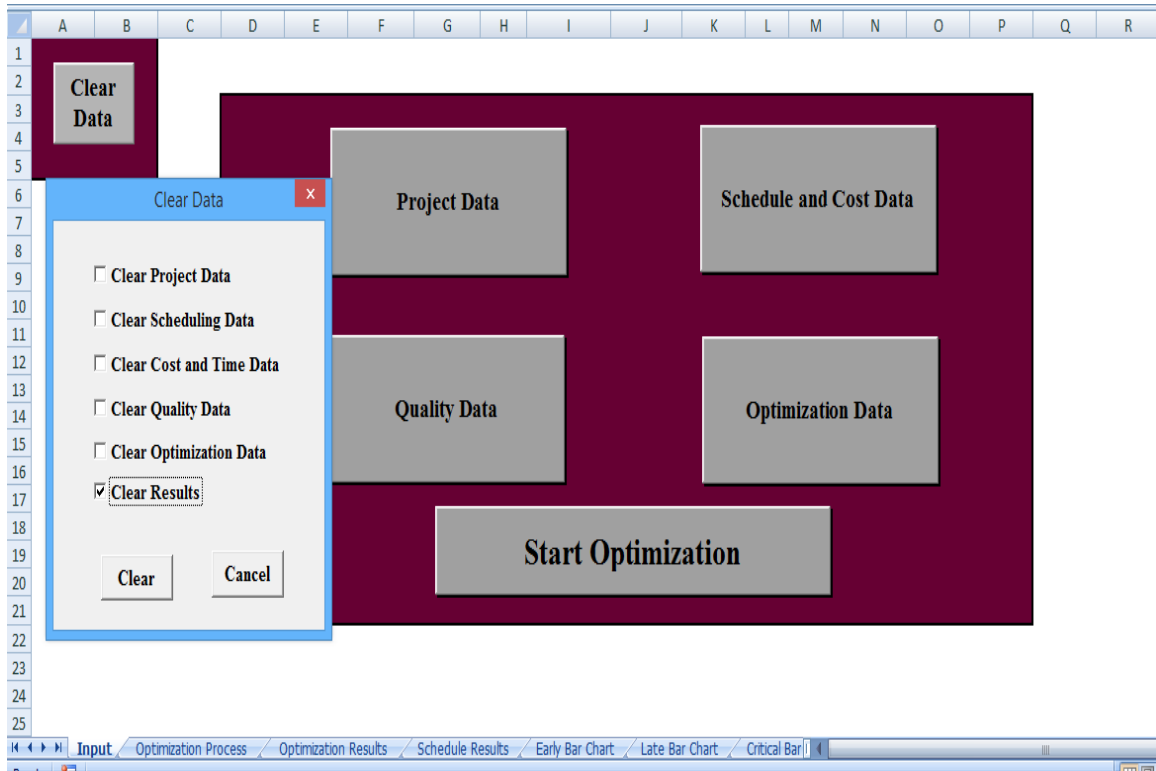
Figure 4. 29: The initialization module of the advanced TCQ model

As shown in Figure 4.30, the project data includes: the project name; project hard deadline that cannot be exceeded; project soft deadline that may be exceeded with a penalty; indirect costs per unit time; a penalty cost per unit time of delay; a bonus incentive per unit time of early completion; and minimum acceptable overall project quality. It is recommended to set relaxed values of constraints of deadline and quality in order not to restrict or direct the optimization process. In addition, such constraints should not conflict with the minimum duration or maximum quality of the project.

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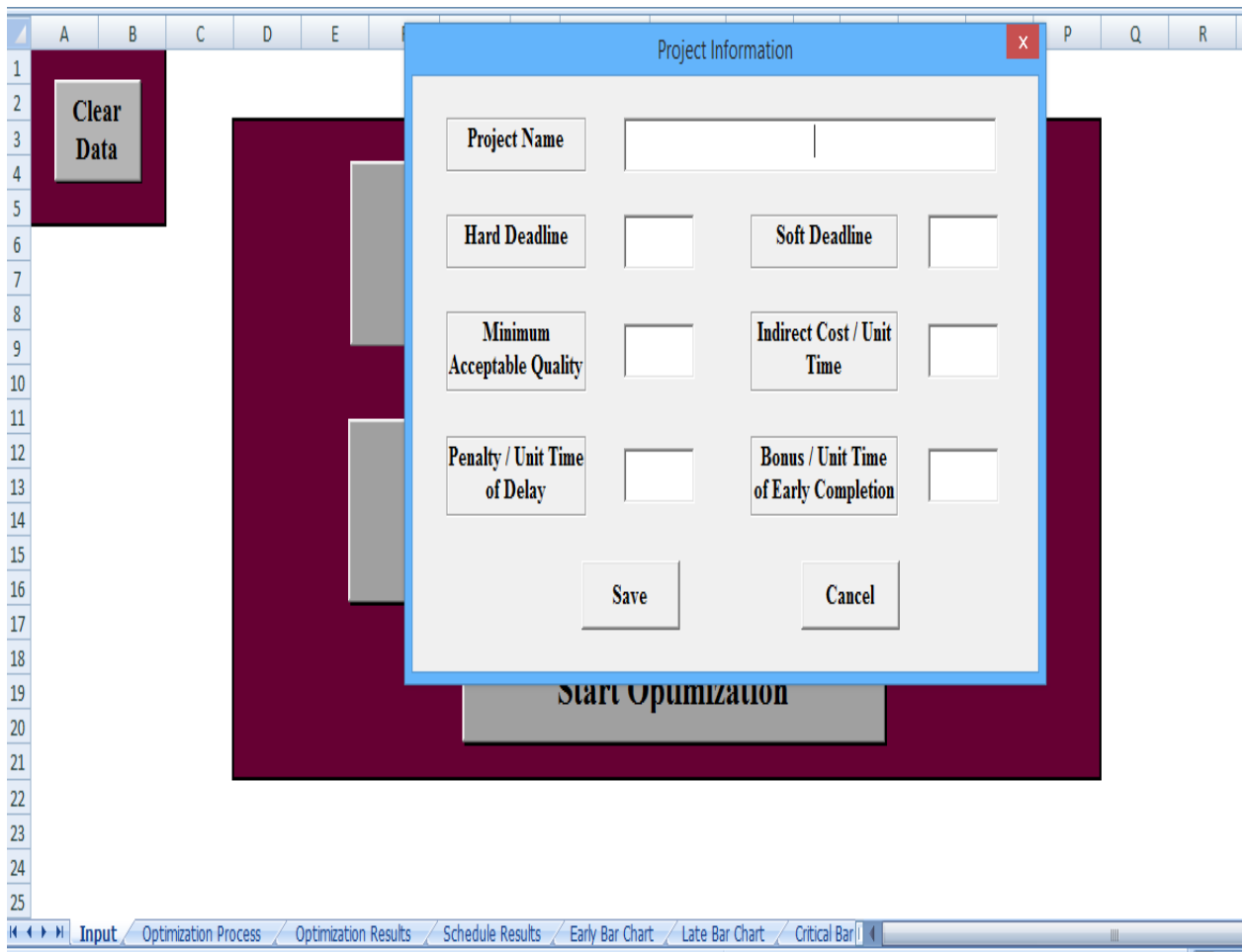
Figure 4.30: The project data of the advanced TCQ model

Figure 4.31 shows the input of schedule and cost data. For each activity, it is required to enter its number, ID, description, predecessors, and successors. For each successor and predecessor, it is required to enter its number, its dependency relationship, and its lag or lead value if existing as shown Figures 4.32 and 4.33. For each activity it is available to enter five various execution options. For each option, it is required to enter a value of its duration and its cost as shown in Figure 4.34.
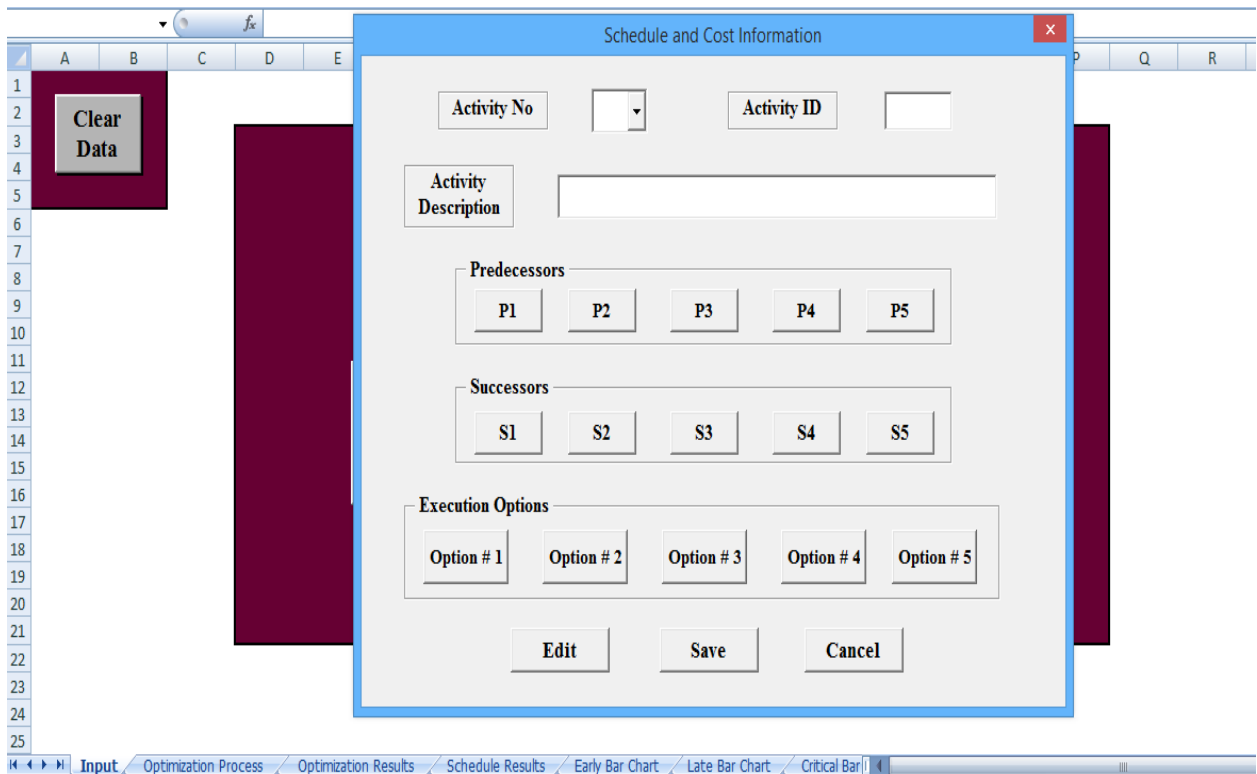
Figure 4.31: The schedule and cost data of the advanced TCQ model
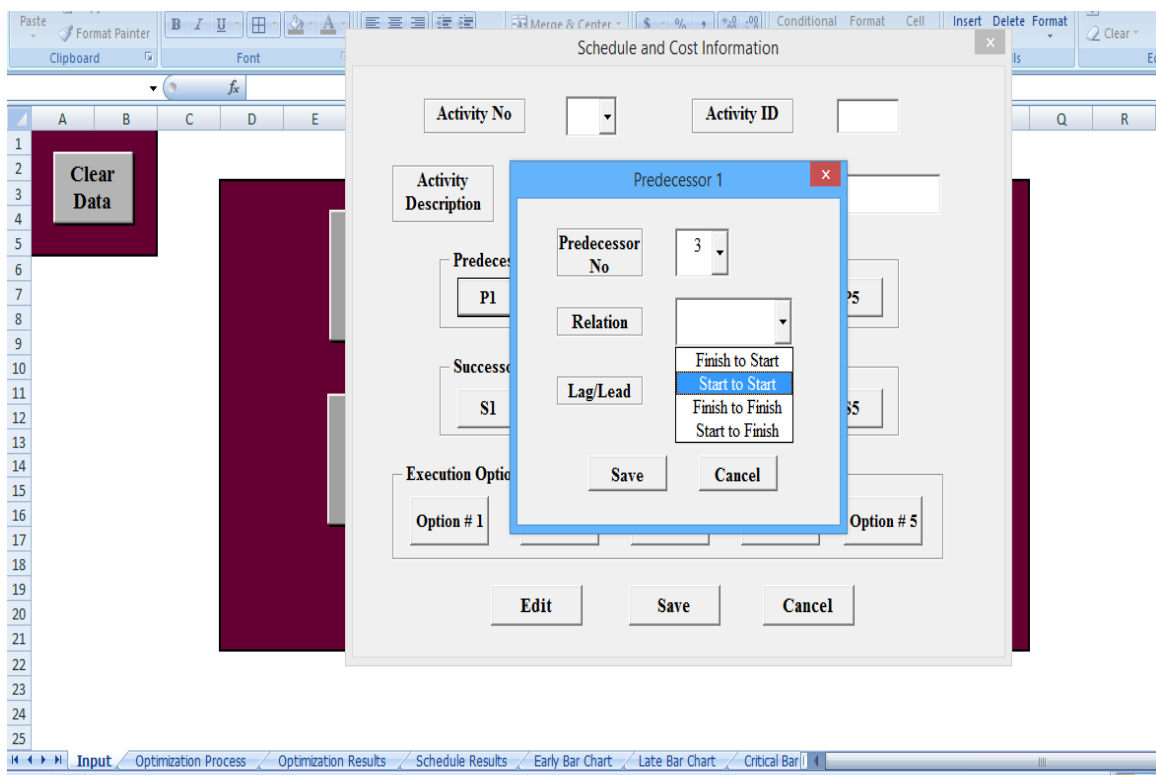
Figure 4.32: The predecessors input of the advanced TCQ model

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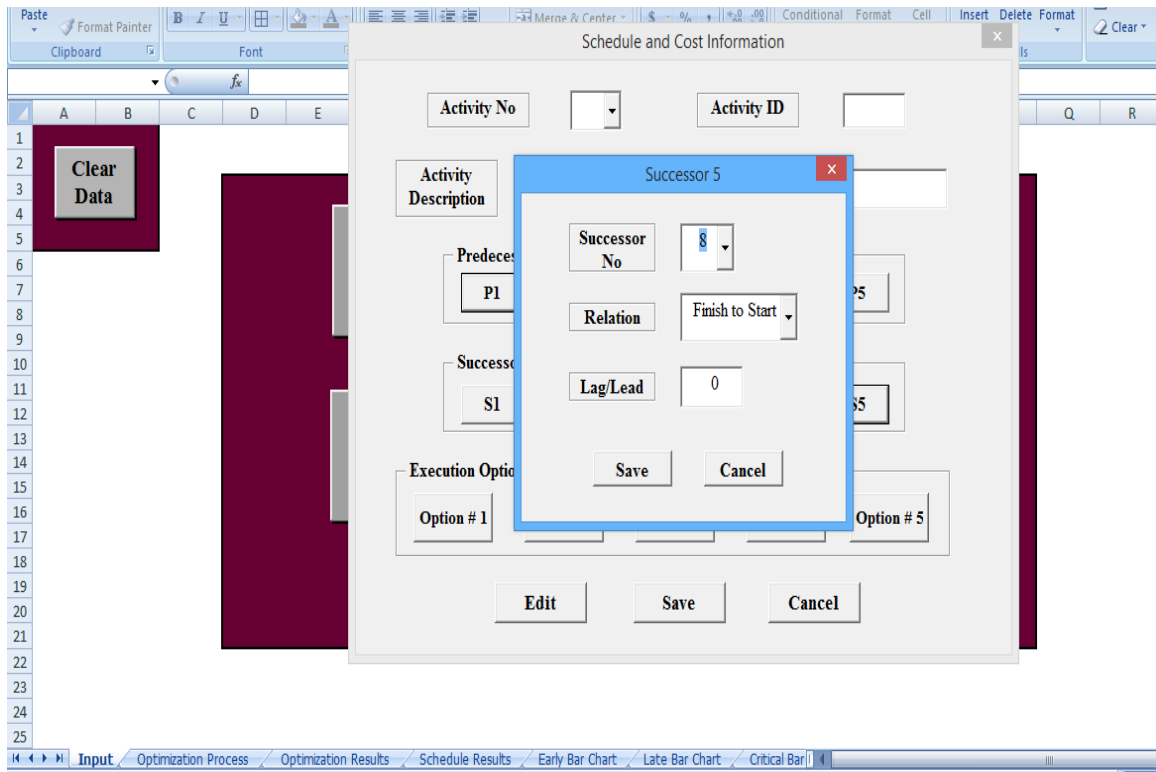
Figure 4.33: The successors input of the advanced TCQ model
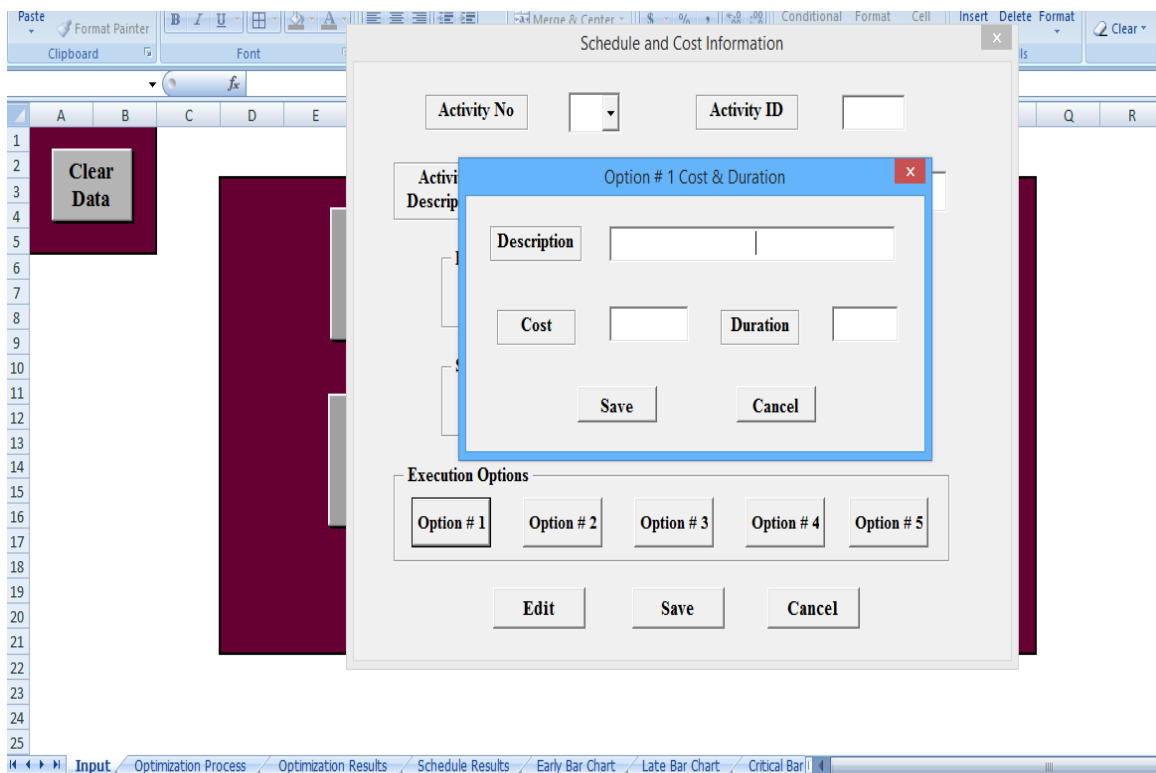
Figure 4.34: Cost and duration data of execution options of the advanced TCQ model

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As shown in Figure 4.35, the user enters the activity number, activity weight, weights of indicators for each activity, and performance of various execution options in such quality indicators. It is obvious that the sum of activities weights within a project equals 100%, the sum of quality indicators within an activity equals 100%, and the performance of execution options does not exceed 100%.
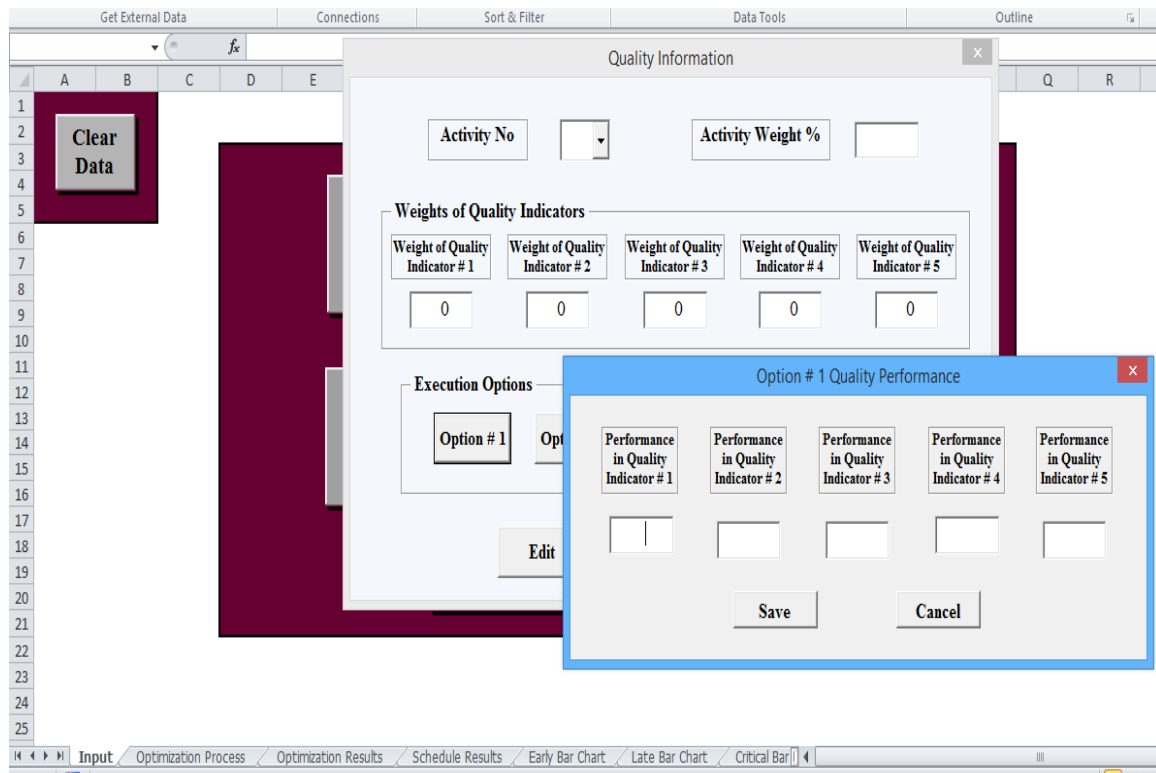
Figure 4.35: The quality data input of the advanced TCQ model

For the optimization data shown in Figure 4.36, it is required to enter a number of population for the GA, a number of generations, crossover rate, and initial mutation rate. Depending on decision makers' preference and the problem conditions, it is also required to select an optimization approach and optimization objectives.

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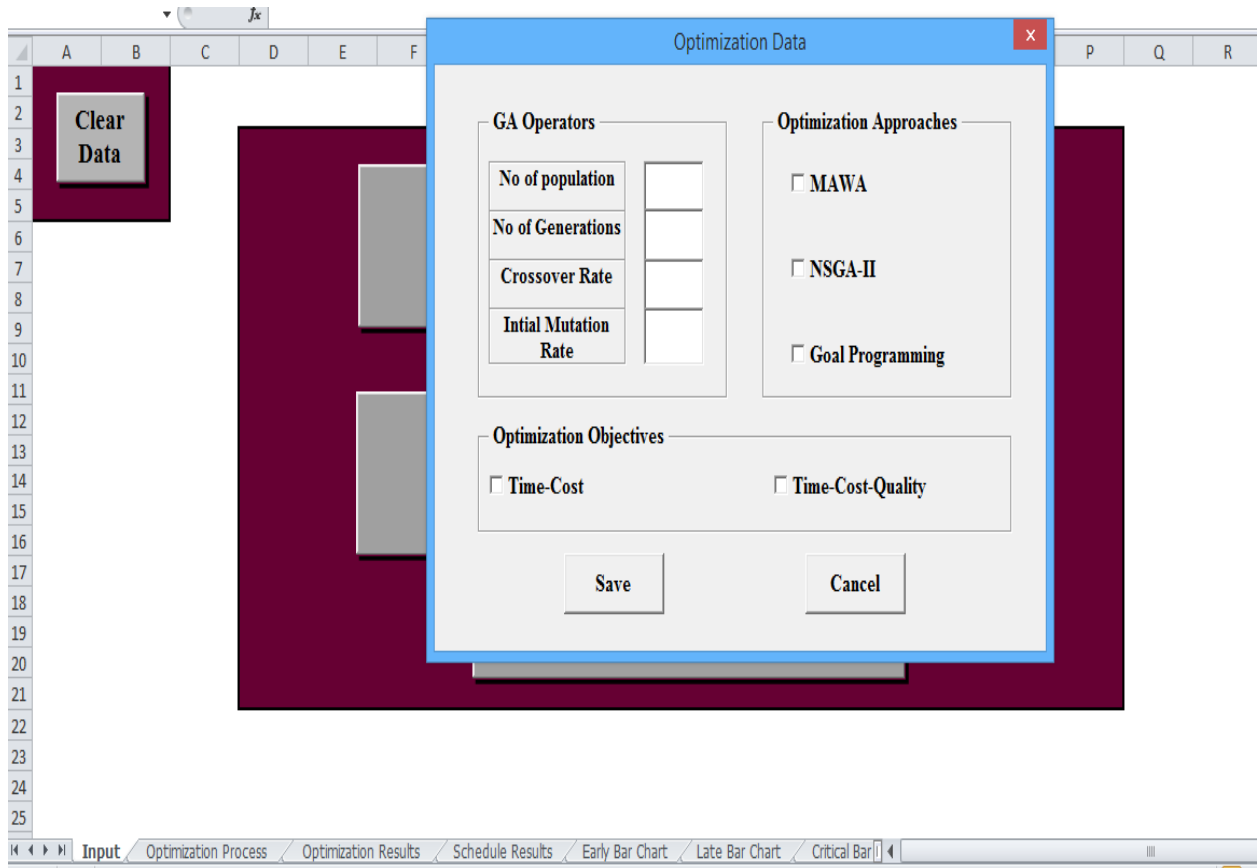
Figure 4.36: The optimization data input of the advanced TCQ model

4.4.2.2 Quality Evaluation Module

The second module is a quality module, in which the quality of each execution option for all activities is calculated. The quality performance at the activity and the project overall quality are computed as previously discussed.

4.4.2.3 Optimization Module

Depending on the selected optimization approach and optimization objectives, the optimization process is conducted as previously illustrated in section 4.4.1.5. Figure 4.37 shows the optimization progress after pressing the Start Optimization button.

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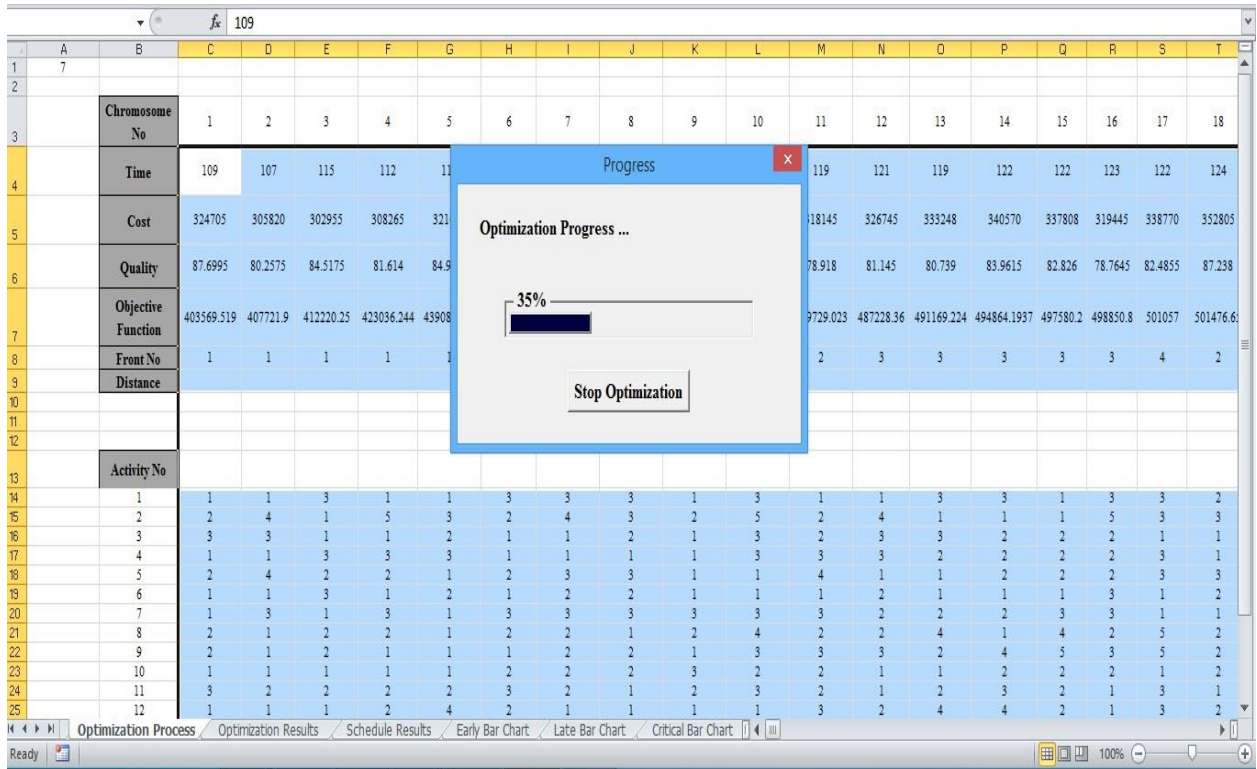
Figure 4. 37: The optimization progress of the advanced TCQ model

4.4.2.4 Output Module

The output module is divided into two categories, which are optimization results and scheduling results.

- **Optimization results** include several optimal execution scenarios as shown in Figure 4.38. Depending on decision makers' preference, the model generates scenarios of maximum and minimum total project duration, cost, and quality in addition to simultaneously optimized scenarios. For each scenario, the model provides a set of execution options for the project's activities and the corresponding project total duration, direct cost, total cost and overall quality

- **Scheduling results** include CPM calculations and bar charts for a selected execution scenario. CPM calculations include ES, EF, LS, LF, TF for each activity and identification of critical activities. Bar charts include the early bar chart, the late bar chart, and the critical bar chat.

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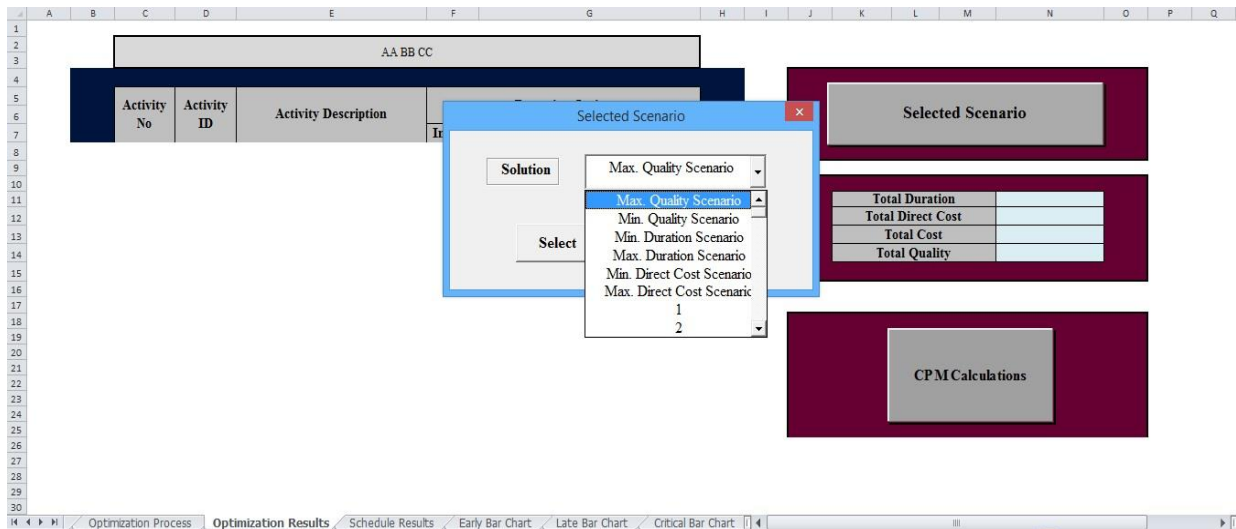
Figure 4. 38: The optimization results of the advanced TCQ model

4.4.3 Model Implementation and Validation

To validate the advanced TCQT model, the same example of the simplified TCQ model, introduced by El-Rayes and Kandil (2005), is analyzed. The project soft and hard deadline are set 110 and 140 respectively. The project indirect cost is assumed 1500 $/day, a penalty of 2000 $ per each delay day after 110 days is assumed, and no incentives is considered. The minimum acceptable overall project quality is assumed 80%. The number of population Npop is 100 chromosomes, the number of generations is 100 iterations, the crossover rate is 0.6, and the initial mutation rate is 0.3. For the optimization approach, the three approaches of GP, MAWA, and NSGAII are examined. For the optimization objectives, both time-cost and time-cost-quality are also examined.

After the user enters the problem data, it is stored in a hidden sheets as shown in Figures 4.39 to 4.41. Figure 4.39 shows the scheduling and precedence data of the example, Figure 4.40 shows the cost and duration data of execution options for each activity, Figure 4.41 shows the quality data of the example including weights of activities, weights of quality indicators, and performance of each execution option in such quality indicators. After the optimization process is completed, optimum solutions are generated as shown in Figure 4.42.

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| Activity No | Activity ID | Activity Description | Predecessors | | | | | | | | | | | | | | | Successors | | | | | | | | | | | | | | |
			P1	Relation	Lag/Lead	P2	Relation	Lag/Lead	P3	Relation	Lag/Lead	P4	Relation	Lag/Lead	P5	Relation	Lag/Lead	S1	Relation	Lag/Lead	S2	Relation	Lag/Lead	S3	Relation	Lag/Lead	S4	Relation	Lag/Lead	S5	Relation	Lag/Lead
1	1	A																5	Finish to Start		6	Finish to Start										
2	2	B																10	Finish to Start													
3	3	C																13	Finish to Start													
4	4	D																14	Finish to Start													
5	5	E	1	Finish to Start														7	Finish to Start		12	Finish to Start										
6	6	F	1	Finish to Start														8	Finish to Start		9	Finish to Start		10	Finish to Start							
7	7	G	5	Finish to Start														11	Finish to Start													
8	8	H	6	Finish to Start														11	Finish to Start													
9	9	I	6	Finish to Start														12	Finish to Start													
10	10	J	2	Finish to Start		6	Finish to Start											12	Finish to Start		14	Finish to Start										
11	11	K	7	Finish to Start		8	Finish to Start											17	Finish to Start													
12	12	L	5	Finish to Start		9	Finish to Start		10	Finish to Start								15	Finish to Start													
13	13	M	3	Finish to Start														16	Finish to Start													
14	14	N	4	Finish to Start		10	Finish to Start											16	Finish to Start		17	Finish to Start										
15	15	O	12	Finish to Start														17	Finish to Start													
16	16	P	13	Finish to Start		14	Finish to Start											18	Finish to Start													
17	17	Q	11	Finish to Start		14	Finish to Start		15	Finish to Start								18	Finish to Start													
18	18	R	16	Finish to Start		17	Finish to Start																									

Figure 4. 39: The scheduling data of the advanced TCQ model

Activity No	No of Options	Option #		1	Option #		2	Option #		3	Option #		4	Option #		5
		Description	Duration	Cost	Description	Duration	Cost	Description	Duration	Cost	Description	Duration	Cost	Description	Duration	Cost
1	5	aaaa	14	2400	bbb	15	2150	cccc	16	1900	dddd	21	1500	eee	24	1200
2	5	aaaa	15	3000	bbb	18	2400	cccc	20	1800	dddd	23	1500	eee	25	1000
3	3	aaaa	15	4500	bbb	22	4000	cccc	33	3200						
4	3	aaaa	12	45000	bbb	16	35000	cccc	20	30000						
5	4	aaaa	22	20000	bbb	24	17500	cccc	28	15000	dddd	30	10000			
6	3	aaaa	14	40000	bbb	18	32000	cccc	24	18000						
7	3	aaaa	9	30000	bbb	15	24000	cccc	18	22000						
8	5	aaaa	14	220	bbb	15	215	cccc	16	200	dddd	21	208	eee	24	120
9	5	aaaa	15	300	bbb	18	240	cccc	20	180	dddd	23	150	eee	25	100
10	3	aaaa	15	450	bbb	22	400	cccc	33	320						
11	3	aaaa	12	450	bbb	16	350	cccc	20	300						
12	4	aaaa	22	2000	bbb	24	1750	cccc	28	1500	dddd	30	1000			
13	3	aaaa	14	4000	bbb	18	3200	cccc	24	1800						
14	3	aaaa	9	3000	bbb	15	2400	cccc	18	2200						
15	1	aaaa	16	3500												
16	5	aaaa	20	3000	bbb	22	2000	cccc	24	1750	dddd	28	1500	eee	30	1000
17	3	aaaa	14	4000	bbb	18	3200	cccc	24	1800						
18	3	aaaa	9	3000	bbb	15	2400	cccc	18	2200						

Schedule Data | **Time & Cost Data** | Optimization Process | Optimization Results | Schedule Results | Early Bar Chart

Figure 4. 40: The duration and cost of execution options of the advanced TCQ model

Activity No	Activity Weight %	Wt of Ind. #1	Wt of Ind. #2	Wt of Ind. #3	Wt of Ind. #4	Wt of Ind. #5	Option # 1					Quality of Option # 1	Option # 2					Quality of Option # 2	Option # 3					Quality of Option # 3	Option # 4					Quality of Option # 4	Option # 5					Quality of Option # 5
							Perf. for Ind. #1	Perf. for Ind. #2	Perf. for Ind. #3	Perf. for Ind. #4	Perf. for Ind.# 5		Perf. for Ind. #1	Perf. for Ind. #2	Perf. for Ind. #3	Perf. for Ind. #4	Perf. for Ind.# 5		Perf. for Ind. #1	Perf. for Ind. #2	Perf. for Ind. #3	Perf. for Ind. #4	Perf. for Ind.# 5		Perf. for Ind. #1	Perf. for Ind. #2	Perf. for Ind. #3	Perf. for Ind. #4	Perf. for Ind.# 5		Perf. for Ind. #1	Perf. for Ind. #2	Perf. for Ind. #3	Perf. for Ind. #4	Perf. for Ind.# 5	
1	3	50	30	20			100	96	98	0	0	98.4	90	89	89	0	0	89.5	86	77	84	0	0	82.9	75	72	73			73.7	63	60	65			62.5
2	5	40	40	20			98	94	99			96.6	87	84	85			91.4	81	92	85			86.2	77	72	70			73.6	60	66	59			62.2
3	8	70	15	15	0	0	100	97	98			99.25	80	82	81			80.45	62	60	63			61.85	100	97	98			99.25	100	97	98			99.25
4	11	50	35	15			99	95	94			96.85	74	71	76			73.25	59	63	64			61.15	99	95	94			96.85	99	95	94			96.85
5	10	60	20	20			100	97	99			99.2	93	89	89			91.4	77	71	72			74.8	61	64	61			61.6	100	97	99			99.2
6	11	50	25	25			95	95	100			96.25	76	74	79			76.25	59	62	68			62	95	95	100			96.25	95	95	100			96.25
7	10	30	30	40			97	99	93			96	70	73	71			71.3	61	62	67			63.7	97	99	93			96	97	99	93			96
8	1	100	0	0			95					95	83					83	75					75	68					68	61					61
9	1	50	50	0			100	99				99.5	97	92				94.5	81	88				84.5	71	75				73	63	64				63.5
10	1	60	40	0			94	97				95.2	79	83				80.6	63	69				65.4	94	97				95.2	94	97				95.2
11	2	70	30	0			96	95				95.7	72	75				72.9	61	66				62.5	96	95				95.7	96	95				95.7
12	3	50	35	15			99	98	95			98.05	89	85	87			87.3	70	71	79			71.7	62	61	63			61.8	99	98	95			98.05
13	7	40	40	20			99	96	97			97.4	73	71	76			72.8	60	62	63			61.4	99	96	97			97.4	99	96	97			97.4
14	6	80	10	10			100	95	98			99.3	79	82	81			79.5	63	67	66			63.7	100	95	98			99.3	100	95	98			99.3
15	7	70	30	0			100	98				99.4																								
16	3	30	30	40			97	96	98			97.1	89	85	87			87	81	79	78			79.2	72	73	74			73.1	67	60	62			62.9
17	6	70	20	10			98	97	99			97.9	73	75	72			73.3	62	65	61			62.5	98	97	99			97.9	98	97	99			97.9
18	5	30	45	25			98	99	94			97.45	75	77	71			74.9	63	66	67			65.35	98	99	94			97.45	98	99	94			97.45

Input / Schedule Data / Time & Cost Data / **Quality Data** / Optimization Process / Optimization Results / Schedule Res

Figure 4. 41: The quality data of the advanced TCQ model

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	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Chromosome No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Time	104	105	105	104	105	104	105	104	105	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	105	104
Cost	324820	291715	290115	324820	290115	305715	291100	318815	293120	323820	314820	299720	308615	322320	311070	295215	308800	296600	319615	304865	311320	303800	323570	306315	299300	291465	321320
Quality	97.629	86.029	85.046	97.629	85.046	92.233	85.683	95.033	86.643	97.326	95.033	89.889	93.062	96.849	93.716	87.349	93.199	88.252	95.489	91.745	93.95	91.032	97.032	92.499	89.432	85.795	96.546
Objective Function																											
Front No	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Distance	INF	INF	INF	INF	INF	INF	0.018369	0.014345	0.013378	0.013118	0.01234	0.01259	0.011847	0.0111777	0.011	0.01088	0.0108	0.010512	0.0105	0.0102	0.0034	0.0033	0.0033	0.0033	0.0033	0.0033	0.0031

Activity No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	2	3	1	3	2	3	1	3	1	1	2	3	1	1	2	1	3	3	3	1	1	1	1	1	2	1
3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4	1	3	3	1	3	3	3	1	3	1	2	3	3	1	2	3	3	3	1	3	2	3	1	3	3	3	1
5	1	4	4	1	4	2	4	1	4	1	1	2	1	2	2	3	1	2	2	2	2	1	1	2	2	4	2
6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7	1	3	3	1	3	1	3	2	2	1	1	2	1	1	1	3	1	3	1	1	1	2	1	1	3	3	1
8	1	2	2	1	2	2	3	2	1	1	1	1	2	1	1	2	3	3	2	2	1	3	1	2	3	2	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16	1	2	5	1	5	2	2	1	2	2	1	2	1	1	3	2	2	4	4	3	2	1	3	2	1	3	2
17	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Quality Data | **Optimization Process** | Optimization Results | Schedule Results | Early Bar Chart | Late Bar Chart

Figure 4. 42: The optimization output of the advanced TCQ model

For the output module, the user selects an execution scenario that provides an execution option for each activity within the project, the total project cost, duration, and quality for that selected scenario as shown in Figure 4.43. By pressing the CPM calculations button, the schedule results are computed as shown in Figure 4.44. The early, late, and critical bar buttons are used to generate the early, late, and critical bar charts of Figures 4.45 to 4.47.
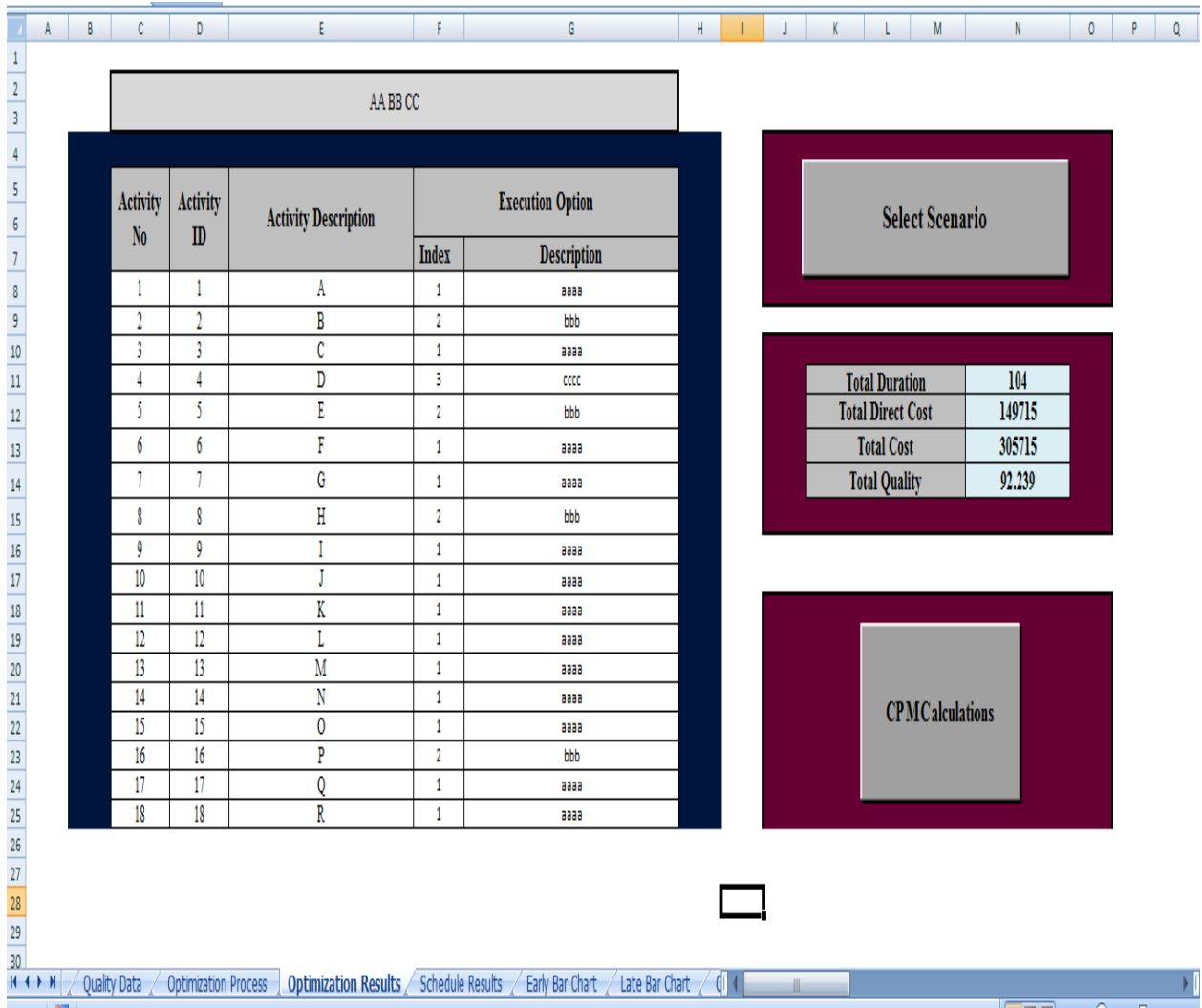
Figure 4. 43: Optimization results for a selected scenario of the advanced TCQ model

Activity No	Activity ID	Activity Description	Activity Duration	Early Start	Early Finish	Late Start	Late Finish	Total Float	Critical Activities
1	1	A	14	0	14	0	14	0	Critical Act.
2	2	B	20	0	20	8	28	8	
3	3	C	15	0	15	38	53	38	
4	4	D	20	0	20	38	58	38	
5	5	E	24	14	38	19	43	5	
6	6	F	14	14	28	14	28	0	Critical Act.
7	7	G	9	38	47	60	69	22	
8	8	H	16	28	44	53	69	25	
9	9	I	15	28	43	28	43	0	Critical Act.
10	10	J	15	28	43	28	43	0	Critical Act.
11	11	K	12	47	59	69	81	22	
12	12	L	22	43	65	43	65	0	Critical Act.
13	13	M	14	15	29	53	67	38	
14	14	N	9	43	52	58	67	15	
15	15	O	16	65	81	65	81	0	Critical Act.
16	16	P	28	52	80	67	95	15	
17	17	Q	14	81	95	81	95	0	Critical Act.
18	18	R	9	95	104	95	104	0	Critical Act.

AA BB CC

Early Bar Chart

Late Bar Chart

Critical Bar Chart

Optimization Results | Schedule Results | Early Bar Chart | Late Bar Chart | Critical Bar Chart | Results

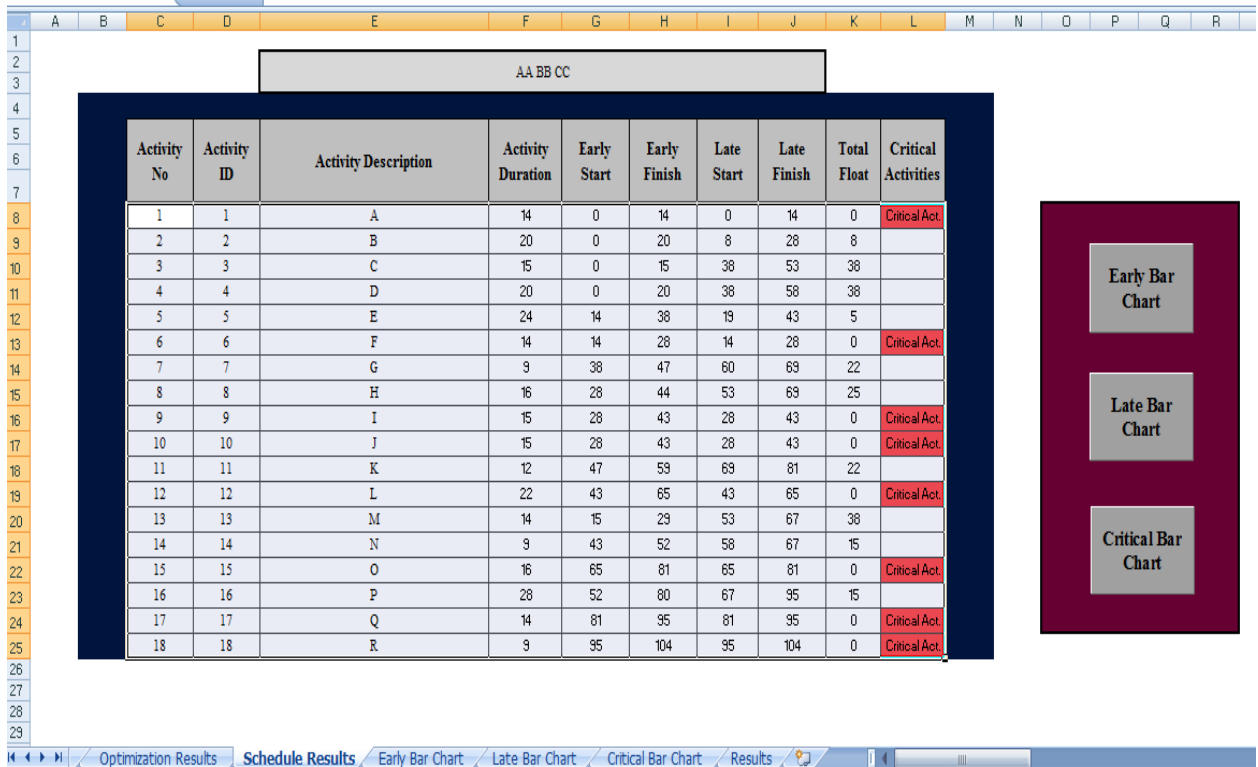**Figure 4. 44: Scheduling results for a selected scenario of the advanced TCQ model**
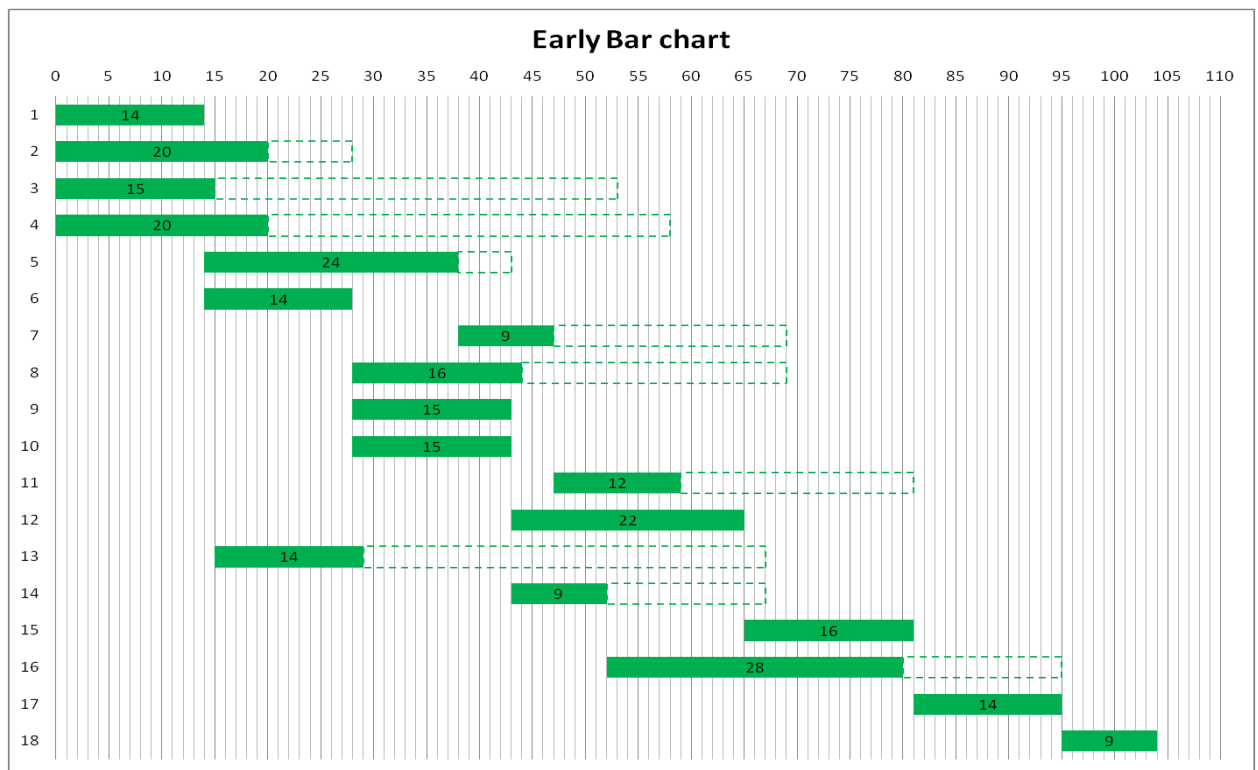
Early Bar chart

Figure 4. 45: Early bar chart for a selected scenario of the advanced TCQ model
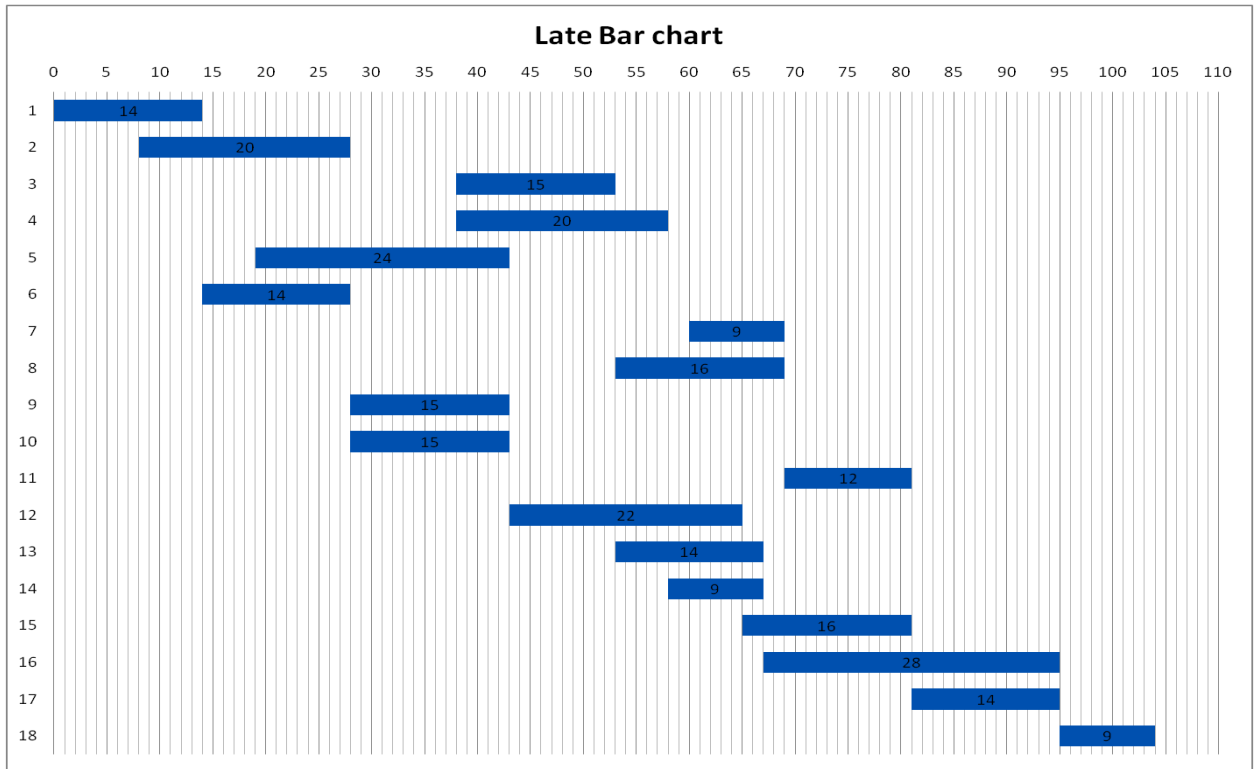
Figure 4.46: Late bar chart for a selected scenario of the advanced TCQ model
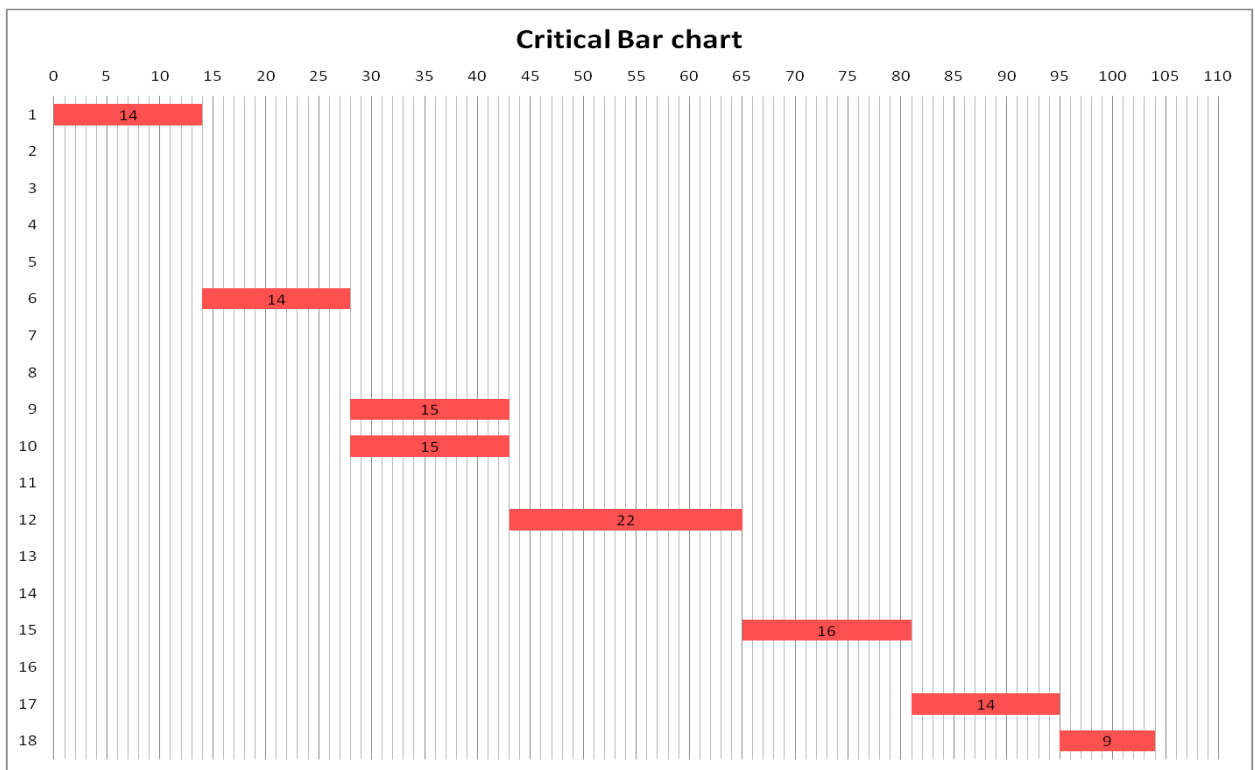
Figure 4. 47: Critical bar chart for a selected scenario of the advanced TCQ model

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4.4.4 Results and Analysis

Tables 4.11 to 4.16 show the advanced TCQ model results for various optimization approaches and various optimization objectives. The following conclusions were reached by the generated results:

- Compared to results that obtained by literature, (Hegazy & Ayed, 1999), (El-Rayes & Kandil, 2005), and (Zheng et al. , 2004), satisfactory results were obtained by the advanced TCQ model.

- Compared to results of the simplified TCQ model utilizing the Evolver add-in, comparable results were obtained by the advanced TCQ model utilizing the self-developed optimization tool.

- It is obvious that the NSGAII approach outperforms the other two approaches in analyzing both TCT and TCQT problems.

- Tables 4.11 and 4.14 demonstrate the impact of objectives' weights of the GP approach on the obtained solutions. Therefore, it is recommended to apply the GP approach when there is a prefrernce for a specific objective.

- Based on conducted tests and according to the developed code, it is recommended to set the population size between 50 and 100 and the number of generations between 100 and 200. It is recommended to set the crossover rate between 0.4 and 0.6 and the initial mutation rate between 0.05 and 0.3.

- For the MAWA approach, it is recommended to reduce the initial mutation rate (Pmi) in order no to disrupt the produced offspring solutions. Pmi of 0.05 generates satisfactory solutions.

- Scheduling results provided by the advanced TCQT model were compared with results produced by MS Project and both were identical.

Table 4.11: The GP approach results of the advanced TCQ model

	The GP Approach Results																								
Solution	Weights of Objectives			Total Duration	Direct Cost	Total Cost	Total Quality	Execution options for activities																	
	Wt	Wc	Wq					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	0	0	104	163,470	319,470	88.95	1	3	3	1	1	1	1	5	1	1	3	1	2	3	1	2	1	1
2	0	1	0	108	122,320	284,320	80.11	1	3	1	3	4	2	3	5	1	1	1	1	3	1	1	5	1	1
3	0	0	1	107	168,755	329,255	97.46	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1
4	0.333	0.333	0.333	104	150,320	306320	92.62	1	1	1	3	2	1	1	1	1	1	1	1	1	1	1	2	1	1

Table 4.12: The MAWA approach results of the advanced TCQ model

	The MAWA Approach Results																					
Solution	Total Duration	Direct Cost	Total Cost	Total Quality	Execution options for activities																	
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	104	161,015	317,015	91.63	1	2	2	1	1	1	2	2	1	1	2	1	1	2	1	1	1	1
2	107	151340	311840	89.71	1	4	1	3	1	1	1	3	2	1	2	1	1	3	1	1	1	1
3	104	145,115	301,115	86.81	1	4	2	3	1	1	2	2	1	1	2	1	1	2	1	1	1	1
4	106	155,070	314070	87.54	1	2	2	1	1	1	3	5	1	1	1	2	3	2	1	4	1	1

Table 4.13: The NSGAII approach results of the advanced TCQ model

	The NSGAII Approach Results																					
Solution	Total Duration	Direct Cost	Total Cost	Total Quality	Execution options for activities																	
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	108	122,400	284,400	80.25	1	3	1	3	4	2	3	3	1	1	1	1	3	1	1	5	1	1
2	104	162820	318820	95.16	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
3	104	150,320	306,320	92.62	1	1	1	3	2	1	1	1	1	1	1	1	1	1	1	2	1	1
4	104	141,100	297100	88.67	1	3	1	3	2	1	3	3	1	1	1	1	1	1	1	2	1	1
5	104	149,820	305820	92.2	1	1	1	3	2	1	1	1	1	1	1	1	1	1	1	4	1	1
6	104	168,820	324820	97.63	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 4.14: The GP approach results of the advanced TCQ model for TCT

	The GP Approach Results for TCT																							
Solution	Weights of Objectives		Total Duration	Direct Cost	Total Cost	Execution options for activities																		
	Wt	Wc				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	0	104	152,858	308,858	1	5	2	2	1	1	1	4	1	1	1	1	3	1	1	3	1	1
2	0	1	108	119,270	281,270	1	5	3	3	4	2	3	5	1	1	3	1	3	3	1	5	1	1
3	0.5	0.5	105	127,270	284,770	1	5	3	3	4	1	3	5	1	1	3	1	3	3	1	5	1	1

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Table 4.15: The MAWA approach results of the advanced TCQ model for TCT

Solution	Total Duration	Direct Cost	Total Cost	Execution options for activities																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	104	140,700	296,700	1	4	1	3	3	1	2	3	1	1	1	1	1	2	1	1	1	1
2	107	130,920	291,420	3	1	3	3	4	1	2	5	1	1	1	1	3	3	1	5	1	1
3	106	136,170	295,170	3	4	1	3	3	1	2	1	1	1	3	1	3	3	1	4	1	1

Table 4.16: The NSGAII approach results of the advanced TCQ model for TCT

Solution	Total Duration	Direct Cost	Total Cost	Execution options for activities																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	104	132,270	288,270	1	5	3	3	3	1	3	5	1	1	3	1	3	3	1	5	1	1
2	108	119,270	281,270	1	5	3	3	4	2	3	5	1	1	3	1	3	3	1	5	1	1
3	105	127,270	284,770	1	5	3	3	4	1	3	5	1	1	3	1	3	3	1	5	1	1

4.4.5 Model Capabilities and Limitations

Results of the application example supports the utilization of the advanced TCQ model in various TCQT and TCT problems due to its effectiveness and efficiency. Capabilities and limitations of the advanced TCQ model are as follows:

4.4.4.1 Capabilities and Strengths of the Advanced Model

- Quality performance evaluation approach for both the activity level and project level.

- Generalized dependency relationships among activities.

- The ability to enter up to five execution options for each activity.

- The ability to enter up to five successors and predecessors for each activity.

- Three various MOO approaches are available.

- Generation of several optimal solutions rather than one solution to provide decision makers with alternatives to choose from depending on their preference.

- The ability to analyze time-cost optimization problems in addition to time-cost-quality optimization problems.

- Robust results with adequate processing time considering the large search space

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- Spreadsheet features and capabilities associated with developing the models in MS Excel.

- Ease of use and simplicity.

- Error handling messages to guide the model user.

4.4.4.2 Limitations and Weaknesses of the Advanced Model

- Premature conversion of the GP and MAWA optimization approaches

- Complexity of data entry for large-scale projects

- Excessive processing time for large-scale projects

- Uncertainty is not considered

4.5 Summary

Three various TCQT models were developed in order to optimize the performance of construction projects in terms of total duration, total cost, and overall quality. The main goal of those three developed models is to optimize the utilization of execution options in order to select an option for each activity within the project to satisfy decision makers' objectives. A simplified TCQ model utilizing the Evolver add in was developed to analyze simple projects with maximum three resource execution options and only finish to start dependency relationships. A stochastic TCQ model capable of considering uncertainty associated with execution options' performance and the whole project's performance with regard to time, cost, and quality was developed to analyze stochastic problems. Moreover, an advanced TCQ model utilizing a self-developed MOO tool was developed. In addition to TCQT analysis, the advanced TCQ model was applied to a TCT analysis and results were satisfactory.

Chapter V: Conclusion

The main objective of any construction project is to finish the project within an estimated budget, according to a pre-specified level of quality, and without any delays. Therefore, the total duration, cost, and quality of construction projects are of great importance for contractors and project managers. Time-cost optimization or TCT is considered one of the most important features of projects' planning and controlling. The main idea of time-cost trade-off is to strike a balance between the decreased indirect costs and the increased direct costs associated with accelerating projects. Owners, consultants, and general contractors should consider quality of work proposed by each subcontractor or execution option in order to make accurate decisions related to execution of construction projects. It is required to determine an optimal or near optimal trade-off among cost, time and quality of construction projects, which means to complete the project at a given deadline or with minimum duration, provided that its total cost is minimized and its overall quality is maximized.

5.1 Conclusions

The main idea of TCQT is to strike a balance among the conflicting objectives of time, cost and quality. There are two categories of trade-off problems: (1) continuous trade off problems, in which the relation among time, cost, and quality has been considered a continuous function; (2) discrete trade-off problems, in which the relation among time, cost, and quality has been considered discrete or isolated. Discrete time-cost-quality relationships are preferred for two main reasons: (1) it is more relevant to real world construction projects; (2) it is suitable for modeling any general time-cost relationship (Tareghian & Taheri, 2006). For optimization techniques, evolutionary algorithms are preferable and commonly used because they can deal with more than one objective, easily achieve diverse solutions, and they are more effective when applied to large-scale problems. Amongst various EA techniques, GA has been extensively utilized for optimization problems in general and

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construction management problems in particular. Multi-objective optimization approaches have been also reviewed. Three approaches of MOO techniques have been discussed, which are goal programming (GP), Pareto optimum, and non-dominated sorting genetic algorithm (NSGA-II). The NSGA-II has demonstrated to be one of the most robust algorithms for MOO problems.

Three TCQT models were developed in MS Excel: the simplified model to optimize the objectives of time, cost, and quality of simple projects; the stochastic model to analyze projects considering uncertainty; and the advanced model to analyze both TCT and TCQT for large-scale projects. The main objective of such models is to find an optimal or near optimal set of execution options for a project's activities in order to minimize the project's total cost, minimize its total duration, and maximize its overall quality. The Evolver add-in software was utilized as an optimization tool for the first two models; however, a self-developed optimization tool utilizing three various optimization approaches was utilized for the advanced model. To validate the developed models and demonstrate their efficiency, they were applied to case studies introduced by literature. Compared to results obtained by literature, satisfactory results were obtained by the developed models. In addition, the advanced TCQ model utilizing the self-developed optimization tool generated comparable results compared to those obtained by the Evolver add-in.

5.2 Research Contributions

This research contributes to improve controlling and planning of construction projects. It facilitates the process of decision making with regards to the duration, cost, and quality of projects. It helps decision makers to select the most appropriate execution options to complete the work of construction projects' activities. The main contributions of this research can be summarized as follows:

- Adequate illustration of existing optimization approaches. This study provided an in-depth review of optimization approaches such as heuristic, mathematical, and evolutionary approaches.

- Extensive review of approaches and methodologies utilized to analyze TCT and TCQ problems.

- Investigating recent MOO techniques and the most effective ones were utilized by the developed models.

- Investigating quality measurement approaches and the most appropriate ones were incorporated into the developed TCQ models.

- The need for incorporating uncertainty when controlling and scheduling construction projects was outlined.

- The utilization of the Evolver add in as a powerful optimization tool is outlined.

- Development of a simplified TCQ model used for simple construction projects.

- Development of a stochastic TCQ model to consider uncertainty associated with execution options and the whole project performance.

- Development of a powerful advanced TCQ model capable of simultaneously minimizing the total project cost and duration, while maximizing the overall project quality.

- Application of three various MOO approaches to be utilized by the advanced TCQ model and TCQT problems in general.

- Development a MS Excel based scheduling tool capable of scheduling problems with generalized dependency relationships.

5.3 Future Research

Despite the simplicity of the developed models and robustness of their obtained results, various other enhancements and improvements are recommended for further extensions of the current research. The following areas are instances of recommendations for future research:

- Utilizing other recent optimization packages such as C-Plex, solver platform, or Quantum.

- Incorporating fuzzy sets or Monte Carlo Simulation to consider uncertainty associated with construction projects in studying the TCQT analysis problems.

- Research on the indicators that affect the quality of execution options of activities in construction projects. Research on activity weights with in different categories of construction projects.

- Incorporating a fourth objective into the optimization process such as increasing safety or reducing risk.

- Incorporating Resource utilization optimization into the model; resource allocation and resource leveling constraints.

- Integration between the optimization model and commercial software such as primavera or MS Project.

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