# MODELING OF TRI-PARAMETER CONTRACTS INTEGRATING COST, TIME AND RISK

by

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## Dedication

To each equally, my pride and joy, my sweet loving Father and Mother.

To my angels, my beautiful four sisters, who mean the world to me.

## Abstract

Delay is a crucial determinant to the success of a construction project as time has an impact on the financial returns and/or the social benefits for public projects. As cost contingencies are essential to mitigate the risk of unforeseen conditions, time contingencies are also as important. For decades, the low-bid system has been the most popular contracting method. Nevertheless, problems arise in the current complex construction industry as owners rely solely on cost, and the time parameter is usually not evaluated as part of the awarding criteria. Recently, the bi-parameter bidding system, A+B, introduced the time parameter to the awarding criteria; yet, risks will not cease to exist. Reducing the duration by compressing the schedule consumes the float of non-critical activities, which reduces the schedule flexibility of a project. Therefore, the likelihood of critical delays occurring increases which lowers the probability of finishing on time. A new tri-parameter system, A+B+R, is introduced and brought into the broader view. The key value of A+B+R system is that it remains within the framework of the competitive bidding system, while controlling the risk resulting from float loss. The A+B+R system does not only take the time parameter into consideration, but it also incorporates the risk parameter into the awarding criteria to diminish the risk of finishing late. Henceforth, project managers can exercise new tradeoffs between cost, time and risk; ultimately, improving the chances of achieving the project objectives. Two different models are proposed for the A+B+R system suggesting a three-way tradeoff, which defines a new optimum project duration. The first model considers stochastic scheduling to quantify the float loss impact at the project level while the second model considers a deterministic approach through the calculation of float loss cost for each activity individually to determine the risk parameter. In this study, application examples are implemented and discussed for both models. Results show that adding the risk parameter in the evaluation criteria changed the ranking of the bidders, which validates the significance of the system. The evaluated risk parameter weighed 3-5% of the original bid price which checks with the typical projects' contingency.


**Search Terms:** Bids; Contracts; Multiparameter bidding; Time-cost-risk tradeoff; Scheduling risk; Project management.

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# Chapter One: Introduction

## 1.1 Overview

The main aim of project management is to complete the project within the allocated budget, time frame and quality constraints. Therefore, the choice of a bidding system (or contracting method) as well as the appropriate awarding criteria are very crucial. Nowadays, public works projects are having very strict guidelines to ensure on-time completion; mainly due to being critical services or having major effects both economically and socially. In many cases, such projects face the risk of losing the funding in case of delays since in public plans, such as highway projects, it requires up to total of ten years to go from inception phase to commissioning [1]. Within the current mature construction industry, public clients place more emphasis on time and quality than cost. Hence, the prequalification process, bidding methods and quality control procedures are more complex and often require more efforts. Otherwise, if the awarding criteria are solely based on the lowest bid, there is an associated risk of low quality, poor performance and extensive delays.

As a result, a new and different approach was required to highlight the monetary value of time during the bidding process. Herbsman and Ellis [2] evaluated a process by employing the valuation of two criteria simultaneously; cost and time. In this process, bidders have to submit the unit price per work item in addition to the proposed duration for the project completion, and the winning bidder is selected on the combined monetary value of multiple components [3]. The time component of the bidders' evaluation process is calculated against a certain cost per day. Ever since, more Public Works agencies have started to consider the value of time in the strategy of any bidding or contracting method. Such strategy allows bidders to bid the number of time units in which the work can be completed [4]. Therefore, any bidder shall try to define the most practical duration to complete the project in addition to a competitive bidding price. This system has often reduced the project's duration without any substantial negative impact on other parameters such as cost and quality [3], [5]. However, projects with shortened durations typically have less flexibility to accommodate delays without prolonging the construction time, besides the lower probability to finish the project on time. For that reason, clients and owners need to evaluate bids with a consideration to the flexibility of the submitted project schedule by contractors and to ensure a rational awarding decision to the appropriate bidder is made. Hence, in order to further enhance the A+B method, an additional consideration should be taken during the evaluation of bids to prevent any kinds of critical delays. Thus, the proposed tri-parameter contracting method (A+B+R) explores and addresses the flexibility Risk parameter of any schedule submitted by contractors for bidding by quantifying the associated schedule risk in a monetary value.

### 1.2 Problem Statement

The most common low bidding system pushes the contractors to further compete and lower their bid prices; yet it has often led to other problems with contractors who mainly bid on the low side. These low bids are often submitted by contractors who are desperately looking to have the business awarded to them especially during the periods of economic recession. These contractors repeatedly do not take into consideration the consequences of radically cutting their costs and bid prices. Eventually, various problems arise such as low quality, poor workmanship and prolonged delays. Ultimately, this has directed to further research and development of alternative bidding systems to reduce such problems. In the case of time-sensitive projects, the bi-parameter bidding system (A+B) tends to solve the main drawback of the low bidding system, which is the price being merely the only awarding criterion without consideration to the time parameter. The established A+B bidding system has resulted in generally shorter construction time as contractors are more aware of the importance of carefully planned schedules to have a better competitive edge. However, crashing the project schedule to obtain shorter duration is associated with the loss of float and flexibility resulting in an increased risk of not completing the project on time. Yet, such an indication of losing the schedule flexibility is not reflected in the bid evaluation stage of the A+B bidding system. This might impose additional risks to the project resulting in an increase of the likelihood of finishing late. Moreover, the quantification of the risk itself is a complicated process taking into consideration the construction time and cost of the project.

## 1.3 Objectives

The main objective of this thesis is to develop a model for a tri-parameter contracting method (A+B+R) incorporating cost, time and risk. The model can be used by clients and owners to evaluate the contractors' submitted bids for their projects.

The detailed objectives are:

1) Develop a tri-parameter (A+B+R) Contracting Method where the Risk (R) parameter is quantified in a stochastic approach (for the entire project) using Monte Carlo Simulation (MCS).
2) Develop a tri-parameter (A+B+R) Contracting Method where the Risk (R) parameter is quantified in a deterministic approach through the calculation of float loss cost (for each activity) resulting from the time-cost tradeoff.

## 1.4 Significance of the Thesis

Project management revolves mainly on finishing any project within the allocated budget and on time while satisfying all the quality requirements. In the past, the competitive low bidding system was, and in fact still is, advantageous to the clients to obtain lower prices for their project and keep the market competitive. Yet, with such a system, the time component is neglected and not considered while evaluating bids. While the current A+B system gives weight to the time component as part of the awarding criteria, problems may still arise when contractors excessively shorten their construction time to increase their awarding chances. Such schedules often result in less flexibility to accommodate any possible delays, and the risk of finishing project behind schedule becomes more serious. Construction projects are full of various risks, and any additional risk will further increase the chances of cost overruns and delays. Hence, the logical approach is to account for the tradeoff between time, cost and flexibility before awarding the project. Besides, it is important to consider and take into account the float loss impact and reduced flexibility in contractors' proposed durations and schedules to find a bid with a risk matching the client's acceptable risk level. The significance of proposing a new tri-parameter system (A+B+R) lies in determining the way to identify a preferable combination of bid price and construction time while maintaining certain flexibility to accommodate non-critical delays without prolonging the overall project duration. Such a measure ensures that there is no impact on the likelihood of finishing the project on time.

## 1.5 Research Methodology

### 1.5.1 Phase One: Preliminary Work

- Formulate a clear statement of the problem with the corresponding research objectives.
- Carry out an extended literature review to further explore previous work in researches and models covering various topics such multi-parameter bidding systems, float consumption, schedule risk quantification, and time-cost-risk tradeoffs.

### 1.5.2 Phase Two: Stochastic Model of A+B+R Contracting Method

- Search for adequate methods that calculate the float loss impact in a stochastic approach by running simulations.
- Develop an initial model for the tri-parameter contracting method (A+B+R), which integrates the quantified risk component related to the loss of float in the time-cost tradeoff problem from the previous step.
- Formulate or obtain examples from the literature that demonstrate the tri-parameter contracting method (A+B+R) and have essential information such as bidding price and construction time, which shall be the application example of the first proposed model.

### 1.5.3 Phase Three: Deterministic Model of A+B+R Contracting Method

- Search for adequate methods that calculate the float loss impact in a deterministic manner considering deterministic normal and compressed conditions for the activities throughout the time-cost tradeoff analysis.
- Develop a second model for the tri-parameter contracting method (A+B+R), which integrates the quantified risk component from the previous step.

- Formulate or obtain examples from the literature with the necessary information of activities costs and durations at different compressed conditions. The example shall be the application of the second proposed model.

### 1.5.4 Phase Four: Analysis of A+B+R Contracting Method

- Analyze the results obtained from the traditional bi-parameter bidding system and the different proposed tri-parameter contracting methods. The results from the tri-parameter models shall be sorted in two classifications; deterministic and stochastic. This step proves the importance and significance of the proposed bidding systems.

## 1.6 Thesis Organization

Chapter One explores the statement of the problem, significance of this research thesis, objectives, and finally the proposed research methodology. Chapter Two presents a literature review of various essential related topics such as the competitive bidding system, the bi-parameter bidding model (A+B), the Total Combined Bid (TCB), the time-cost tradeoff, and finally the risks of A+B model. Chapter Three discusses thoroughly the first proposed stochastic model of the tri-parameter contracting method (A+B+R) with an application example. Chapter Four discusses the second proposed deterministic model of the A+B+R system in addition to an application example as well. Finally, Chapter Five presents the summary and conclusions of the thesis in additions to recommendations for future work and considerations.

# Chapter Two: Literature Review

## 2.1 Competitive Bidding

Literature defines no specific “best overall” bidding strategy as the situation of the tendering conditions varies from one particular project to another. Yet, for the last few decades, the majority of construction projects (more than 40 percent) have had the competitive low bid system as the main procuring strategy whereas the bidding price being the main criteria to award the project to the winning contractor [6], [7]. Harp [8] points out the idea of competitive bidding had been in practice specifically in New York State since 1847 until 1898 when it became a principal legislation for all bidding activities in the public sector. Back then, the basic idea of the low bid system was to provide maximum benefits to the public in return for their tax money with the bidding process being objective and completely independent of other factors such as political or social [2]. Likewise, the low bid system is most convenient for both parties as contractors are only concerned with defining a competitive profit markup level on top of the construction cost based on the resources, capital and technical abilities; whereas the client has to only award the project to the lowest bidder [9]. Another added advantage of the low bid system is that the contractors are continuously trying to lower the cost with technological and managerial advancements to remain competitive [10]. In some occasions, additional considerations are taken into account while awarding the contract; for example, related previous experience to undertake the new project, management capabilities, availability of facilities and skilled labor, financial stability, safety records, and the reputation in the market [11].

The conventional low bid system is by far the most frequently used system to award construction projects [12]. However, due to the cost being the only evaluating criteria, the low bid system has several drawbacks especially within the public sector: quality issues, poor performance, prolonged delays and increased claims from variations [2], [13]. In many cases, clients might ultimately pay the lowest bidder more than another bidder with a higher initial price with better overall commitment and quality. For example, in Hong Kong, the same low bid system was evaluated to be the main reason for all the delays in projects deliveries [14]. In addition, Tam and Shen [13] claim that contractors make up for their low bid price by reducing the quality or through claims and variations. Consequently, it is evident that more efficient bidding systems need to be developed for the construction industry.

Several trials and modifications to the low bid system have been incorporated by researchers in order to overcome the various drawbacks. Some of the modifications to the system include newly defined terms such as “responsible reasonable bidder,” one who is not the lowest bidder, but rather the closest one to a specific calculated average based on other bidders [15]. Moreover, other variations to the main system is by disqualifying abnormally low bids from contractors that may cause problems at a later stage, or “bracketing” which considers bids which are within a range of the Engineer’s original estimate [15]. Multiparameter bid system was tried over several years in the U.S. to include other parameters to the cost such as time and quality being represented as a money value through certain mathematical calculations and weights giving to each relevant factor [2].

Public clients are becoming more conscious about the importance of reduced construction time due to the positive contributions to the society and the economy. Clients are often concerned about the construction time and push for early completion of their projects, because it contributes positively to the return of their investments as delays naturally cause loss of possible business opportunities which is regarded as potential profits. More specifically, in the case of public projects such as highway projects, delays can cause inconvenience, traffic disruptions, and longer commuting time [13]. The attempts to further reduce the project duration are through the new contracting methods such as fast tracking [13], [16] or by setting new requirements for the conventional competitive low bid system.

Another example of an innovative method is the bi-parameter bidding system, also known as A+B method, where the bidding strategy includes bidding on price and time with the main purpose of accelerating construction at the lowest possible cost [17], [18]. As the Time parameter has become an important consideration, the invitation to bids ask for the submission of Total Combined Bid (TCB) which includes the price in addition to the contract time expressed in a dollar value.

Herbsman et al. [17] defined contract time as “the maximum time allowed for the contractor to complete all the work as specified in the contract documents.” Nevertheless, although it varies from one contract to another, the main principle of this system is to provide a monetary value to the Time parameter by providing a Unit Time Value (UTV) to each unit of construction time; which is considered the basis to determine the monetary value of the contractor’s proposed contract time. From a legal point of view, the basic principle of A+B method does not conflict with the legal principles of the competitive low bid system, and therefore, it requires no significant changes to the bidding and awarding procedures [8].

### 2.2 A+B Bidding Method

The U.S. Army Corps of Engineers has called this “newly” developed system as Bidding on Cost-Time. It has, however, several other name designations [19]. The same system is also known as A+B method, Cost Plus Time Contracting, or bi-parameter bidding [17], [20]. The system has been used by the U.S. Army Corps of Engineers for 15 years [17]. A+B method has been successfully experimented by several American Departments of Transportation (DOTs) all over the states since it was recommended by the Federal Highway Agency in 1991 [17], [21] and formally approved in 2002 [20]. The reason for such recommendation was the severe delays of most highway construction projects in the urban areas with high traffic volume causing additional inconvenience to the public. On the other side of the world, more specifically in Hong Kong, the requirement of implementing the A+B method started in 1990 after the successful trials in the U.S.

The A+B method emphasizes the importance of minimizing the construction time in case of highway projects due to their adverse impact until they are actually completed and available for service. In this system, the main principle is that contractors are required to submit a bid package containing both components; A representing the price and B for the project time. While component A is determined using the regular way as in the low bid system, component B is calculated with the multiplication of the proposed project duration and the Unit Time Value (UTV). The main advantage of such a system is that the reductions in projects durations are achieved through the actual competition among the bidders.

Another variation of the A+B bidding system is to include additional clauses for incentives and disincentives (Plus I/D) in regards to the project completion duration [4], [21]. The use of such clauses serves as an additional financial encouragement for the awarded contractor to complete the project earlier than the contract time. Herbsman et al. [17] explained that the incentive clause has several versions in which the financial incentives to the contractor vary from an unlimited amount to a limited total amount; for instance, not to exceed a certain percentage of the total project cost (i.e., 5%, 10%). Ultimately, the contractor's additional costs for expediting the construction activities should be lower than the incentives as an effective encouragement [18]. In contrast, the disincentives serve as penalty for completing the project later than the agreed contract time. Yet, some practitioners argued that in the traditional low bid system, the project duration, which later becomes the contract time upon a successful award, is estimated by the Engineer as part of the tender documents. Whereas in the A+B bidding method, the contract time is the contractor's proposed project duration; therefore, the incentives should be disregarded in the cases of early completion since the contractors themselves establish the contract time with the project award [17]. However, researchers counter argued that in such cases, the incentive system encourages the contractor to further finish the project not only in shorter duration than the Engineer's estimate, but even shorter than the awarded bidder's original proposed duration in the bid package to earn additional profits. The only concern is the possibility of contractors inflating their construction time during the bid in order to gain substantial amount of the incentive fees [17]. A suggested solution is to reject bids if the proposed contract time is longer than the original Engineer's estimate [22].

Yet the important advantage of the A+B method combined with the I/D clause is double motivation for contractors to reduce time. Firstly, low proposed time is achieved by the competition among contractors to have the project awarded, and secondly, further reductions are achieved through the incentive fees [17]. Secondly, the relationship between the contractor and the client is typically less adversarial which is accounted to the fact that the contractor can receive incentive money. Nevertheless, and if included, the incentive/disincentive (I/D) value are regularly specified by the client and has the same value as the defined UTV in the tender documents for every project [19] except in some States that use a different set of parameters to determine I/D values [17]. Eventually if not included, the contractors do not receive any incentive for early completion nor pay any disincentive other than the agreed liquidated damages specified in the contract documents.

Many experts are not familiar with the practical principle of the A+B method, though many researchers, such as Herbsman and Ellis [2], Herbsman [19] and Clark [23], explained the theory behind it. Lambropoulos [1] also evaluated the most common bidding systems under the European Union Legislation and proposed a modified version which incorporated the utility curves of the construction time to complete a project as a component of the bidding system.

Shen et al. [7] investigated the construction market in China and identified the essential factors in a multiple parameters bidding system in the local market (i.e. the contractor's competitiveness level compared to other contractors in the prequalified list) to ensure the project is awarded to the appropriate responsible bidder. Furthermore, Herbsman and Ellis [2] discussed the advantages and disadvantages of multi-parameter bidding systems in addition to the quantification of these parameters as in cost, time, quality, safety, durability, security and maintenance. The quantification methodology consists of point system given to each required parameters from the client's point of view. They also conducted a research over 14 different projects, which were awarded using A+B bidding system, concluding that major reductions in the projects durations and consequently cost savings were achieved in 11 out of 14 projects. The savings were calculated considering the contractor's proposed duration and price as compared to the owner's.

Herbsman [19] also evaluated the use of the A+B method since there was no specific systematic evaluation technique for the method. He studied the time reductions in the cases in which the A+B method has been used as the awarding strategy. Data from over 100 highway projects all around the United States were collected and analyzed with the conclusion that the higher competition among bidding contractors resulted in significant time reductions with no major cost added compared to the conventional low bid system. One of the findings in the same study regarding the estimated completion time is that in 91% of the time, the contractors' proposed construction time was shorter or at least equal to the estimate of the Engineer. The positive results were accounted to the improved project planning of contractors considering the time component as part of the awarding criteria and the motivation for contractors to finish projects in shorter durations than the original estimate of the client. Another finding is that in most scenarios, the cost of the projects is not increased in the A+B method compared to that of the cost of similar projects that had traditional low bid system. This is attributed to the fact that contractors would still compete to win the award by keeping their cost estimates on the "low side" by improving the accuracy of scheduling, planning and efficient management, and hence win the project award.

Strong et al. [20] also confirmed the effectiveness of the A+B method through a research project consisting of 9 case studies. They indicated that the A+B method is the most effective bidding system that leads to shorter construction duration Furthermore, an investigation, which was done by Tam and Shen [13] using data of 24 different projects in Hong Kong that had the A+B method as the bidding system, recommended to steer away from "blind consideration" of the low bid system to award projects. The investigation concluded that the A+B method resulted in shorter total project durations compared to the low bid system with an average of 37 to 50 days (11.4–17.4% reduction) depending on the project type. Also, an analysis by Herbsman [19] done on the A+B method with its different variations concluded that 20-50% time reductions were achieved by utilizing the A+B method rather than the traditional low bid system. Another conclusion is that the use of incentive and disincentive fees only in the low bid system is less effective than the A+B method and this has resulted in a decrease in the number of such contracts in the U.S.

Abdollahipour and Jeong [18] studied the impact of the Unit Time Value (UTV) on contractors' bidding strategies and how the client can optimize the value of UTV in order to increase the competitiveness among contractors. Innovatively, Ahn et al. [3] suggested a modified A+B method in which a third parameter, Environmental Cost, is added to the system. The purpose of the research was to reveal the potential impact of environment cost component to the awarding criteria with a conclusion that the proposed modification can count as additional incentives for sustainable construction works.

In order to ensure an optimum tradeoff between cost and time resulting in a minimum TCB, El-Rayes [21] proposed an optimization model for the planning and utilization of resources on an activity level due to the important impact on the overall project duration and total cost. The model consists of different alternatives to determine the optimum crew size and their productivity level through a dynamic programming formulation in two paths: forward (locally on an activity level) and backward (globally on a project level). In addition, Tam and Shen [13] developed a mathematical optimization model to calculate the optimal bid parameters for the bidding price and time for each contractor. Shr et al. [4] formulated a model to determine the optimum low bid price and time when incentive/disincentive fees are present.

## 2.3 Unit Time Value (UTV)

The integration of contract time to the TCB is done through the multiplication of the time duration and UTV. Several studies [17] explained UTV as a representation of the cost of delays to the clients which consists of the both direct and indirect costs. The clients have to calculate the value of unit time in order to determine these costs. Direct costs are related to the increasing moving costs or temporary facilities. Indirect costs are a measure of the general and job overheads as well as other costs as in the loss of possible business opportunities and potential profits. Additionally, liquidated damages, which are present in most construction contracts, can be another measure of time value or possible losses to the client. Liquidated damages are defined by Murdock and Hughes [24] as a "fixed rate of money that is entered into the appendix to the contract which becomes payable by a party to a contract if certain specified breaches occur."

In the highway construction industry, UTV is defined as the daily road-user cost (RUC) in which to this date has no developed standard computational methods to determine an appropriate value for RUC [13]. However, an approximation can be determined by DOTs taking into consideration the economic benefits of the road and the fuel expenses due to the longer travel time and longer travel distances [21]. Generally speaking, Herbsman [19] reported that RUC can range from 1,000 USD to 200,000 USD per day.

## 2.4 Total Combined Bid (TCB)

Herbsman et al. [17] pointed out that the A+B bidding strategy is one of the four most popular systems being used by DOTs recently which positively resulted in the elimination of inefficient contractors. The incorporation of the time component into the bid price is illustrated in Equation 1 [17] that is used to determine the winning contractor with the lowest TCB.

$$TCB = ECC + (RUC \text{ x } EPD) \qquad \text{(Equation 1)}$$

Where;

TCB = Total Combined Bid

ECC = Estimated Construction Cost

RUC = Daily Road-User Cost

EPD = Estimated Project Duration

However, a more generalized form of the same equation is given in Equation 2 [7] for any price-time bi-parameter bidding strategy.

$$TCB = p + (UTV \text{ x } t) \qquad \text{(Equation 2)}$$

Where;

TCB = Total Combined Bid

p = contractor's bidding price

UTV = Unit Time Value specified by client

t = contract time proposed by the contractor

For example, if the contractor bids a price of p = 10,000,000 USD and a proposed duration of t = 300 days, and RUC or UTV of 15,000 USD/day then using Equation 2,

$$TCB = 10{,}000{,}000 + (300 \text{ x } 15{,}000) = 14{,}500{,}000 \text{ USD}$$

Herbsman [19] gave a real example of contractors' bidding results from a highway project constructed in North Carolina. Through the bid evaluation stage, Bidder A had the lowest cost part and Bidder B had the shortest duration for the construction time part. Yet Bidder C had the lowest Total Combined Bid and eventually was awarded the project.

A common confusion for the public and other practitioners regarding the use of the A+B method is that the winning lowest combined bidder does not have the lowest price, and more money is being paid for the project [19]. However, the issue can be illustrated using the above example of the project in North Carolina. The actual difference in the cost part between the lowest Bidder A, and the winning Bidder B was 19,518,537 – 19,371,550 = 146,987 USD, while the time savings gained by Bidder B was 762 – 672 = 90 days.  Considering that RUC was equal to 7000 USD/day which was specified by DOT of North Carolina for that particular project, the direct cost savings in terms of time reductions was 90 x 7000 = 630,000 USD resulting in a net gain and saving in the overall cost of the project to 630,000 – 146,987 = 483,013 USD. It is worth mentioning that the actual savings would be even higher in reality since the RUC defined for this project did not include the indirect costs due to the difficulty in quantifying these values [17].

## 2.5 Cost-Time Relationship

In most projects, it often becomes necessary to reduce the project duration at an added cost. The time duration and construction cost for any particular project are highly interrelated in most cases [25]. For that reason, scheduling and the dynamics between time and cost are the focus in much of the literature. The analysis between these two elements is important to evaluate various alternatives and combinations of different construction costs and the corresponding durations depending on the allocated resources which affect this interrelationship between time and cost [7].

Callahan et al. [25] has reported that for every project, and for every construction company, there is an optimum cost-time balancing point (normal point) that gives the contractor the lowest possible construction cost with a certain project construction duration. Furthermore, Clough and Sears [26] explain that the increase of the cost from the normal point is higher when the required project duration is shorter than the normal time, than the increase of the cost in the case if the duration is longer. In other words, the project duration shortening or reduction has a larger impact on the cost than the case of time extension. For example, adding extra shifts, overtime hours and shorter material deliveries to reduce the project duration will result in an increase of the direct cost, while generally any extension to the project duration will increase the indirect cost of the project.

The exercise of accelerating a project to reduce the total duration is often called "crashing." The minimum time to which a project can be reduced to is referred to as the "project crash time," with the associated cost referred to as the "project crash cost" [26]. Due to several factors such as the technical abilities and management skills from one contractor to another, each contractor has a specific normal point for every project that represents his or her lowest construction cost and the corresponding construction time. A suggested quadratic or second-order polynomial function describes the interrelationship between cost and time [4]. The constants of the quadratic function for the interrelationship can be approximated using three different combinations of bid price and the corresponding construction time based on previous experience of the contractor [7]. The three points consist of the shortest duration point (crash point), the most likely bid duration point and the third point which corresponds to the lowest construction cost (normal point). Using these three sets of data, the unknown constants ($a$, $b_1$, $b_2$) are determined, and the quadratic formula can be derived.

Over the years, many researchers have discussed the topic of the cost-time tradeoff using a widely used technique known as least-cost scheduling. However, Isidore and Back [27] discussed the major drawback of applying this technique, which is the lack of any statistical procedures. Project activities will always have variability in the duration and cost due to the different conditions and uniqueness of each project; therefore, it was important to have a statistical level of confidence to overcome the drawback of the least-cost scheduling.

Contractors now face a new dilemma in which they have to decide the right combination of bidding price and project duration to ensure a competitive edge by submitting a lower TCB value than the rest of the participating bidders. Such a system has changed the approach that most contractors take as their bidding strategy as they pay more attention to their project scheduling techniques because the Time parameter has a weight in the evaluation criteria. Moreover, contractors start to take into consideration the relative importance of cost as well as the time value for any particular project to the client to form a bidding strategy that increases their chances of being awarded the project.

The A+B bidding method incorporates the time and Cost parameters into the awarding criteria, as a result, contractors require an optimum strategy to utilize their resources and minimize their construction time and cost. Construction time is generally reduced by assigning additional resources to the project, which naturally leads to increase in the project cost; hence, in most cases, there is a conflict between the two objectives of reducing time and cost. However, Herbsman et al. [17] explained that such evaluation is conducted by the contractors on an economical basis, and whether they are able to earn higher profit rates with the investment of additional resources and so on.

## 2.6 Risk of A+B

Project Management Institute [28] defines risk as any uncertain event in which if it occurs, it will have a positive or a negative impact on any of the project's objectives: time, cost, or quality. Risks are inherent in all projects regardless of their nature of complexity [29]. Henceforth, identifying and assessing such potential risks are important elements of successful project management. These risks can be classified into two categories based on their source; internal risks in which eventually can be controlled by proper risk management approach, and external risks that are out of control. Generally speaking, the nature of risk in construction projects is due to the involvement of several entities with different interests [30], the prolonged life cycle, and complexity [31]. That being said, the effort in the process of identifying all risks in any project is inefficient and time-consuming [30], and the notion of eliminating all risks in construction projects is impossible [30]. Yet, construction delays are still one of the most recurring risks in the construction industry and often jeopardize most of the project's objectives especially that they are directly associated with cost and schedule overruns [32]. The serious impact of construction delays lies in the fact that it negatively affects the overall economy of a country rather than the project alone, especially as discussed earlier in the case of public projects.

Although the A+B method overcomes many of the drawbacks of the low bid system, potential problems may still arise when the A+B method is specified as the bidding system. Clients might rush into awarding the project to a contractor with a non-flexible schedule that has a high chance of delays and not finishing on time, which defies the main benefit of implementing A+B as the bidding system in the first place. In addition, bidding contractors may be too keen to win the award, and hence, they might irresponsibly underestimate the construction time in order to have better chances of being awarded [22]. Such situations would result in the contractor trying to minimize any possible financial losses by sacrificing quality and workmanship. Besides, there is another risk of encountering delays due to unrealistic scheduling in which the contractor cannot finish the project according to the plan and specifications [9]. Therefore, to rely on these awarding criteria is risky on the short and long run of the project life cycles. Consequently, recent research concluded the importance of incorporating risk models in construction bids especially that contractors might choose not to do so in order to increase their chances of winning the award [31]. Such risk is often difficult to be validly measured and may add considerable uncertainty and complexity, and the quantification and minimization of such a parameter is considered a challenge [33].

Contractors often expedite the construction time by crashing the activities along the critical path in the project network to obtain a shorter overall duration for the project. The crashing process often results in more critical paths emerging in the network which ultimately increases the likelihood of the contractor finishing late too [34]. Another result of crashing and shortened duration of the critical path is that non-critical activities eventually have less float. In principle, float defines the units of time an activity can be delayed without affecting the original project duration, or primarily, float is an indication of the project's flexibility in its scheduling and planning scheme [34]. Float is an important element of the scheduling process since it fairly measures the ability of the project's network to absorb potential delays without an impact on the total construction time. Hence, float contributes in mitigating the risk of delays in case of uncertainties and unforeseen circumstances that might occur throughout the project duration [29]. Construction schedules are often developed at the early planning stage of the project with several assumptions [24]; therefore, float is essential to minimize the impact of any unforeseen circumstances that the planner did not account for. Moreover, in many cases, the assumptions made at the planning stage would change later on. Hence, float helps in reducing the impact of such changes [35]. Furthermore, El-Sayegh [30] explained how changes by owners could pose potential risks to delay the competition of project. This is especially true when the project schedule lacks any float or flexibility to accommodate for these changes. In other words, float reduces risks and increases opportunities.

Time is money, and similarly, float is money as well and any float or flexible time taken away from a schedule has to be compensated for or replaced by a monetary value [34]. Thus, in the A+B method, it is important that the winning criteria should also somehow consider the value of flexibility in schedules presented by the total float available. Although the proposed tri-parameter contracting method (A+B+R) does not mitigate all the risks in a construction project, the main incentive is to eliminate the added potential risks caused by the crashed schedules since contractors compete to have shorter project durations as well. In all cases, other risks such as Act of God are considered external and cannot be controlled in all the projects regardless of the initial bidding system. Also, such external risks are often considered as part of the contingency in the total bidding price. Another benefit of the suggested A+B+R is to eliminate “schedule games.” Al-Gahtani [36] explained these games in which contractors play with the schedule to reserve and hide the float by increasing activity durations or making changes in the project network. However, in the case of A+B+R bidding method, having visible float in the network increases the awarding chance to contractor; hence, they have to be cautious with these “schedule games.”

# Chapter 3: Stochastic Model of A+B+R System

## 3.1 Introduction

The significance of the proposed tri-parameter contracting method (A+B+R) is to account for the importance of considering the flexibility and schedule Risk parameter for any schedule submitted by all bidders. The main idea is that the schedule Risk parameter is quantified on the basis of the float loss in compressed schedules in which contractors try to achieve a shorter project duration. Although shorter durations help bidders to stand a better competitive edge in the original bi-parameter bidding system (A+B), clients and owners should anticipate risks of potential delays resulting from these compressed schedules. Hence, the risk quantification process takes into account the added risk due to the consumption of float that could have been a safe margin to diminish the impact of any delay that might occur. Not only that, float is also important for clients and owners to incorporate change orders without extending the project duration as long as only the available float is consumed. Thus, preventing contractors to claim for additional compensation in money or time. As a result, it is a logical approach that clients and owners incorporates a specific methodology to measure and quantify such a Risk parameter (R) in all bidders' submitted schedules as an essential parameter in the evaluation process.

## 3.2 Stochastic Tri-parameter (A+B+R) Model

The main principle of the tri-parameter contracting method (A+B+R) is the fact that compressed schedules are often associated with lower probabilities of finishing on time due to the reduced available float days in non-critical activities. The first model of the tri-parameter contracting method (A+B+R) in this chapter considers a stochastic approach to determine the probabilistic project durations based on the activities' mean durations and the standard deviation of each. Correspondingly, the probabilistic project duration is determined along the path of the critical activities in the network. Monte Carlo Simulation (MCS) will be the basis of the stochastic system, as well as the way of calculating the probability of finishing the project associated with each bidder's schedule. The approach is that the proposed system takes into consideration the probabilistic project duration of the bidder's compressed schedule at a certain specific probability level. This probability level is defined based on the deterministic and stochastic analysis done on the Engineer's estimated baseline schedule for the same project. In other words, the difference between the deterministic and probabilistic project duration is the result of the float loss from the original base schedule, which shall be interpreted as an extra added cost in the A+B+R system. This systematic approach is essential for clients and owners to evaluate all submitted bids with their relevant costs, durations and schedules, and eventually award the project while understanding the risks associated with the winning bid. The suggested analysis approach for the A+B+R system consists of four main stages as the following: (1) Analysis of Engineer's Baseline Schedule; (2) Analysis of Bidders' Schedules; (3) Quantification of Schedule Risk; (4) Tri-parameter Contracting Model. Table 3.1 demonstrates all the symbols and notations, which are used throughout the stochastic model, and their corresponding representations for ease of reference at any stage.

**Table 3.1: List of Symbols and Description for Stochastic A+B+R Model**

| Symbol | Description |
|---|---|
| $A_i$ | Cost parameter for Bidder i; i = 1, 2, .. n |
| $B_i$ | Time parameter for Bidder i; i = 1, 2, .. n |
| $D_{det,eng}$ | Deterministic Duration for Engineer |
| $D_{det,i}$ | Deterministic Duration for Bidder i; i = 1, 2, .. n |
| $D_{prob,i}$ | Probabilistic Duration for Bidder i; i = 1, 2, .. n |
| $M_{eng}$ | Mean Project Duration for Engineer |
| $M_i$ | Mean Project Duration for Bidder i; i = 1, 2, .. n |
| **MCS** | Monte Carlo Simulation |
| **PDF** | Probability Distribution Function |
| $POF_{eng}$ | Probability of Finishing on deterministic duration for Engineer |
| $POF_i$ | Probability of Finishing on deterministic duration for Bidder i; i = 1, 2, .. n |
| $R_i$ | Risk parameter for Bidder i; i = 1, 2, .. n |
| $Std_{eng}$ | Standard Deviation for Engineer project duration |
| $Std_i$ | Standard Deviation for Bidder i project duration; i = 1, 2, .. n |
| $SR_i$ | Schedule Risk in time units for Bidder i; i = 1, 2, .. n |
| $TCB_i$ | Total Combined Bid for Bidder i; i = 1, 2, .. n |
| **UTV** | Unit Time Value |
| **n** | Number of Bidders |

### 3.2.1 Stage 1 - Analysis of Engineer's Baseline Schedule

The baseline, or normal, schedule is taken from the Engineer's estimate in order to be used as a reference comparison point for all other schedules submitted by different bidders. First, the conventional deterministic schedule analysis using the Critical Path Method (CPM) is performed in order to calculate the deterministic duration ($D_{det,eng}$) as well as to determine the critical and non-critical activities with their available total float. The second step is to define the Probability Distribution Function (PDF) for the activities durations including their mean durations and standard deviation in order to perform the stochastic analysis for the baseline schedule by MCS using @Risk for Excel. The mean durations and standard deviations shall be determined by the Engineer either through experienced approximation or from historical data. After performing the simulation on the Engineer's schedule, the mean project duration ($M_{eng}$), standard deviation ($Std_{eng}$) and the Probability of Finishing ($POF_{eng}$) the project on the deterministic duration are all determined. These outputs shall be the basis and reference points for the analysis of Bidders' schedules at later stages. As for the probability of finishing, Equation 3 illustrates the corresponding probability function.

$$POF_{eng} = \mathrm{P}(x \leq D_{det,eng}) \qquad \text{(Equation 3)}$$

Where;

$POF_{eng}$ = Probability of Finishing on deterministic duration for Engineer

x = Random variable representing the project duration

$D_{det,eng}$ = Deterministic Duration for Engineer

### 3.2.2 Stage 2 - Analysis of Bidders' Schedules

Similarly, a preliminary deterministic analysis using CPM is performed on all Bidders' schedules. The analysis considers the mean activities durations submitted by Bidders themselves in order to determine the corresponding final deterministic project duration ($D_{det,i}$) for each bidder. The next step is performing the stochastic analysis by first defining PDF for the activities durations to be the same as the one in Engineer's schedule. It is a matter of fact that the standard deviation is an essential element of any stochastic analysis which greatly impacts the variation of the results. Therefore, the standard deviations for all activities in bidders' schedules shall be the same as the ones considered initially in the Engineer's schedule analysis. The main objective of this measure is to ensure a reference unbiased values for the standard deviations where the final results will have a logical ground for comparison between Bidders' schedules and the Engineer's. Finally, the results from performing MCS on each Bidder's schedule shall be the probabilistic project mean duration ($M_i$), project standard deviation ($Std_i$) and the probability of finishing ($POF_i$) the project on the original Bidder's deterministic duration as explained in Equation 4.

$$POF_i = P(x \leq D_{det,i}) \qquad \text{(Equation 4)}$$

Where;

$POF_i$ = Probability of Finishing on deterministic duration for Bidder i; i = 1, 2, .. n

x = Random variable representing the project duration

$D_{det,i}$ = Deterministic Duration for Bidder i; i = 1, 2, .. n

### 3.2.3 Stage 3 - Quantification of Schedule Risk

The main objective of the third stage is to quantify the schedule risk in the bidders' schedules in order to incorporate it in the Total Combined Bid (TCB). The purpose is to penalize bidders for highly compressed schedules that are very risky and have high tendency to be behind the schedule due to the reduced flexibility. The scenario is caused by the float loss in non-critical activities, which results in lower probability of finishing on time than the one related with the Engineer's baseline schedule. Henceforth, the first step is to determine the corresponding Bidder's probabilistic project duration ($D_{prob,i}$) at a certain unified probability level for all bidders, which is the Engineer's probability of finishing ($POF_{eng}$) previously determined. Equation 5 illustrates the required calculation.

Let $X$ be $D_{prob,i}$;

Determine $X$ such that: $P(x \leq X) = POF_{eng}$ (Equation 5)

Where;

$D_{prob,i}$ = Probabilistic Duration for Bidder i; i = 1, 2, .. n

x = Random variable representing the project duration

$POF_{eng}$ = Probability of Finishing on deterministic duration for Engineer

The rationale behind the previous step is that owners and clients should evaluate alternative bidders' durations at the desired comfortable probability level without an increase in the project risk. Accordingly in Equation 6, the Schedule Risk ($SR_i$) measured in time unit, which is caused by the impact of the float loss, is calculated from the difference between the Bidder's probabilistic duration ($D_{prob,i}$) corresponding to $POF_{eng}$ and the original Bidder's deterministic duration ($D_{det,i}$).

$$SR_i = D_{prob,i} - D_{det,i} \qquad \text{(Equation 6)}$$

Where;

$SR_i$ = Schedule Risk in time units for Bidder i; i = 1, 2, .. n

$D_{prob,i}$ = Probabilistic Duration for Bidder i; i = 1, 2, .. n

$D_{det,i}$ = Deterministic Duration for Bidder i; i = 1, 2, .. n

Eventually, for each bidder, the next step is to determine the Risk parameter ($R_i$), measured in monetary value, and to incorporate in the tri-parameter contracting method as an additional cost. The calculation for $R_i$ represented in Equation 7 is performed by the product of the $SR_i$ and the Unit Time Value (UTV) defined initially by the client or the owner as part of the original bi-parameter bidding system (A+B).

$$R_i = SR_i \times UTV \qquad \text{(Equation 7)}$$

Where;

$R_i$ = Risk parameter for Bidder i; i = 1, 2, .. n

$SR_i$ = Schedule Risk in time unit for Bidder i; i = 1, 2, .. n

UTV = Unit Time Value

### 3.2.4 Stage 4 - Tri-parameter Contracting Model

In the fourth and final stage, the client and owner shall evaluate all submitted bids based on the outputs from the third stage. The quantification of the schedule risk in bidders' schedules shall be the main inputs in the proposed model of the tri-parameter contracting method (A+B+R). As observed, the proposed system has a third parameter, which is the Risk (R), added up to the original two parameters of the bi-parameter bidding system; the Cost parameter (A), and the Time parameter (B). The Cost parameter is basically the actual monetary value submitted by the bidder presenting the bid price. On the other hand, as illustrated in Equation 8, the Time parameter is the product of the Bidder's submitted deterministic duration for the project and the Unit Time Value defined by the client.

$$B_i = D_{det,i} \text{ x } UTV \quad \text{(Equation 8)}$$

Where;
$B_i$ = Time parameter for Bidder i; i = 1, 2, .. n
$D_{det,i}$ = Deterministic Duration for Bidder i; i = 1, 2, .. n
UTV = Unit Time Value

As a final step, all the determined three parameters shall be summed up to compute the Total Combined Bid (TCB) for each bidder as illustrated in Equation 9. These computed TCB values are used to evaluate all bidders, and the winning bid shall be the bidder with the lowest TCB.

$$TCB_i = A_i + B_i + R_i \quad \text{(Equation 9)}$$

Where;
$TCB_i$ = Total Combined Bid for Bidder i; i = 1, 2, .. n
$A_i$ = Cost parameter for Bidder i; i = 1, 2, .. n
$B_i$ = Time parameter for Bidder i; i = 1, 2, .. n
$R_i$ = Risk parameter for Bidder i; i = 1, 2, .. n

All the four stages and the different steps for the proposed tri-parameter contracting method (A+B+R) are summarized in a flowchart shown in Figure 3.1.

| | |
|---|---|
| **STAGE 1** | - Determine Deterministic Duration ($D_{det,eng}$) for Engineer |
| | ↓ |
| | - Define PDF* for Activities Durations in Engineer's Schedule |
| | ↓ **Stochastic Analysis using MCS*** |
| | - Mean Project Duration ($M_{eng}$) & Standard Deviation ($Std_{eng}$)<br>- Determine Engineer's Schedule $POF_{eng}$* |

↓

| | |
|---|---|
| **STAGE 2** | - Determine Deterministic Duration ($D_{det,i}$) for Bidder i |
| | ↓ |
| | - Define PDF for Activities Durations same as Engineer's Schedule |
| | ↓ **Stochastic Analysis using MCS** |
| | - Mean Project Duration ($M_i$) & Standard Deviation ($Std_i$)<br>- Determine Bidder i Schedule $POF_i$ |

↓

| | |
|---|---|
| **STAGE 3** | - Determine Bidder i Probabilistic Duration ($D_{prob,i}$) at $POF_{eng}$ |
| | ↓ |
| | - Determine $SR_i* = D_{prob,i} - D_{det,i}$<br>- Determine $R_i* = SR_i \times UTV*$ |

↓

| | |
|---|---|
| **STAGE 4** | - Tri-parameter Contracting Method Model: $TCB_i* = A_i* + B_i* + R_i$ |
| | ↓ |
| | - Determine Lowest $TCB_i$ |

PDF: Probability Distribution Function MCS: Monte Carlo Simulation

POF: Probability Of Finishing SR: Schedule Risk R: Risk parameter

UTV: Unit Time Value TCB: Total Combined Bid A: Cost parameter

B: Time parameter

**Figure 3.1: Flowchart of Stochastic A+B+R System**

## 3.3 Model Application Example

For the purpose of demonstrating the proposed tri-parameter contracting method with all the stages and necessary steps, a hypothetical example is formulated and implemented. The example consists of a project with eleven different activities along with their respective durations and precedence relationships. The idea of having a simple network is to resemble a simple real project, whereas different bidders are likely to have the same network logic between the activities but with slightly different durations. This assumption is essential in order to have a better analysis and understanding of the results, which shall be compared and discussed at a later stage. The example has five different schedules; one being the Engineer's that is considered to the normal baseline and reference to the evaluation, and the other four which are submitted by the four bidders. The bidders' schedules are compressed versions of the Engineer's, and this assumption goes with the fact that Engineers often overestimate project durations than the actual needed to complete the project. It also extends the typical objective of the original bi-parameter bidding system in which bidders compete on having shorter project durations to have a lower Total Combined Bid than the competition. Another assumption is that bidders' schedules are compressed to a different extent from one to another in order to illustrate the concept and the impact of varying schedule flexibility associated with the available total float in each.

In general, crashing activities and compressing schedules to a certain magnitude often results in lower total project cost due to the savings in indirect costs. However, this is only true until the project reaches the optimum duration point in which the total cost is the lowest; any further attempt to crash the project would result in increasing total cost. Therefore, the principle of time-cost tradeoff is taken into consideration with the hypothetical cost values in the example in order to resemble a bidding scenario similar to the reality. As a result, between the different bidders, the total cost starts to decrease when the project is initially crashed from the Engineer's normal project duration up to a certain point where the total cost starts to increase again. Finally, as explained in the previous sections, the standard deviations for all activities in bidders' schedules shall be considered exactly the same as in the Engineer's estimate. This step is more logical since the Engineer can have a historical reference to what reasonable standard deviation an activity can have from previous completed projects. Moreover, such a measure helps avoiding bidders from reducing their apparent schedule risk by selecting low false standard deviations for their activities, which results in a project with low variance and good probability of finishing on time that is not necessarily correct. Hence, for the sake of this hypothetical example, the Engineer's estimate is set to have a standard deviation for each activity equal to 15% of its original normal duration. The Unit Time Value for this example shall be 14,000 USD/Day and the rest of the project data are listed in Table 3.2.

**Table 3.2: Example Project Data**

| Activity | Predecessor | Mean Duration (days) | | | | |
|---|---|---|---|---|---|---|
| | | Engineer | Bidder 1 | Bidder 2 | Bidder 3 | Bidder 4 |
| **A** | - | 12 | 12 | 12 | 10 | 9 |
| **B** | A | 20 | 20 | 20 | 20 | 20 |
| **C** | A | 25 | 25 | 25 | 25 | 25 |
| **D** | A | 34 | 32 | 30 | 29 | 29 |
| **E** | B | 32 | 32 | 32 | 32 | 31 |
| **F** | B, C, D | 29 | 28 | 27 | 26 | 25 |
| **G** | D | 27 | 27 | 27 | 27 | 27 |
| **H** | E | 28 | 28 | 28 | 28 | 28 |
| **I** | F | 30 | 29 | 27 | 27 | 25 |
| **J** | F, G | 21 | 21 | 21 | 21 | 21 |
| **K** | H, I, J | 15 | 14 | 14 | 13 | 12 |
| **Total Cost (USD)** | | 2,400,000 | 2,275,000 | 2,175,000 | 2,225,000 | 2,290,000 |

### 3.3.1 Example Stage 1 - Analysis of Engineer's Baseline Schedule

As illustrated in the precedence diagram in Figure 3.2, the deterministic analysis for the Engineer's schedule using CPM shows that the critical path is A→D→F→I→K, and the total deterministic project duration ($D_{det,eng}$) is 120 days. Furthermore, the total float available for all non-critical activities in the network is listed in Table 3.3.

Secondly, to perform the stochastic analysis on the same schedule, the activities duration are assumed to be normally distributed; though, any other suitable probability distribution function can be used if enough historical data is available. Using @Risk for Excel to perform MCS, the number of simulations is set at 10 with 10,000 iterations each. The difference between the two is that the iteration is a smaller calculation unit within a simulation. Each iteration represents a new set of random numbers taken from the assigned PDF of the variables in order to calculate a new result for the required output. Hence, it is important to have enough iteration runs in order to have a converging and accurate consolidated single value of the required output at the end of all simulation runs. In Figure 3.3, the simulation results for the Engineer's schedule shows that the mean project duration ($M_{eng}$) is 121.019 days with a standard deviation ($Std_{eng}$) of 7.671 days, while the probability of finishing ($POF_{eng}$) on time at the original deterministic project duration is only 46.4%.

Using Equation 3,

$$POF_{eng} = P(x \leq D_{det,eng})$$

$$POF_{eng} = P(x \leq 120) = 46.4\%$$

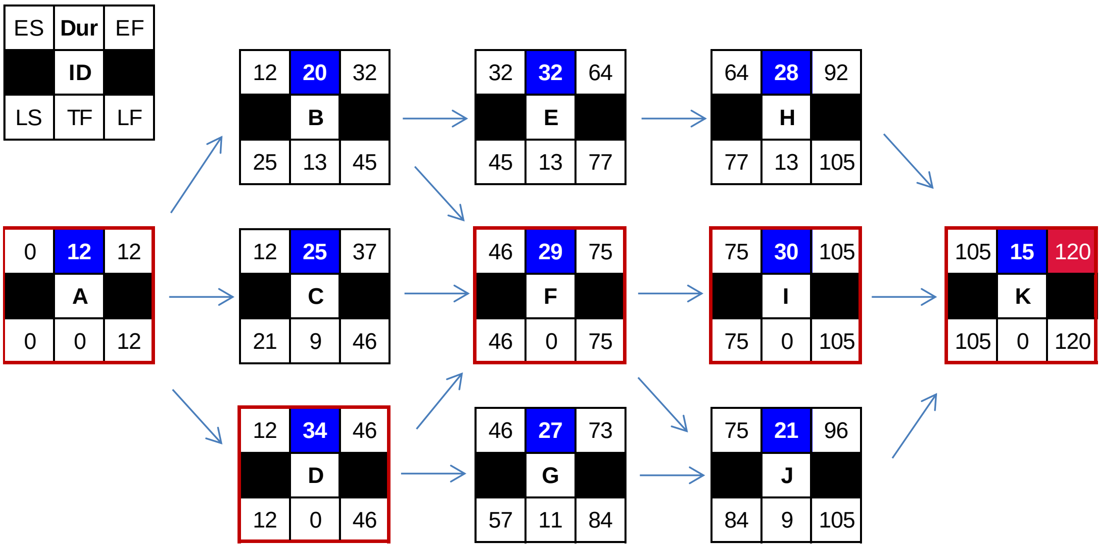


**Figure 3.2: Precedence Diagram for Engineer**

**Table 3.3: Activities Total Float in Engineer's Schedule**

| Activity | Total Float (Days) |
|---|---|
| A | 0 |
| B | 13 |
| C | 9 |
| D | 0 |
| E | 13 |
| F | 0 |
| G | 11 |
| H | 13 |
| I | 0 |
| J | 9 |
| K | 0 |

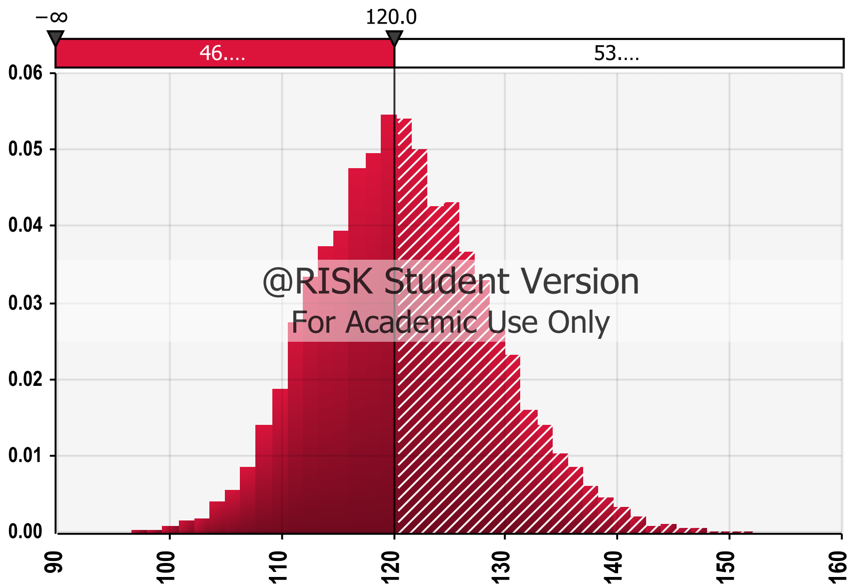


**Figure 3.3: Simulation Result for Engineer**

### 3.3.2 Example Stage 2 - Analysis of Bidders' Schedules

A similar deterministic analysis is performed for all bidders' schedules using CPM and their corresponding precedence diagrams are illustrated in Figure 3.4, 3.5, 3.6 and 3.7. For Bidder 1, the critical path is A→D→F→I→K which is similar to the Engineer's; yet, the project deterministic duration ($D_{det,1}$) is 115 days. For Bidder 2 and 3, the critical path remains the same; however, the resulting project deterministic duration for Bidder 2 is 110 days, and for Bidder 3 is even shorter at 105 days. Another expected observation is that the available float for non-critical activities further reduced from one bidder to another as a result of compressing the schedule to have a shorter total duration.. This observation is further validated by looking at the schedule of Bidder 3, for instance, which has three near-critical activities (B, E, and H) with relatively low available float. Finally, the fourth Bidder 4 has the shortest deterministic project duration ($D_{det,4}$) which is 100 days only. However, due to the extremely compressed schedule in comparison to the baseline, two additional critical paths are introduced besides the original one for a total of three paths: (1) A→D→F→I→K; (2) A→B→F→I→K; (3) A→B→E→H→K.

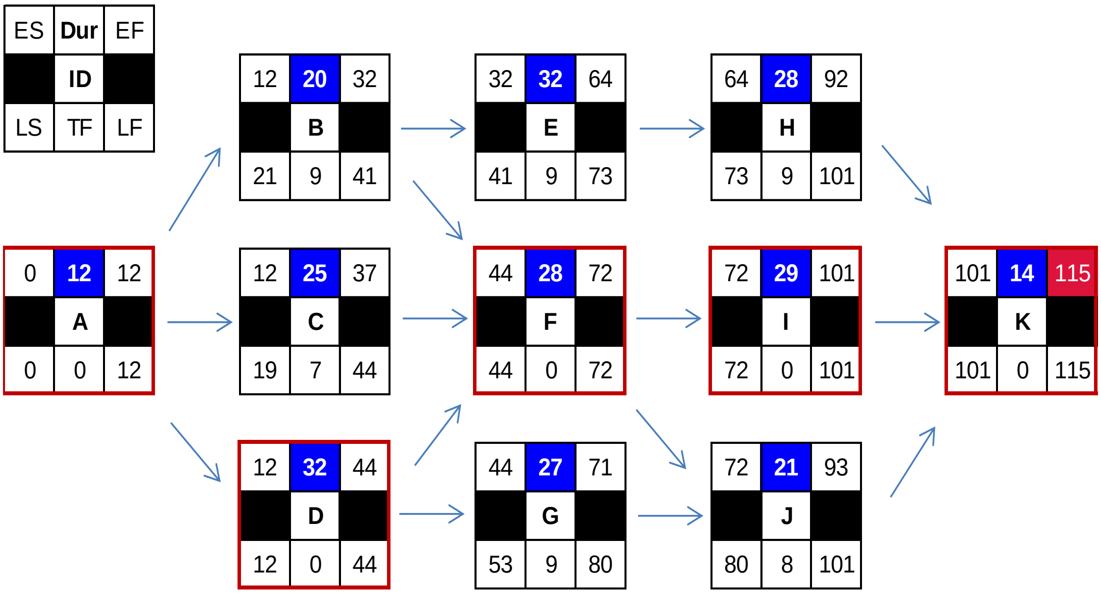


**Figure 3.4: Precedence Diagram for Bidder 1**

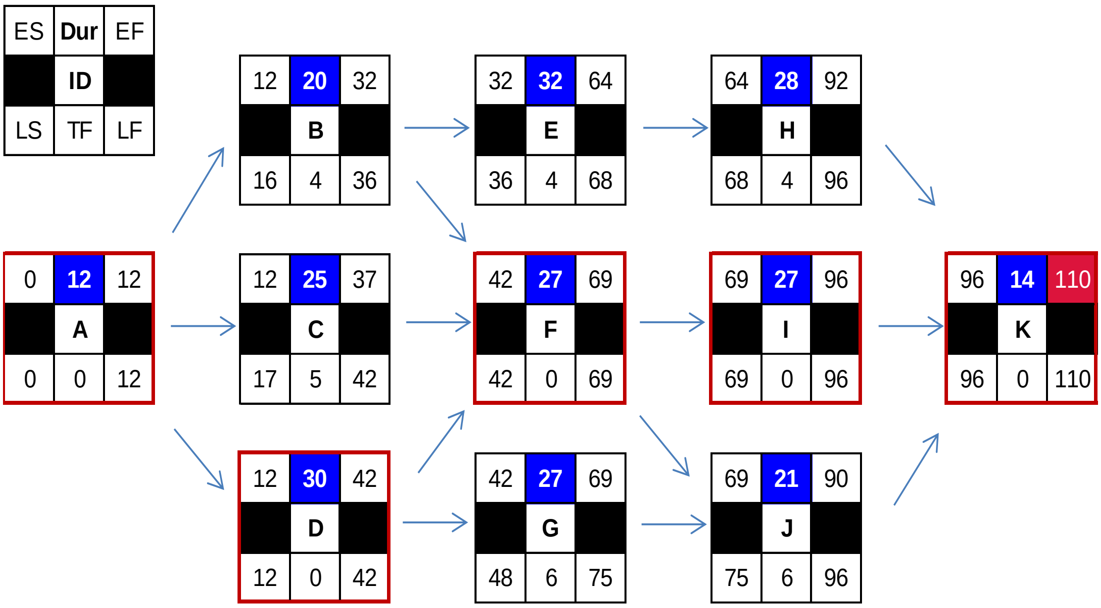


**Figure 3.5: Precedence Diagram for Bidder 2**

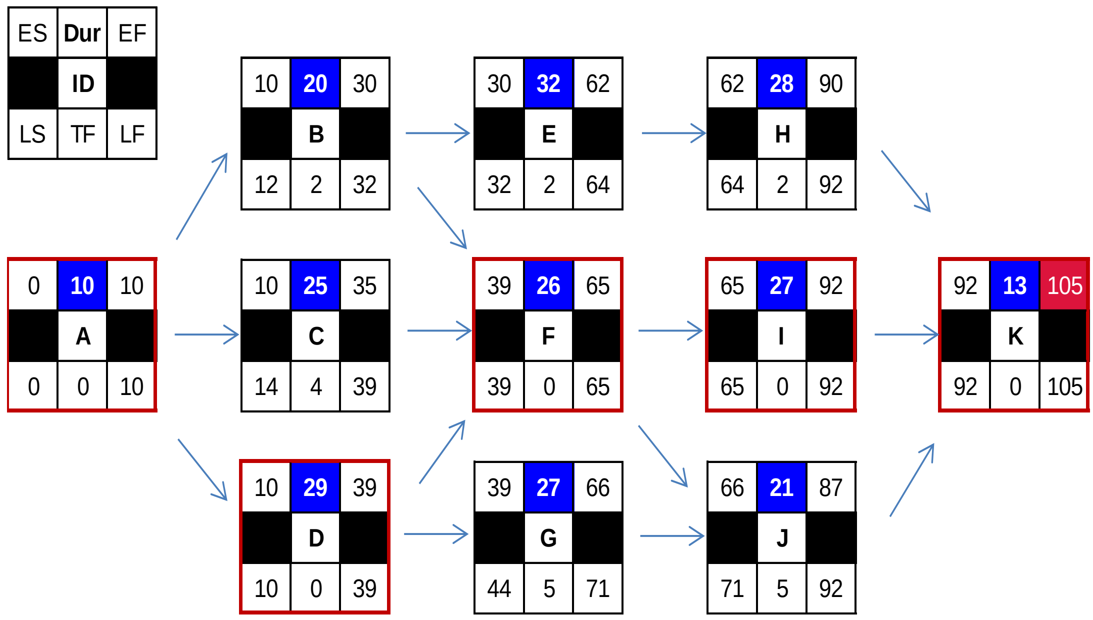


**Figure 3.6: Precedence Diagram for Bidder 3**

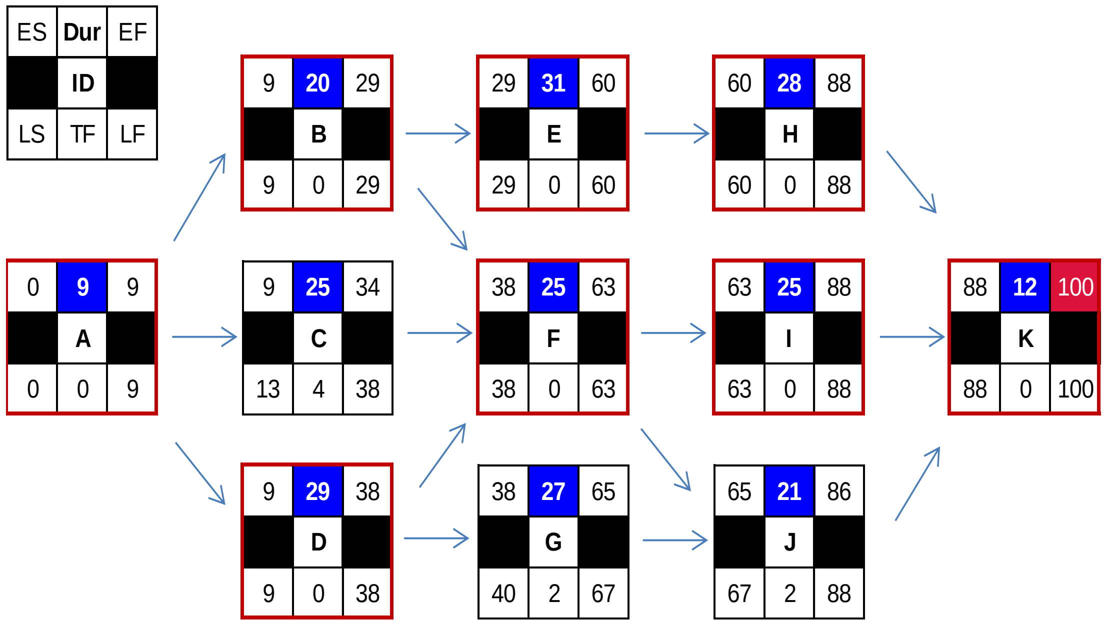


**Figure 3.7: Precedence Diagram for Bidder 4**

The following step is to perform the stochastic analysis as in Stage 1 on all bidders' schedules. Probability Distribution Functions (PDF) for the activities durations are defined to be normally distributed, and the standard deviations are the same ones used in Stage 1. Likewise, MCS is performed through @Risk for Excel with similar settings of 10 simulations and 10,000 iterations each. Figures 3.8, 3.9, 3.10 and 3.11 represent the graphs for the simulations performed for each bidder's schedule. The main results that are of interest are the probabilistic project mean duration ($M_i$), project standard deviation ($Std_i$) and the probability of finishing ($POF_i$) the project on the original bidder's deterministic duration, which was determined in the previous step. For Bidder 1, the mean project duration ($M_1$) is 116.849 days, standard deviation ($Std_1$) is 7.292 days, and $POF_1$ of 41.2%. For Bidder 2, the mean project duration ($M_2$) is 113.563 days, standard deviation ($Std_2$) is 6.706 days, and $POF_2$ of 30.4%. For Bidder 3, the mean project duration ($M_3$) is 109.413 days, standard deviation ($Std_3$) is 6.601 days, and $POF_3$ of 26.0%. Finally, for Bidder 4, the mean project duration ($M_4$) is 105.671 days, standard deviation ($Std_4$) is 6.431 days, and $POF_4$ of 18.8%.

As an example for Bidder 1, and using Equation 4,

$$POF_1 = \mathrm{P}(x \leq D_{det,1})$$

$$POF_1 = \mathrm{P}(x \leq 115) = 41.2\%$$

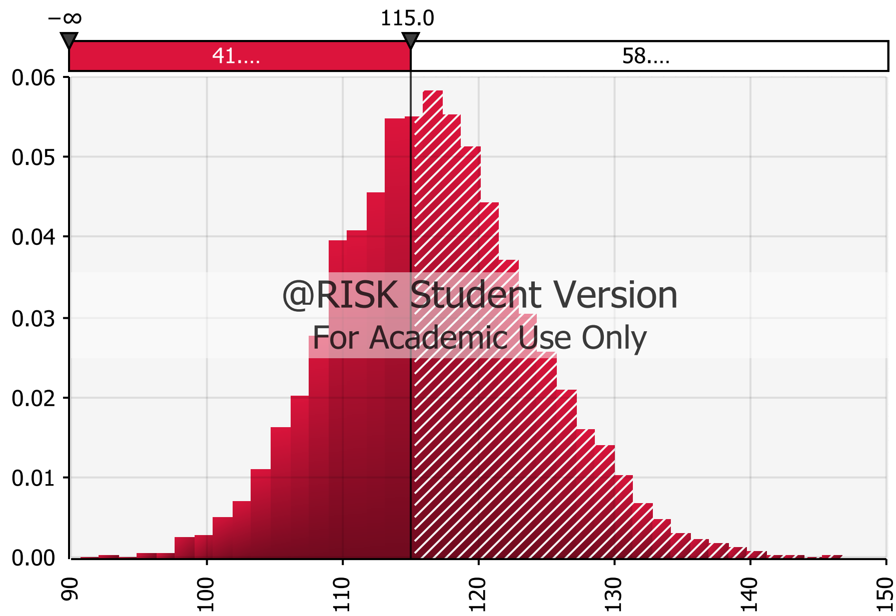


**Figure 3.8: Simulation Result for Bidder 1**

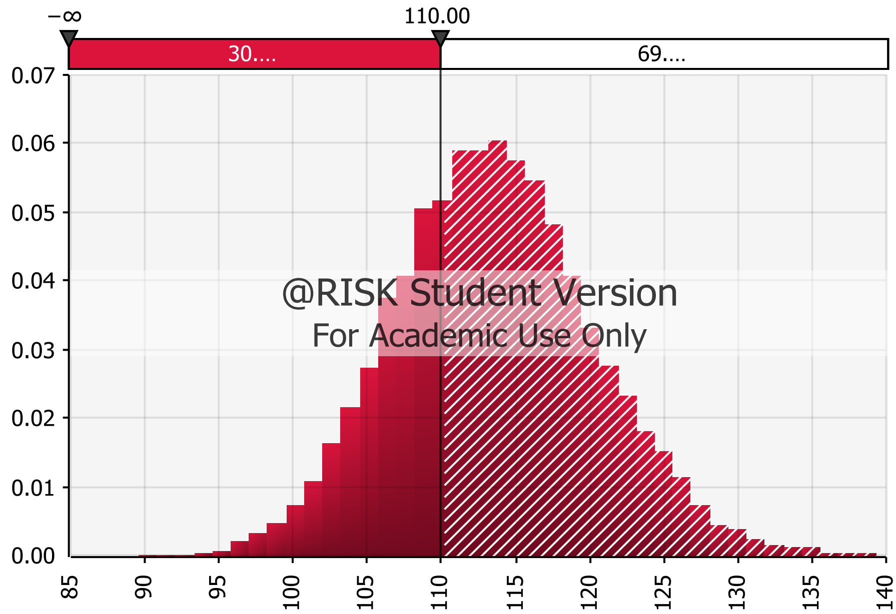


**Figure 3.9: Simulation Result for Bidder 2**

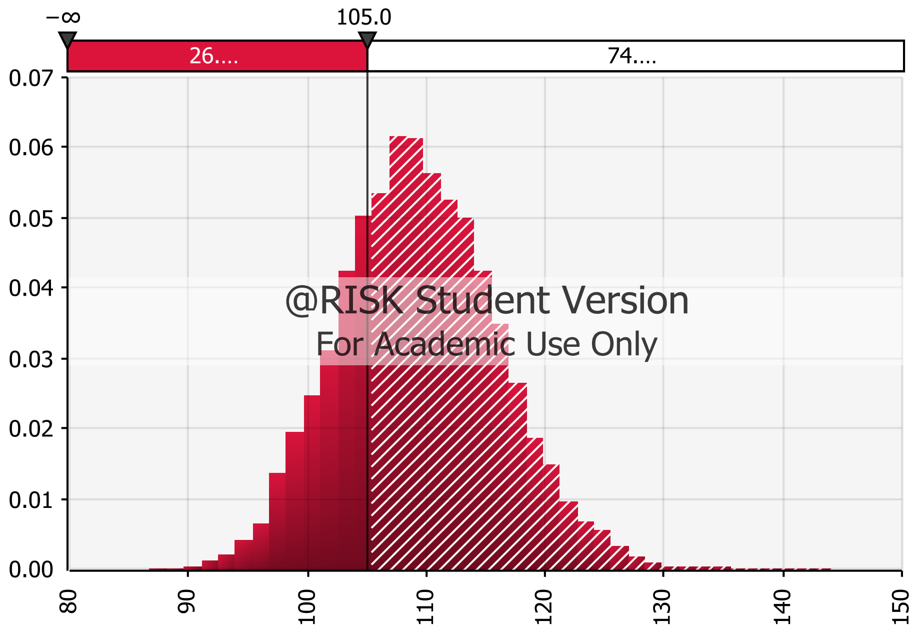


**Figure 3.10: Simulation Result for Bidder 3**

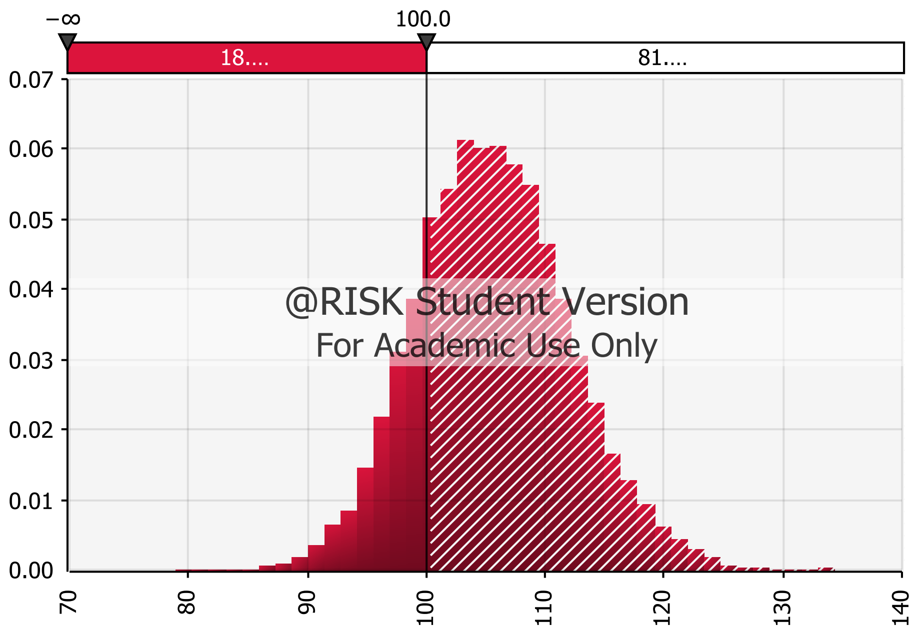


**Figure 3.11: Simulation Result for Bidder 4**

The results of the deterministic, as well as the stochastic analysis, of both the Engineer's and bidders' schedules are summarized in Table 3.4.

**Table 3.4: Deterministic and Stochastic Project Durations for Bidders**

| Bidder ID | CPM Deterministic Duration (Days) | Mean Project Duration (Days) | Standard Deviation (Days) | Probability of Finishing on Deterministic Duration |
|---|---|---|---|---|
| **Engineer** | 120 | 121.019 | 7.671 | 46.4% |
| **Bidder 1** | 115 | 116.849 | 7.292 | 41.2% |
| **Bidder 2** | 110 | 113.563 | 6.706 | 30.4% |
| **Bidder 3** | 105 | 109.413 | 6.601 | 26.0% |
| **Bidder 4** | 100 | 105.671 | 6.431 | 18.8% |

### 3.3.3 Example Stage 3 - Quantification of Schedule Risk

In Stage 3, the approach is to use the outcomes of the first two stages in order to quantify the schedule risk found in all bidders' schedules. As explained in earlier sections, the major risk part in compressing a schedule results from the float loss and increasing tendency of near-critical activities to become on the critical path. The proposed methodology for the quantification of the schedule risk is to determine the bidders' new project durations ($D_{prob,i}$) which correspond to the Engineer's probability of finishing ($POF_{eng}$) determined in Stage 1. Consequently, the added risk due to the float loss would be part of the final evaluation done by clients and owners, who desire a certain safe POF committed by all bidders. For this particular example, it was determined earlier in Stage 1 that the Engineer's probability of finishing ($POF_{eng}$) is 46.4%. As seen in Figures 3.12, 3.13, 3.14 and 3.15, if the POF value is fixed for the bidders' schedule analysis, the corresponding new probabilistic project durations ($D_{prob,i}$) are 116.00, 112.77, 108.60, and 104.90 days for Bidder 1, 2, 3, and 4 respectively.

As an example for Bidder 1, using Equation 5,

Let $X$ be $D_{prob,1}$

Determine $X$ such that: $P(x \leq X) = POF_{eng} = 46.4\%$

$X = D_{prob,1} = 116$ days

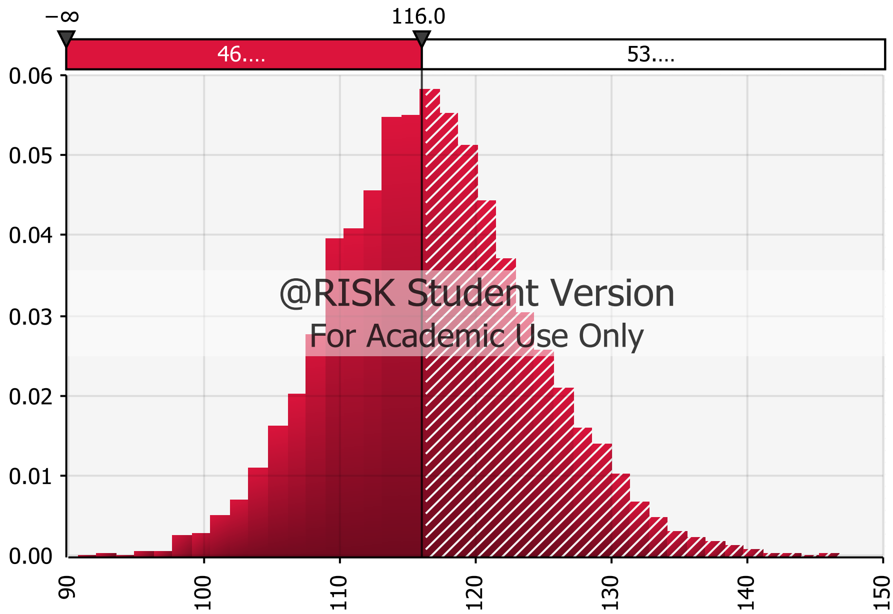


**Figure 3.12: Bidder 1 Probabilistic Duration at $POF_{eng}$**

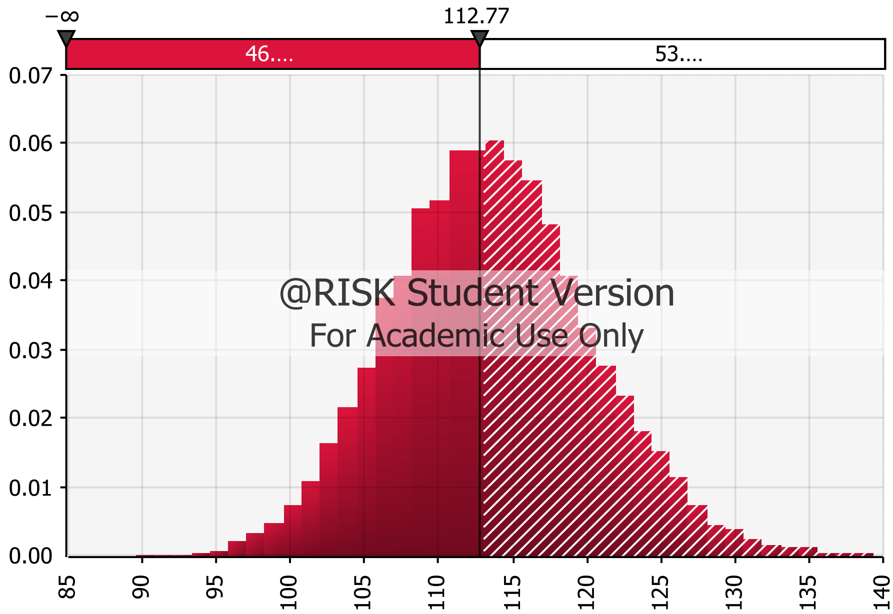


**Figure 3.13: Bidder 2 Probabilistic Duration at $POF_{eng}$**

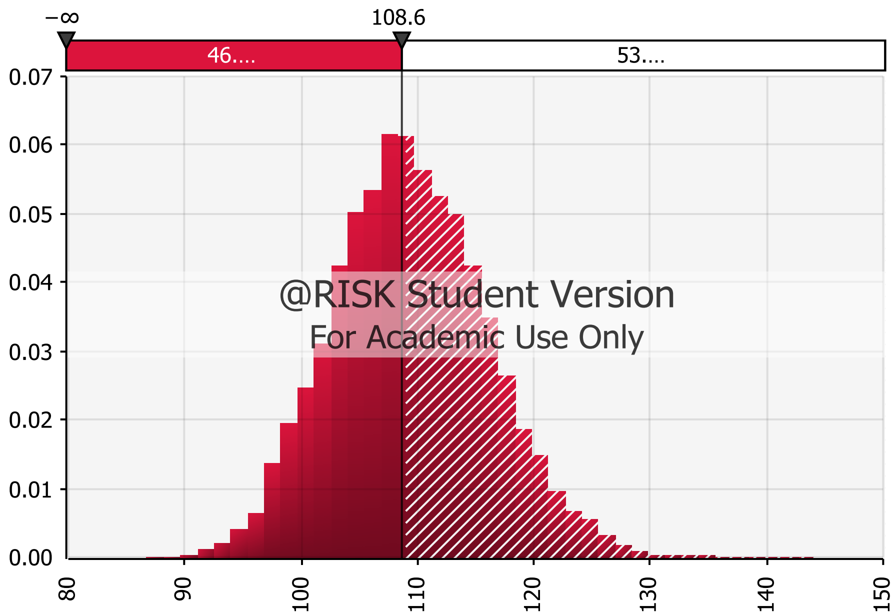


**Figure 3.14: Bidder 3 Probabilistic Duration at $POF_{eng}$**

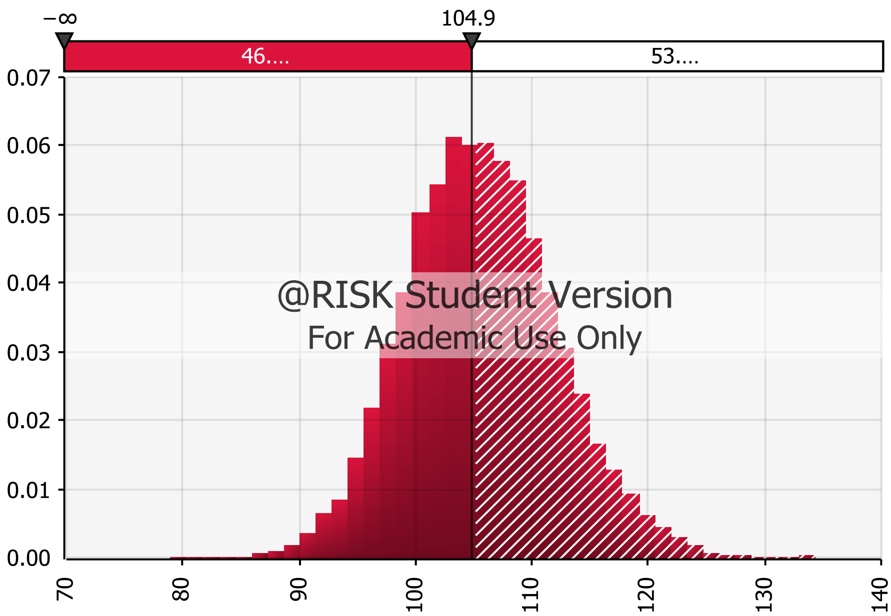


**Figure 3.15: Bidder 4 Probabilistic Duration at $POF_{eng}$**

The next step is to determine the Schedule Risk ($SR_i$) which calculates the difference between the bidder's probabilistic duration ($D_{prob,i}$) found in the previous step and the original bidder's deterministic duration ($D_{det,i}$).

As an example for Bidder 1, using Equation 6,

$$SR_1 = D_{prob,1} - D_{det,1}$$

$$SR_1 = 116.0 - 115.0 = 1 \text{ day}$$

This calculation can be interpreted as the need of one additional day to extend the proposed project duration by Bidder 1 in order to maintain the desirable probability of finishing defined by the client or the owner. Similar calculations are performed for the rest of the bidders to calculate their relevant SR, and the results are 2.77, 3.60 and 4.9 days for Bidder 2, 3, and 4 respectively.

The final step in Stage 3 is to quantify the schedule risk in a monetary value represented by the Risk parameter (R) in order to be incorporated in the final Total Combined Bid (TCB) for each bidder. As explained earlier, the Risk parameter can be calculated with the product of previously determined Schedule Risk (SR) for each bidder and Unit Time Value (UTV) defined by the client initially.

As an example for Bidder 1, using Equation 7,

$$R_1 \text{ (USD)} = SR_1 \text{ (days) x } UTV \text{ (USD/day)}$$

$$R_1 = 1 \text{ (day) x 14,000 (USD/day) = 14,000 USD}$$

Similarly, the relevant Risk parameter for the remaining bidders shall be 38,780 USD, 50,400 USD, and 68,600 USD for Bidder 2, 3, and 4 respectively.

### 3.3.4 Example Stage 4 - Tri-parameter Contracting Model

In Stage 4, the final evaluation to determine the winning bid is performed by calculating the corresponding Total Combined Bid (TCB) for each bidder in accordance to the proposed tri-parameter contracting method (A+B+R), and eventually the lowest TCB shall be the winning bid. The only remaining parameter to be determined, which is the Time parameter (B), is calculated using Equation 8.

As an example for Bidder 1, using Equation 8,

$$B_1 \text{ (USD)} = D_{det,1} \text{ (days) x } UTV \text{ (USD/day)}$$

$$B_1 = 115 \text{ (days) x 14,000 (USD/day) = 1,610,000 USD}$$

Additionally, if the same calculation is performed for the rest of the Bidders, the Time parameter ($B_i$) are 1.54, 1.47, and 1.40 million USD for Bidder 2, (3), and (4) respectively. At this point, all three parameters of the tri-parameter contracting method (A+B+R) are determined, and the last step is to calculate each bidder's TCB to determine the lowest.

As an example for Bidder 1,
$A_1$ = 2,275,000 USD, $B_1$ = 1,610,000 USD, $R_1$ = 14,000 USD, and using Equation 9,

$$TCB_1 = A_1 + B_1 + R_1$$

$$TCB_1 = 2{,}275{,}000 + 1{,}610{,}000 + 14{,}000 = 3{,}899{,}000 \text{ USD}$$

Finally, the summary for the remaining calculations and results for all the bidders are listed in Table 3.5, which concludes that Bidder 3 is the winning bidder by having the lowest TCB of the tri-parameter contracting method equal to 3,745,400 USD.

**Table 3.5: Breakdown of A+B+R Parameters for Bidders**

| Bidder ID | A (USD) | $D_{det,i}$ (Days) | $D_{prob,i}$ (Days) | B (USD) | SR (Days) | R (USD) | A +B +R (USD) |
|---|---|---|---|---|---|---|---|
| **Engineer** | 2,400,000 | 120 | 120.00 | 1,680,000 | 0 | - | 4,080,000 |
| **Bidder 1** | 2,275,000 | 115 | 116.00 | 1,610,000 | 1 | 14,000 | 3,899,000 |
| **Bidder 2** | 2,175,000 | 110 | 112.77 | 1,540,000 | 2.77 | 38,780 | 3,753,780 |
| **Bidder 3** | 2,225,000 | 105 | 108.60 | 1,470,000 | 3.6 | 50,400 | 3,745,400 |
| **Bidder 4** | 2,290,000 | 100 | 104.90 | 1,400,000 | 4.9 | 68,600 | 3,758,600 |

## 3.4 Discussion of Results

A deep and thorough analysis of the results of the previous example is essential in order to understand the importance and impact of the proposed tri-parameter contracting method (A+B+R). To begin with, as illustrated in both Table 3.6 and Figure 3.16, the tri-parameter contracting method has indeed changed the final ranking of submitted bids differently than the ranking based on the conventional low bidding system or even the bi-parameter bidding system (A+B). For instance, if the project is to be awarded solely based on the bid price which is the basis of the competitive bidding system, then Bidder 2 shall be the winner by having the lowest cost of 2.175 million USD. However, if the bi-parameter bidding system (A+B) is considered, then the winning bidder shall be Bidder 4 instead by having the best combination of price and project duration among all bidders with a total combined value of 3.69 million USD. Nevertheless, as explained in earlier chapters, the bi-parameter bidding system neglects the negative impact of the conventional time-cost tradeoff and the resulting float loss that could add an unnecessary schedule risk to the project. Therefore, the significance of the proposed tri-parameter contracting method (A+B+R) is the consideration of such a Risk parameter as part of the bids evaluation process. Such a system would help the owners and clients to determine the winning bid representing the best combination of price, project duration, and an acceptable level of schedule risk. This principle is validated by Bidder 3 in the discussed example, which has the lowest total combined value under the tri-parameter contracting method of 3.745 million USD.

**Table 3.6: List of Final Ranking of Bidders**

| Bidder ID | A (USD) | Rank | A+B (USD) | Rank | A +B +R (USD) | Final Rank |
|---|---|---|---|---|---|---|
| **Bidder 1** | 2,275,000 | 3 | 3,885,000 | 4 | 3,899,000 | 4 |
| **Bidder 2** | 2,175,000 | 1 | 3,715,000 | 3 | 3,753,780 | 2 |
| **Bidder 3** | 2,225,000 | 2 | 3,695,000 | 2 | 3,745,400 | 1 |
| **Bidder 4** | 2,290,000 | 4 | 3,690,000 | 1 | 3,758,600 | 3 |

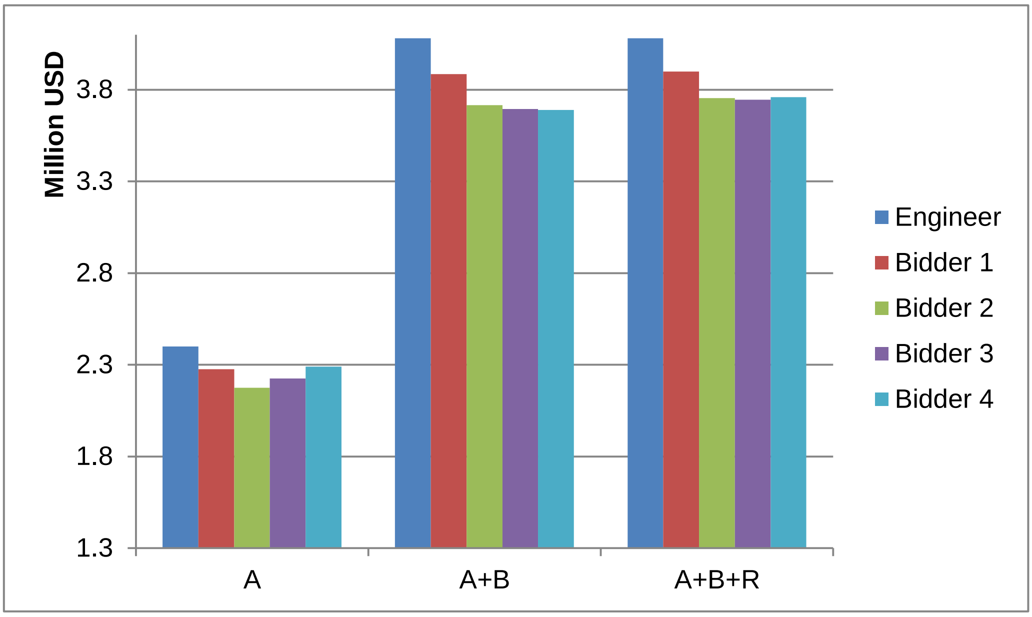


**Figure 3.16: Evaluation of Bidders on Different Bidding Systems**

In order to further understand the approach and the methodology of the proposed tri-parameter contracting method, it is essential to consider the time-cost tradeoff and the resulting float loss. To begin with, Table 3.7 and Figure 3.17 illustrate the reduction in the available total float in the original non-critical activities (B, C, E, G, H, and J) from one bidder to another as the schedule gets further compressed and a shorter project duration is reached. In addition, the schedule risk for each bidder's schedule is plotted to show the relationship between the available float and corresponding risk. As anticipated, the consumption of the available float increases the schedule risk in the compressed schedules as the activities become near-critical or even critical in extreme situations such as the case with Bidder 4. This situation and the impact of float loss can be also further validated by looking at Figure 3.18 which explains the decline of probability of finishing the project on the original deterministic project duration as the schedule gets further compressed from one bidder to another. Furthermore, the relationship between float loss and reduced probability of finishing is evident by examining the similar dropping trend line for both variables against the crashed project durations. Eventually, these remarks help understanding the full picture of the time-cost-risk tradeoff, and the importance of considering the schedule Risk parameter as a part of the bidding system prior to the project award.

**Table 3.7: Activities Total Float in Bidders' Schedules**

| Activity | Engineer | Bidder 1 | Bidder 2 | Bidder 3 | Bidder 4 |
|---|---|---|---|---|---|
| A | 0 | 0 | 0 | 0 | 0 |
| B | 13 | 9 | 4 | 2 | 0 |
| C | 9 | 7 | 5 | 4 | 4 |
| D | 0 | 0 | 0 | 0 | 0 |
| E | 13 | 9 | 4 | 2 | 0 |
| F | 0 | 0 | 0 | 0 | 0 |
| G | 11 | 9 | 6 | 5 | 2 |
| H | 13 | 9 | 4 | 2 | 0 |
| I | 0 | 0 | 0 | 0 | 0 |
| J | 9 | 8 | 6 | 5 | 2 |
| K | 0 | 0 | 0 | 0 | 0 |

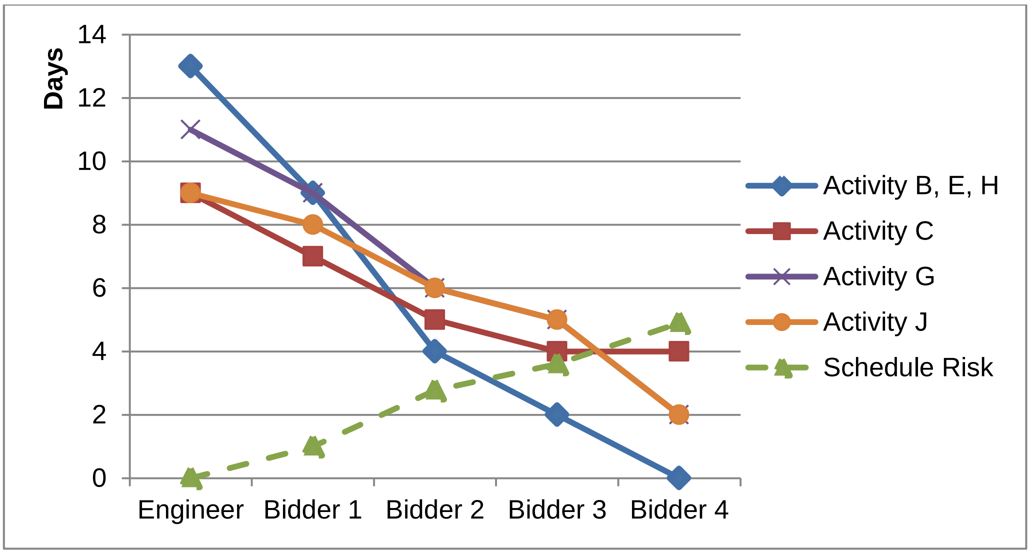


**Figure 3.17: Non-Critical Activities Total Float and Schedule Risk**

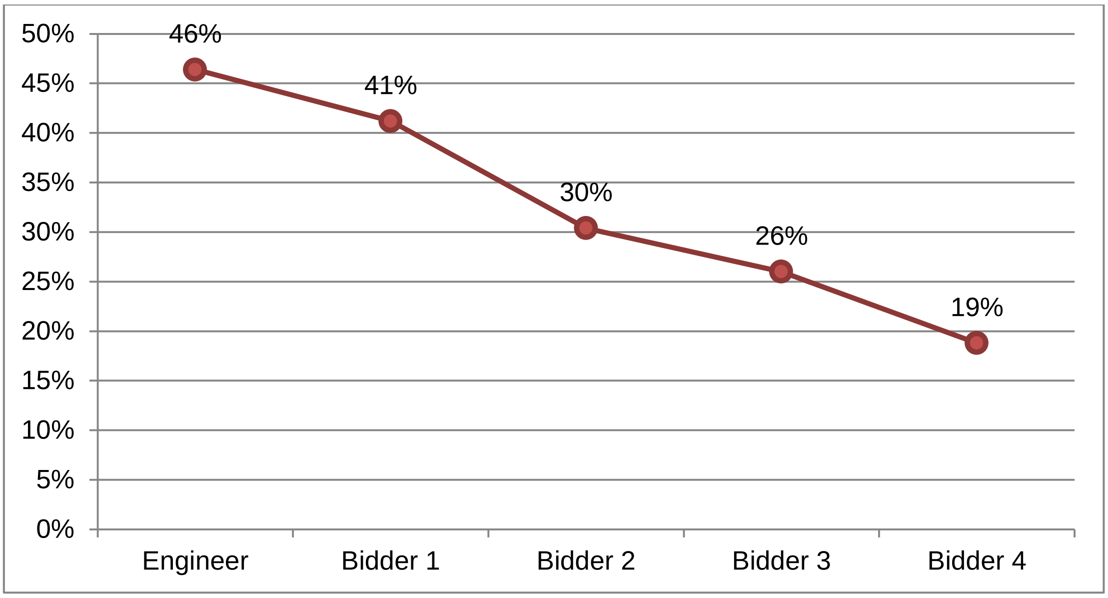


**Figure 3.18: Project Probability of Finishing**

The new proposed tri-parameter contracting method (A+B+R) highlights a new concept to the long established time-cost tradeoff by adding another dimension to it. This is due to the consideration given to the effect of float loss and the associated impact it can have on adding risk of potential delays due to the reduced flexibility within the schedule. Therefore, it is important to explore the quantification of the Risk parameter and its relative weight in the bidding system in order to understand its impact. Often, and depending on the project and circumstances, contingencies could be anywhere from 2% to 5% of the total cost including direct and indirect. In most cases, these contingencies shall cover all various types of risks including controlled and uncontrolled risks. For that purpose, Table 3.8 summarizes the percentages of the relevant weight between the bidders' original costs and their measured Risk parameter in a dollar value. As seen from the numbers of the discussed example, the schedule risk value could reflect up to 3% of the bidder's cost, which is a reasonable margin considering the usual contingency bidders consider as part of their cost. Ultimately, as illustrated in Figure 3.19, the consideration of the added schedule risk and the cost changes the curve of the original time-cost tradeoff with the purpose of reflecting the increasing Risk parameter as the project becomes more risky with a compressed duration.

**Table 3.8: Cost and Risk parameters for all Bidders**

| Bidder ID | A (USD) | R (USD) | R/A |
|---|---|---|---|
| **Bidder 1** | 2,275,000 | 14,000 | 0.62% |
| **Bidder 2** | 2,175,000 | 38,780 | 1.78% |
| **Bidder 3** | 2,225,000 | 50,400 | 2.27% |
| **Bidder 4** | 2,290,000 | 68,600 | 3.00% |

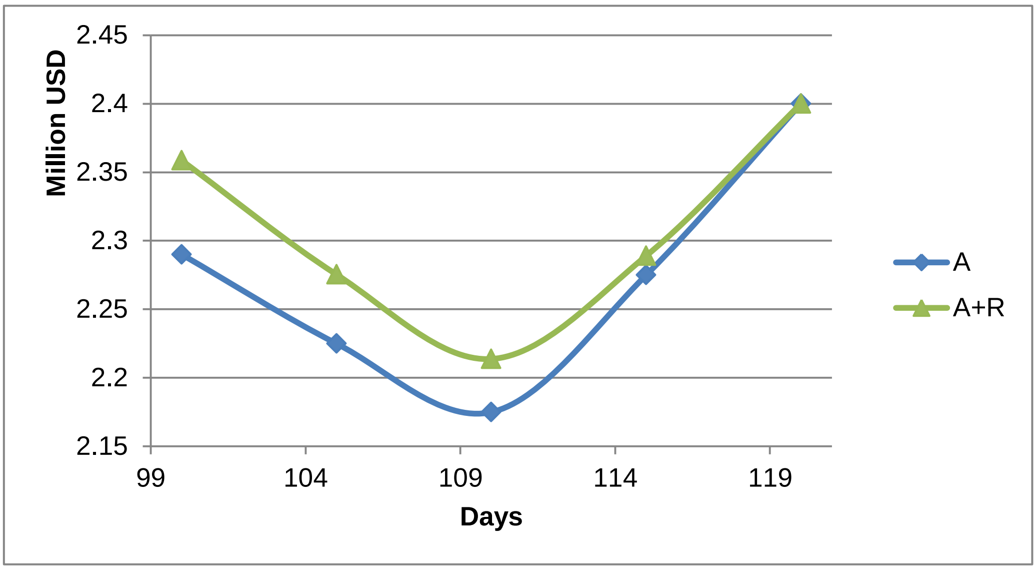


**Figure 3.19: A vs. A+R Curves**

The proposed tri-parameter contracting method (A+B+R) allows for a new concept of a tradeoff between cost-time-risk concurrently. Depending on the nature of the project and its urgency, clients and owners can define the level of acceptable risk at which a bid with a competitive price and duration can be determined and have the final award. This new concept of the three-way tradeoff modifies the original curve of the time-cost tradeoff by shifting it upwards to reflect the added schedule Risk parameter. As seen in Figure 3.20, the magnitude of the shift increases as the project duration decreases and becomes more critical. This is mainly due to the consumption of available float and reduced flexibility. The most important outcome of shifting the curve is the fact that a new optimum project duration point is present in which the lowest combination of real cost, time cost, and risk cost is achieved; hence, the actual effect of the proposed tri-parameter contracting method is validated.

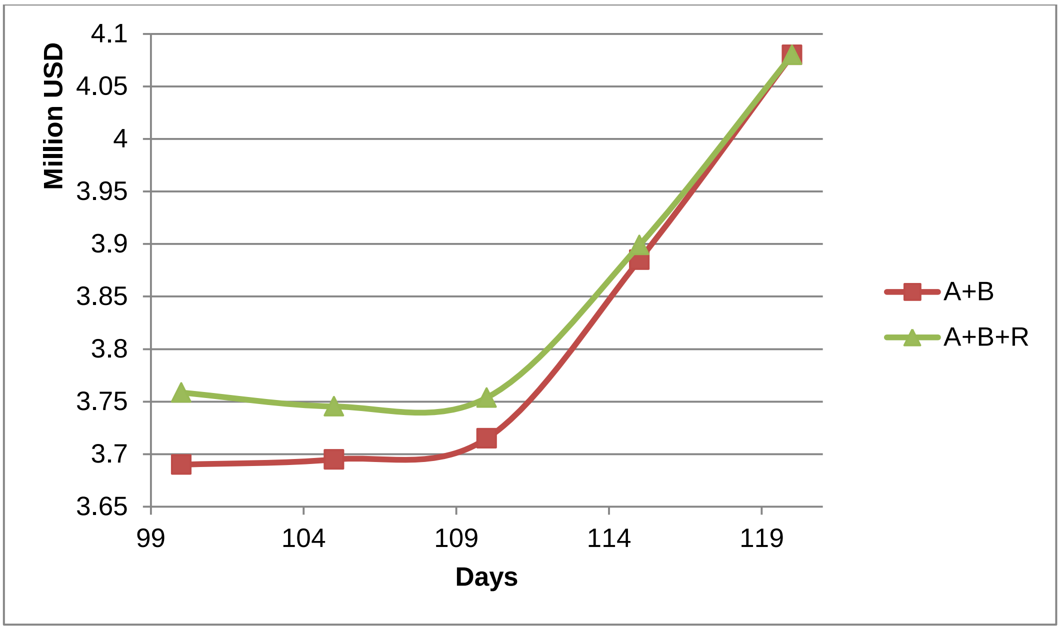


**Figure 3.20: A+B vs. A+B+R Curves**

# Chapter Four: Deterministic Model of A+B+R System

## 4.1 Introduction

Similar to the previously discussed stochastic model of the tri-parameter contracting method (A+B+R), the main objective of the deterministic model is to quantify the schedule risk caused by compressing schedules and consuming the available total float. The proposed deterministic model is based on the scheme of De La Garza et al. [34] in which they suggest that the available total float resulting from CPM analysis should have a commercial value for consumption. In view of that, a cost impact model is formulated for consuming float in the case of starting non-critical activities later than the planned early start dates. Likewise, the second deterministic model considers the same principle of determining a certain monetary value or cost for consuming float, and then the additional cost shall be summed up as the Risk parameter (R) of bidders' submitted schedules. A thorough detailed model of the proposed deterministic tri-parameter contracting method (A+B+R) with all the associated stages and steps shall be discussed in the remainder of this chapter, in addition to an application example.

## 4.2 Deterministic Tri-parameter (A+B+R) Model

While the first discussed model of the tri-parameter contracting method (A+B+R) considers a stochastic approach, the second model considers a deterministic one instead to determine the project duration using the Critical Path Method (CPM). As a result, the deterministic project duration is determined along the path of the critical activities in the network. However, considering the 'byproduct' of this analysis which is the non-critical activities and their total float, De Le Garza et al. [37] stated that in many cases, additional critical activities and paths are created when total float is consumed for any reason. As a result, projects in these cases will have a higher likelihood of finishing late behind the original schedule. This validates the importance of the risk quantification process to consider the likelihood of finishing late due to the consumption of float. Eventually, the risk quantification process determines the Risk parameter (R) in all bidders' submitted schedules as a parameter in the bids evaluation performed by clients and owners.

The methodology to determine the Risk parameter (R) associated with float loss is by assigning a monetary value for the available total float for each activity. Based on the cost impact model of De La Garza et al. [34], the proposed methodology requires estimation for both the Early Finish Cost (EFC) and the Late Finish Cost (LFC) in a similar manner to the exercises in the case of estimating the crashing cost for activities. While EFC represents the ideal and most efficient situation with the necessary flexibility, LFC is an estimate when the flexibility is nonexistent under critical circumstances. The idea is that the estimator determines both EFC and LFC irrespective of the final schedule completed by the planner. Only after the estimator and planner are done with their tasks, all the activities on the critical path will be considered at their LFC cost considering the fact that they do not have any available float or flexibility. Ultimately, the difference between these two costs shall be the measure of the added schedule risk which will quantify the Risk parameter (R) as explained in later sections of this chapter. In the same manner, the suggested analysis approach for the deterministic A+B+R system consists of four main stages as follows: (1) Analysis of Engineer's Baseline Schedule; (2) Analysis of Bidders' Schedules; (3) Quantification of Risk parameter; (4) Tri-parameter Contracting Model. Table 4.1 demonstrates all the symbols and notations, which are used throughout the deterministic model, and their corresponding representations.

**Table 4.1: List of Symbols and Description for Deterministic A+B+R Model**

| Symbol | Description |
|---|---|
| $A_i$ | Cost parameter for Bidder i; i = 1, 2, .. n |
| $B_i$ | Time parameter for Bidder i; i = 1, 2, .. n |
| CPM | Critical Path Method |
| $D_{eng}$ | Deterministic Duration for Engineer |
| $D_i$ | Deterministic Duration for Bidder i; i = 1, 2, .. n |
| $EFC_j$ | Early Finish Cost for Activity j; j = A, B, .. m |
| $FC_{eng,j}$ | Engineer Float Cost for Activity j; j = A, B, .. m |
| $FC_{i,j}$ | Float Cost for Activity j in Bidder i schedule; i = 1, 2, .. n, j = A, B, .. m |
| $FLC_{eng}$ | Float Loss Cost for Engineer |
| $FLC_i$ | Float Loss Cost for Bidder i; i = 1, 2, .. n |

**Table 4.2: List of Symbols and Description for Deterministic A+B+R Model (continued)**

| | |
|---|---|
| **$LFC_j$** | Late Finish Cost for Activity j; j = A, B, .. m |
| **$R_i$** | Risk parameter for Bidder i; i = 1, 2, .. n |
| **$TF_{eng,j}$** | Activity j Total Float in Engineer schedule; j = A, B, .. m |
| **$TF_{i,j}$** | Activity j Total Float in Bidder i schedule; i = 1, 2, .. n, j = A, B, .. m |
| **$TCB_i$** | Total Combined Bid for Bidder i; i = 1, 2, .. n |
| **UTV** | Unit Time Value |
| **N** | Number of Bidders |
| **m** | Number of Activities |

### 4.2.1 Stage 1 - Analysis of Engineer's Baseline Schedule

The Engineer's schedule shall be considered as the baseline normal schedule, as well as the reference to compare the different schedules submitted by all the bidders. First, the conventional deterministic schedule analysis is performed using Critical Path Method (CPM) to determine the project duration ($D_{eng}$) besides the list of critical and non-critical activities with their available total float ($TF_{eng,j}$). The second step is to determine the Float Cost ($FC_{eng,j}$) for each activity in the Engineer's Schedule which is the difference between the estimated Early Finish Cost (EFC) and the Late Finish Cost (FLC) as shown in Equation 10. These two estimated costs are determined by the Engineer either through experienced approximation or from historical data of previous projects.

$$FC_{eng,j} = LFC_j - EFC_j \qquad \text{(Equation 10)}$$

Where;

$FC_{eng,j}$ = Engineer Float Cost for Activity j; j = A, B, .. m

$LFC_j$ = Late Finish Cost for Activity j; j = A, B, .. m

$EFC_j$ = Early Finish Cost for Activity j; j = A, B, .. m

The final step of this stage is to determine the complete Float Loss Cost ($FLC_{eng}$) in the Engineer's schedule due to the fact that some activities shall be critical after performing the CPM analysis; therefore, these critical activities are considered at their LFC. Correspondingly, as illustrated in Equation 11, Float Loss Cost ($FLC_{eng}$) is the sum of all the Float Cost ($FC_{eng,j}$) of the critical activities that has zero float.

$$FLC_{eng} = \sum FC_{eng,j} \text{ ; for } TF_{eng,j} = 0 \qquad \text{(Equation 11)}$$

Where;

$FLC_{eng}$ = Float Loss Cost for Engineer

$FC_{eng,j}$ = Engineer Float Cost for Activity j; j = A, B, .. m

$TF_{eng,j}$ = Activity j Total Float in Engineer schedule; j = A, B, .. m

### 4.2.2 Stage 2 - Analysis of Bidders' Schedules

Similarly to the previous stage, a deterministic analysis using CPM is performed on each bidder's schedule, and the corresponding project duration ($D_i$) is determined along with the respective list of critical and non-critical activities as well as the Total Float ($TF_{i,j}$) for each activity. Although the model of De La Garza et al. [34] requires the contractors or bidders to disclose the commercial value of the total float available in their schedules, the proposed model of A+B+R bidding system takes the Engineer's estimates for EFC and LFC of each activity. The objective of this assumption is to use the estimated costs as a reference for unbiased comparison between the Engineer's and bidders' schedules. For the critical activities in bidder's schedule with zero float, the Float Cost ($FC_i$) shall be the same difference between the Engineer's estimates for $EFC_j$ and $FLC_j$. However, for non-critical activities which have a lower positive total float than the one found in Engineer's schedule, the assumption is that the Float Cost ($FC_{i,j}$) cost rate is uniformly distributed throughout the entire original total float duration. Accordingly, the Float Cost ($FC_{i,j}$) for these activities shall be determined based on the number of the consumed float units and the float cost rate. These calculations steps are illustrated in Equation 12.

$$FC_{i,j} = \begin{cases} FC_{eng,j} & \text{; if } TF_{i,j} = 0 \\ (FC_{eng,j} / TF_{eng,}) \text{ x } (TF_{eng,j} - TF_{i,j}) & \text{; if } TF_{i,j} \neq 0 \end{cases} \qquad \text{(Equation 12)}$$

Where;

$FC_{i,j}$ = Float Cost for Activity j in Bidder i schedule; i = 1, 2, .. n, j = A, B, .. m

$FC_{eng,j}$ = Engineer Float Cost for Activity j; j = A, B, .. m

$TF_{i,j}$ = Activity j Total Float in Bidder i schedule; i = 1, 2, .. n, j = A, B, .. m

$TF_{eng,j}$ = Activity j Total Float in Engineer schedule; j = A, B, .. m

Correspondingly, as shown in Equation 13, the last step is to determine the schedule Float Loss Cost ($FLC_j$) for each bidder, which is the sum of all the calculated Float Cost ($FC_{i,j}$) for each and every activity.

$$FLC_j = \sum FC_{i,j} \qquad \text{(Equation 13)}$$

Where;

$FLC_i$ = Float Loss Cost for Bidder i; i = 1, 2, .. n

$FC_{i,j}$ = Float Cost for Activity j in Bidder i schedule; i = 1, 2, .. n, j = A, B, .. m

### 4.2.3 Stage 3 - Quantification of Risk Parameter

The main objective of the third stage is to quantify the Risk parameter (R) for each bidder in order to determine the Total Combined Bid (TCB) at a later stage. Similar to the stochastic model discussed in Chapter Three, the Risk parameter shall penalize bidders for having reduced flexibility due the highly compressed schedules and float loss. Eventually, these schedules are likely to be late and behind schedule due to the lower probability of finishing on time than the Engineer’s schedule. Although, the schedule risk is also present in the Engineer’s schedule, the assumption is that the owners and clients agree to that existing risk level, and would only be concerned in the case of any additional higher risk. Hence, considering such a rationale, the Risk parameter (R) for each bidder, which represents the impact of the float loss, is calculated from the difference between the bidder’s Float Loss Cost ($FLC_i$) and the Engineer’s Float Loss Cost ($FLC_{eng}$) as illustrated in Equation 14.

$$R_i = FLC_i - FLC_{eng} \qquad \text{(Equation 14)}$$

Where;

$R_i$ = Risk parameter for Bidder i; i = 1, 2, .. n

$FLC_i$ = Float Loss Cost for Bidder i; i = 1, 2, .. n

$FLC_{eng}$ = Float Loss Cost for Engineer

### 4.2.4 Stage 4 - Tri-parameter Contracting Model

In the fourth stage, the evaluation process of all submitted bids is performed considering the three parameters of the proposed tri-parameter contracting method

(A+B+R): the Cost parameter (A), the Time parameter (B), and the Risk parameter (R). As explained in Chapter Three, the Cost parameter represents the actual bid monetary value submitted by the bidder, while the Time parameter is the product of the bidder's project duration and the Unit Time Value defined by the client as illustrated previously in Equation 8. The final step of the model is to sum all the three parameters to compute the Total Combined Bid ($TCB_i$) for each bidder as illustrated in Equation 15 below. Ultimately, the winning bid shall be the Bidder with the lowest TCB.

$$TCB_i = A_i + B_i + R_i \qquad \text{(Equation 15)}$$

Where;

$TCB_i$ = Total Combined Bid for Bidder i; i = 1, 2, .. n

$A_i$ = Cost parameter for Bidder i; i = 1, 2, .. n

$B_i$ = Time parameter for Bidder i; i = 1, 2, .. n

$R_i$ = Risk parameter for Bidder i; i = 1, 2, .. n

All four stages and the associated different steps are summarized in the flowchart shown in Figure 4.1.

## 4.3 Model Application Example

In order to demonstrate the deterministic model of the tri-parameter contracting method, an extension to the schedule in the example of De La Garza et al. [34] is formulated. Although, the number of activities with their durations and different estimated costs are identical to the original schedule in the example, the precedence relationships are changed in order to emphasize the impact of float loss. Another note is that the estimated costs in the original example are multiplied by 100,000 in order to comprehend the figures easily. Moreover, four additional compressed versions of the same schedule are formulated to represent the schedules submitted by the different bidders. More importantly, the same assumptions of the example in Chapter Three are considered herein: (1) Engineers often overestimate project duration; (2) bidders compete on having shorter project durations to have a lower Total Combined Bid; (3) bidders' schedules are compressed differently to show the impact of varying schedule flexibility and different available total float. Lastly, the Unit Time Value considered for this example project is assumed to be 185,000 USD per month, and the remaining project data are listed in Tables 4.2 and 4.3.

| | |
|---|---|
| **STAGE 1** | - Perform CPM* on Engineer's Schedule<br>- Determine Engineer's Project Duration ($D_{eng}$)<br>- Determine Total Float ($TF_{eng,j}$) for Activity j |
| | ↓ |
| | - Determine Float Cost: $FC_{eng,j}* = LFC_j* – EFC_j*$<br>- Determine Engineer's Float Loss Cost:<br>$FLC_{eng} = \sum FC_{eng,j}$ ; for Activity j with $TF_{eng,j} = 0$ |
| | ↓ |
| **STAGE 2** | - Perform CPM on Bidder i Schedule<br>- Determine Bidder i Project Durations ($D_i$)<br>- Determine Total Float ($TF_{i,j}$) for Activity j |
| | ↓ |
| | - Determine Float Cost:<br>$FC_{i,j} = \begin{cases} FC_{eng,j} & ;\ \text{if } TF_{i,j} = 0 \\ (FC_{eng,j} / TF_{eng,j}) \times (TF_{eng,j} - TF_{i,j}) & ;\ \text{if } TF_{i,j} \neq 0 \end{cases}$<br>- Determine Bidder i Float Loss Cost<br>$FLC_i = \sum FC_{i,j}$ |
| | ↓ |
| **STAGE 3** | - Determine Risk parameter: $R_i* = FLC_i – FLC_{eng}$ |
| | ↓ |
| **STAGE 4** | - Tri-parameter Contracting Method Model: $TCB_i* = A_i* + B_i* + R_i$ |
| | ↓ |
| | - Determine Lowest $TCB_i$ ; |

CPM: Critical Path Method    TF: Total Float    FC: Float Cost
FLC: Float Loss Cost    LFC: Late Finish Cost    EFC: Early Finish Cost
R: Risk parameter    TCB: Total Combined Bid    A: Cost parameter
B: Time parameter

**Figure 4.1: Flowchart of Deterministic A+B+R System**

**Table 4.3: Example Project Data**

| Activity | Predecessor | Mean Duration (months) | | | | |
|---|---|---|---|---|---|---|
| | | Engineer | Bidder 1 | Bidder 2 | Bidder 3 | Bidder 4 |
| **A** | - | 8 | 8 | 7 | 6 | 6 |
| **B** | A | 9 | 8 | 8 | 7 | 6 |
| **C** | B | 8 | 8 | 7 | 7 | 7 |
| **D** | - | 4 | 4 | 4 | 4 | 4 |
| **E** | A, D | 14 | 13 | 12 | 11 | 10 |
| **F** | D | 6 | 6 | 6 | 6 | 6 |
| **G** | D | 5 | 5 | 5 | 5 | 5 |
| **H** | G | 7 | 7 | 7 | 7 | 7 |
| **I** | E, F, H | 3 | 3 | 3 | 3 | 3 |
| | | | | | | |
| **Total Cost (USD)** | | 6,600,000 | 6,500,000 | 6,325,000 | 6,525,000 | 6,675,000 |

**Table 4.4: Activities Early and Late Finish Costs**

| Activity | Early Finish Cost (USD) | Late Finish Cost (USD) |
|---|---|---|
| **A** | 1,000,000 | 1,150,000 |
| **B** | 1,500,000 | 1,650,000 |
| **C** | 800,000 | 960,000 |
| **D** | 500,000 | 590,000 |
| **E** | 400,000 | 420,000 |
| **F** | 300,000 | 360,000 |
| **G** | 800,000 | 960,000 |
| **H** | 600,000 | 690,000 |
| **I** | 700,000 | 930,000 |

### 4.3.1 Example Stage 1 - Analysis of Engineer's Baseline Schedule

The precedence diagram in Figure 4.2 shows the CPM analysis for the Engineer's schedule which identifies two critical paths: (1) A→B→C; (2) A→E→I, while the total project duration ($D_{eng}$) is 25 months. Additionally, the available total float for all non-critical activities in the network is listed in Table 4.4.

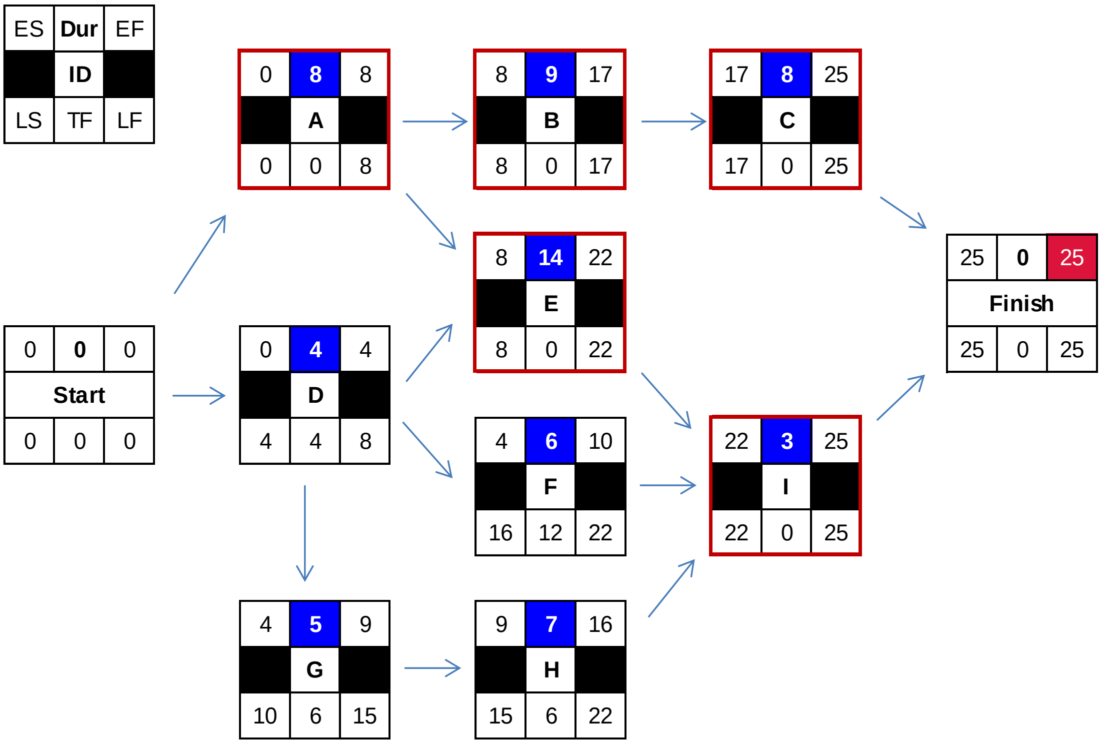


**Figure 4.2: Precedence Diagram for Engineer**

**Table 4.5: Activities Total Float in Engineer's Schedule**

| Activity | Total Float (Months) |
|---|---|
| **A** | 0 |
| **B** | 0 |
| **C** | 0 |
| **D** | 4 |
| **E** | 0 |
| **F** | 12 |
| **G** | 6 |
| **H** | 6 |
| **I** | 0 |

The second step is to determine the Float Cost ($FC_{eng,j}$) as the difference between the estimated Early Finish Cost ($EFC_j$) and the Late Finish Cost ($FLC_j$). The results are shown in Table 4.5 and a sample calculation is illustrated for Activity A.

Using Equation 10,

$$FC_{eng,A} = LFC_A - EFC_A$$
$$= 1{,}150{,}000 - 1{,}000{,}000 = 150{,}000 \text{ USD}$$

**Table 4.6: Activities Float Cost for Engineer**

| Activity | Engineer Float Cost (USD) |
|---|---|
| **A** | 150,000 |
| **B** | 150,000 |
| **C** | 160,000 |
| **D** | 90,000 |
| **E** | 20,000 |
| **F** | 60,000 |
| **G** | 160,000 |
| **H** | 90,000 |
| **I** | 230,000 |

The last step of this stage is to determine the complete Float Loss Cost ($FLC_{eng}$) in the Engineer's schedule considering all critical activities at their respective LFC.

Using Equation 11,

$$FLC_{eng} = \sum FC_{eng,j} \text{ ; for } TF_{eng,j} = 0$$
$$= FC_{eng,A} + FC_{eng,B} + FC_{eng,C} + FC_{eng,E} + FC_{eng,I}$$
$$= 150k + 150k + 160k + 20k + 230k = 710{,}000 \text{ USD}$$

### 4.3.2 Example Stage 2 - Analysis of Bidders' Schedules

A similar CPM analysis is performed for all bidders' schedules and their corresponding precedence diagrams are illustrated in Figures 4.3, 4.4, 4.5, and 4.6. For Bidders 1, 2, and 3 the two original critical paths remain the same as the Engineer's: (1) A→B→C; (2) A→E→I. Yet, their project durations ($D_i$) are shorter at 24, 22, and 20 months instead for Bidder 1, 2 and 3 respectively. Nevertheless, for Bidder 4, which has the shortest project duration of 19 months, two additional critical paths are presented due to the intensive crashing of activities to reduce the total duration. The four critical paths for Bidder 4 are: (1) A→B→C; (2) A→E→I; (3)

D→E→I; (4) D→G→H→I. Another important remark is that the available total float for non-critical activities reduces from one bidder to another the further the project duration is shortened.

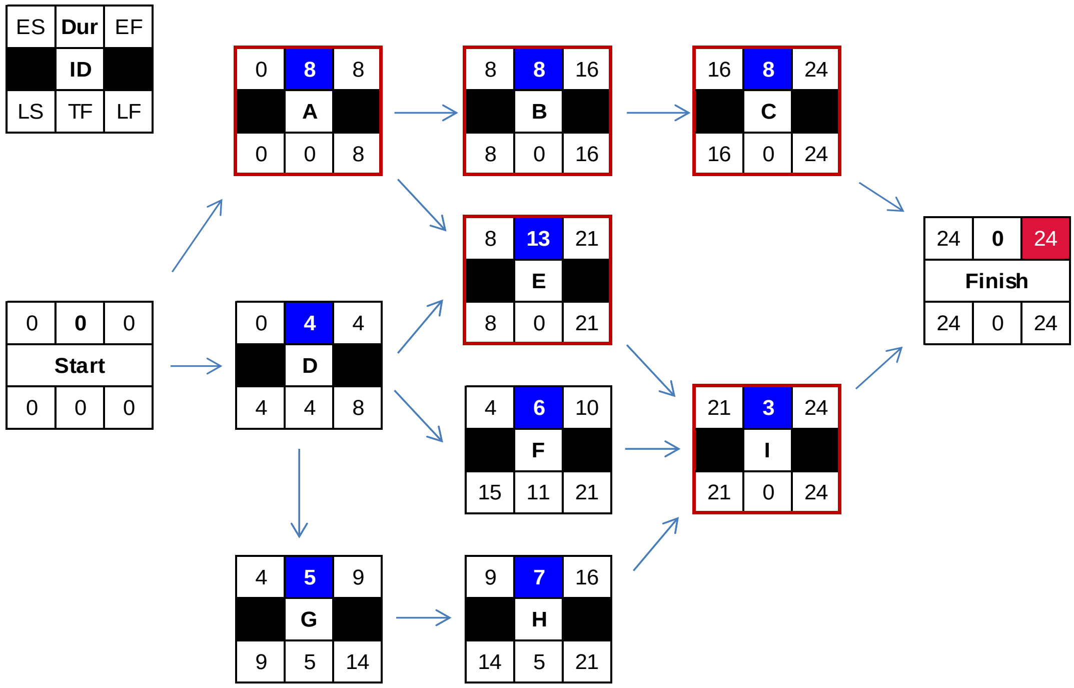


**Figure 4.3: Precedence Diagram for Bidder 1**

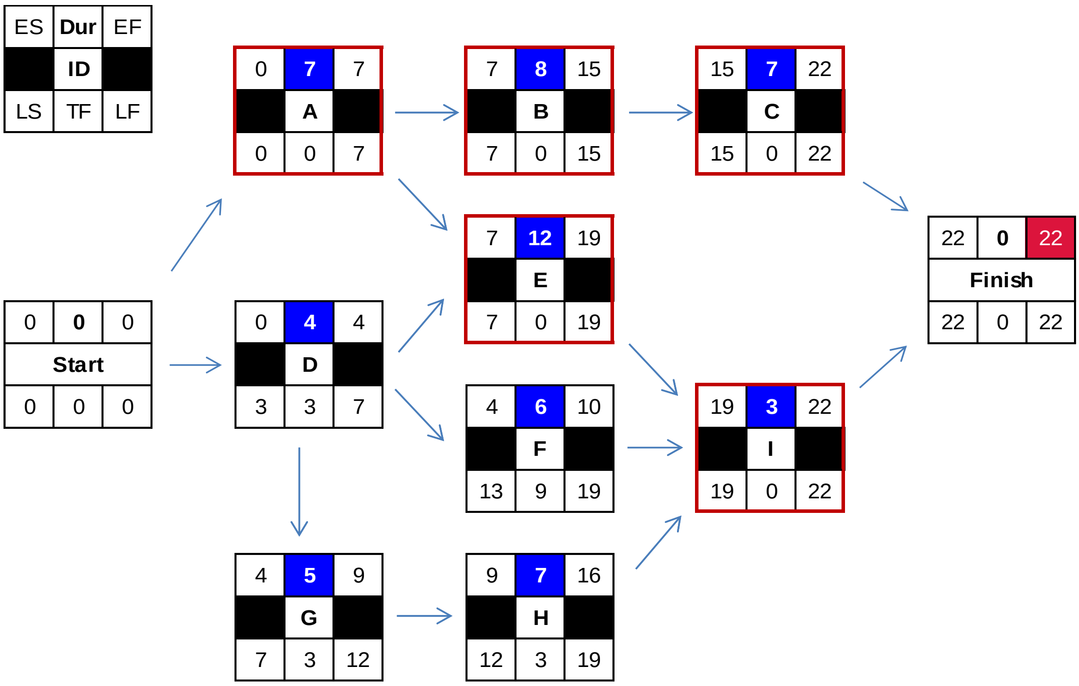


**Figure 4.4: Precedence Diagram for Bidder 2**

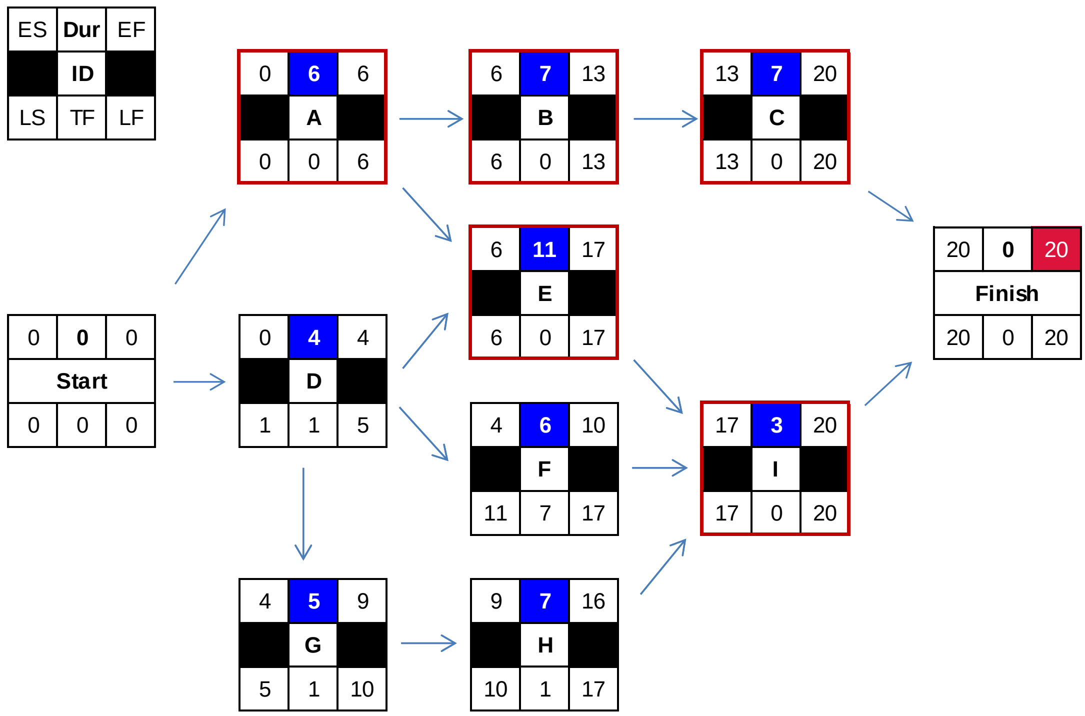


**Figure 4.5: Precedence Diagram for Bidder 3**

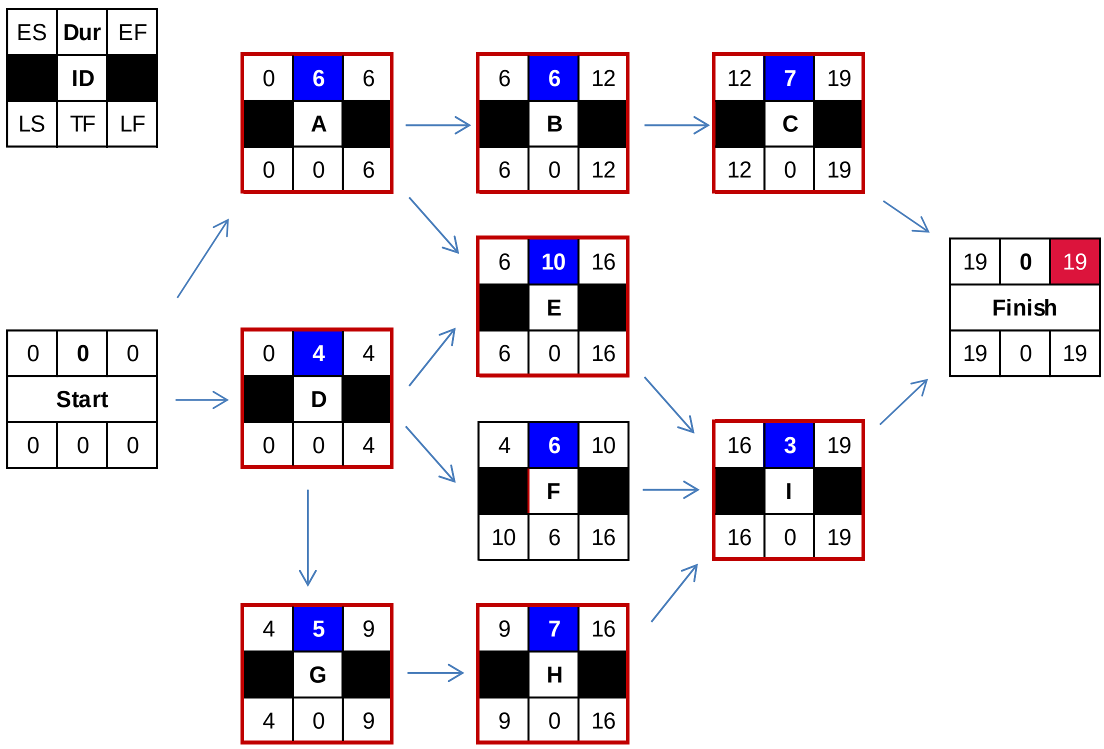


**Figure 4.6: Precedence Diagram for Bidder 4**

Secondly, the Float Cost ($FC_{i,j}$) for each activity in every bidder's schedule shall be calculated. As explained previously, in the case of critical activities with zero float, the Float Cost ($FC_{i,j}$) is the difference between the Engineer's estimates for $EFC_j$ and $FLC_j$. Nevertheless, for non-critical activities, the Float Cost ($FC_{i,j}$) is calculated based on the float cost rate and the number of float units consumed from the original Engineer's Schedule. For illustration purposes, the calculation procedures for Activity C and H in the schedule of Bidder 1 are shown, while the results summary for all bidders' activities are summarized in Table 4.6.

As an example for Bidder 1, using Equation 12,

$$FC_{i,j} = \begin{cases} FC_{eng,j} & ; \text{if } TF_{i,j} = 0 \\ (FC_{eng,j} / TF_{eng,}) \text{ x } (TF_{eng,j} - TF_{i,j}) & ; \text{if } TF_{i,j} \neq 0 \end{cases}$$

For Activity C: $TF_{1,C} = 0$,

$$FC_{1,C} = FC_{eng,C} = 160{,}000 \text{ USD}$$

For Activity H: $TF_{1,H} = 5$,

$$FC_{1,H} = (FC_{eng,H} / TF_{eng,H}) \text{ x } (TF_{eng,H} - TF_{1,H})$$

$$= (90{,}000/6) \text{ x } (6\text{-}5) = 15{,}000 \text{ USD}$$

**Table 4.7: Activities Float Cost for Bidders**

| | Float Cost (USD) | | | |
|---|---|---|---|---|
| **Activity** | **Bidder 1** | **Bidder 2** | **Bidder 3** | **Bidder 4** |
| **A** | 150,000 | 150,000 | 150,000 | 150,000 |
| **B** | 150,000 | 150,000 | 150,000 | 150,000 |
| **C** | 160,000 | 160,000 | 160,000 | 160,000 |
| **D** | 0 | 22,500 | 67,500 | 90,000 |
| **E** | 20,000 | 20,000 | 20,000 | 20,000 |
| **F** | 5,000 | 15,000 | 25,000 | 30,000 |
| **G** | 26,667 | 80,000 | 133,333 | 160,000 |
| **H** | 15,000 | 45,000 | 75,000 | 90,000 |
| **I** | 230,000 | 230,000 | 230,000 | 230,000 |

At last, the final step in this stage is to determine the schedule Float Loss Cost ($FLC_i$) for each bidder considering the calculated Float Cost ($FC_{i,j}$) for each.

As an example for Bidder 1, using Equation 13,

$$FLC_i = \sum FC_{i,j}$$

$$FLC_1 = FLC_{1,A} + FLC_{1,B} + FLC_{1,C} + FLC_{1,D} + FLC_{1,E} + FLC_{1,F} + FLC_{1,G} + FLC_{1,H} + FLC_{1,I} = 756,667 \text{ USD}$$

Similarly for the rest of the bidders,

$FLC_2$ = 872,500 USD

$FLC_3$ = 1,010,833 USD

$FLC_4$ = 1,080,000 USD

#### 4.3.3 Example Stage 3 - Quantification of Risk Parameter

The Risk parameter (R) for each bidder is determined in Stage 3 in order to determine the Total Combined Bid (TCB). Hence, as per the previously explained methodology, the Risk parameter (R) which indicates the cost impact of float loss, is calculated from the difference between the bidder's Float Loss Cost ($FLC_i$) and the Engineer's Float Loss Cost ($FLC_{eng}$).

As an example for Bidder 1, using Equation 14,

$$R_i = FLC_i - FLC_{eng}$$

$$R_1 = FLC_1 - FLC_{eng}$$

$$= 756,667 - 710,000 = 46,667 \text{ USD}$$

Similarly for the rest of the bidders,

$R_2$ = 162,500 USD

$R_3$ = 300,833 USD

$R_4$ = 370,000 USD

#### 4.3.4 Example Stage 4 - Tri-parameter Contracting Model

At last in Stage 4, the Total Combined Bid (TCB) for each bidder is calculated based on the three parameters: the Cost parameter (A), the Time parameter (B), and the Risk parameter (R). However, the Time parameter (B) has to be determined for each bidder before adding up all the three parameters.

As an example for Bidder 1, using Equation 8,

$$B_1 \text{ (USD)} = D_1 \text{ (months)} \times UTV \text{ (USD/month)}$$

$$B_1 = 24 \text{ (months)} \times 185{,}000 \text{ (USD/month)} = 4{,}440{,}000 \text{ USD}$$

Moreover, for the rest of the bidders, the Time parameter (B) shall be 4.07, 3.70, and 3.515 million USD for Bidder 2, 3, and 4 respectively. Next, the last step is to calculate each bidder's TCB to determine the lowest winning bid accordingly.

As an example for Bidder 1,
$A_1$ = 6,500,000 USD, $B_1$ = 4,440,000 USD, $R_1$ = 46,667 USD

Using Equation 15,

$$TCB_i = A_i + B_i + R_i$$

$$TCB_1 = A_1 + B_1 + R_1$$

$$TCB_1 = 6{,}500{,}000 + 4{,}440{,}000 + 46{,}667 = 10{,}986{,}667 \text{ USD}$$

Finally, the summary of the calculations for all the bidders are listed in Table 4.7. From the results, Bidder 3 shall be the winning bidder by having the lowest TCB of the tri-parameter contracting method equal to 10,525,833 USD.

**Table 4.8: Breakdown of A+B+R Parameters for Bidders**

| Bidder ID | A (USD) | Duration (months) | B (USD) | R (USD) | A +B +R (USD) |
|---|---|---|---|---|---|
| **Engineer** | 6,600,000 | 25 | 4,625,000 | - | 11,225,000 |
| **Bidder 1** | 6,500,000 | 24 | 4,440,000 | 46,667 | 10,986,667 |
| **Bidder 2** | 6,325,000 | 22 | 4,070,000 | 162,500 | 10,557,500 |
| **Bidder 3** | 6,525,000 | 20 | 3,700,000 | 300,833 | 10,525,833 |
| **Bidder 4** | 6,675,000 | 19 | 3,515,000 | 370,000 | 10,560,000 |

## 4.4 Discussion of Results

Primarily, as illustrated in both Table 4.8 and Figure 4.7, it is essential to observe that the proposed deterministic tri-parameter contracting method changed the winning bid. For example, if the competitive bidding system is considered, then the project shall be awarded to Bidder 2 with the lowest cost of 6.325 million USD. On the other hand, Bidder 3 shall be the awarded bidder if the bi-parameter bidding system (A+B) is considered, then the winning bidder shall be Bidder 4 instead by having the most competitive price and project duration with a Total Combined Bid value of 10.19 million USD. However, it is established that the significance of the proposed tri-parameter contracting method (A+B+R) is the incorporation of the Risk parameter as part of the evaluation process. Consequently, the winner bid shall have the most competitive price, project duration, and reasonable level of the risk in the schedule; for instance in the discussed example, Bidder 3 has the lowest Total Combined Bid of 10.525 million USD considering the tri-parameter contracting method.

**Table 4.9: List of Final Ranking of Bidders**

| Bidder ID | A (USD) | Rank | A+B (USD) | Rank | A +B +R (USD) | Final Rank |
|---|---|---|---|---|---|---|
| **Bidder 1** | 6,500,000 | 2 | 10,940,000 | 4 | 10,986,667 | 4 |
| **Bidder 2** | 6,325,000 | 1 | 10,395,000 | 3 | 10,557,500 | 2 |
| **Bidder 3** | 6,525,000 | 3 | 10,225,000 | 2 | 10,525,833 | 1 |
| **Bidder 4** | 6,675,000 | 4 | 10,190,000 | 1 | 10,560,000 | 3 |

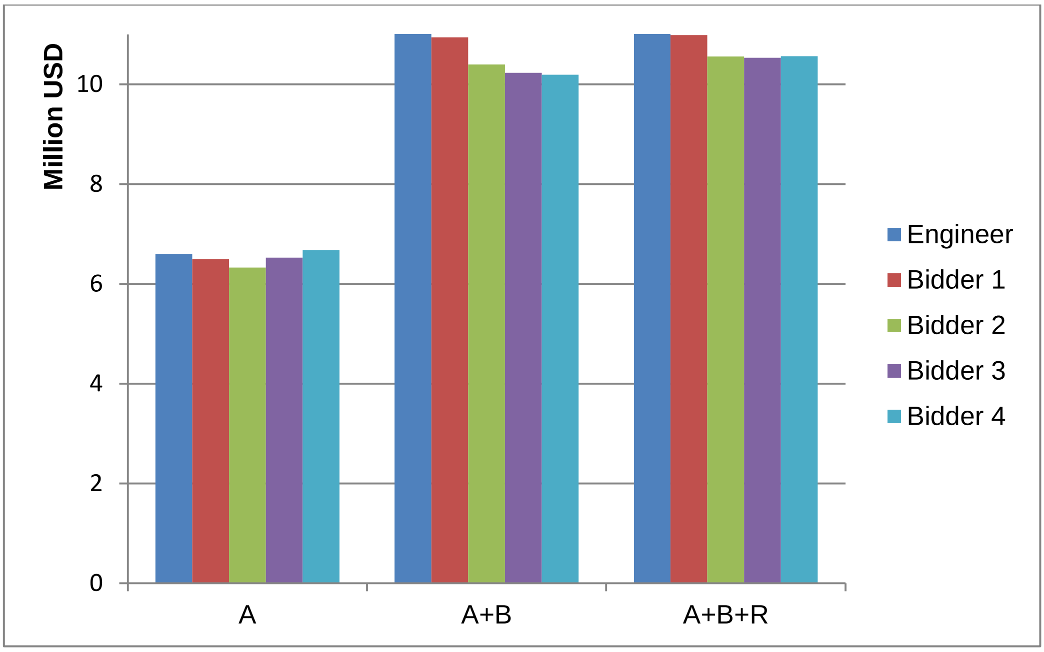


**Figure 4.7: Evaluation of Bidders on Different Bidding Systems**

Referring to the discussion in Chapter 3, an important point was concluded about the interrelationship between the reduction in the available total float in the non-critical activities and the reduced probability of finishing the project on time. For this particular example as seen in Table 4.9 and Figure 4.8, the drop in total float in the original non-critical activities (D, F, G, and H) is presented for each bidder's schedule; evidently, the shorter the project duration is, the higher the consumption of float. Furthermore, in Figure 4.9, the Float Cost for the same non-critical activities is plotted for each bidder to show the increasing costs associated with higher float loss and shorter project durations. Nevertheless, as observed from the two figures, both the float consumption and Float Cost have an inverse kind of a relationship. More importantly, considering that the Risk parameter in the model is rather a measure of the Float Cost, it validates the principle that an increase in this specific risk is caused by consuming the float in non-critical activities. Ultimately, these interpretations support the importance of considering the time-cost-risk tradeoff as well as the tri-parameter contracting method (A+B+R).

**Table 4.10: Activities Total Float in Bidders' Schedules**

| Activity | Total Float (Months) | | | | |
|---|---|---|---|---|---|
| | Engineer | Bidder 1 | Bidder 2 | Bidder 3 | Bidder 4 |
| A | 0 | 0 | 0 | 0 | 0 |
| B | 0 | 0 | 0 | 0 | 0 |
| C | 0 | 0 | 0 | 0 | 0 |
| D | 4 | 4 | 3 | 1 | 0 |
| E | 0 | 0 | 0 | 0 | 0 |
| F | 12 | 11 | 9 | 7 | 6 |
| G | 6 | 5 | 3 | 1 | 0 |
| H | 6 | 5 | 3 | 1 | 0 |
| I | 0 | 0 | 0 | 0 | 0 |

As with the stochastic model in, the proposed deterministic tri-parameter contracting method (A+B+R) stresses the change to the existing time-cost tradeoff by adding the Risk parameter. As explained on several occasions, the Risk parameter considers the impact of float loss and on increasing the likelihood of finishing the project late. In addition, to explore the relevant weight between the bidders' original costs and their measured risks, the numbers are summarized in Table 4.10. From the figures of the application example, the Risk parameter reflects up to 5.5% of the bidder's cost which is a rational margin as discussed previously considering the typical project contingency. In addition, Figure 4.10, illustrates the impact of adding the Risk parameter to the Cost parameter in the curve of the conventional time-cost tradeoff. The observation is that an increase in the risk is projected when the schedule gets compressed for the purpose of having shorter project duration.

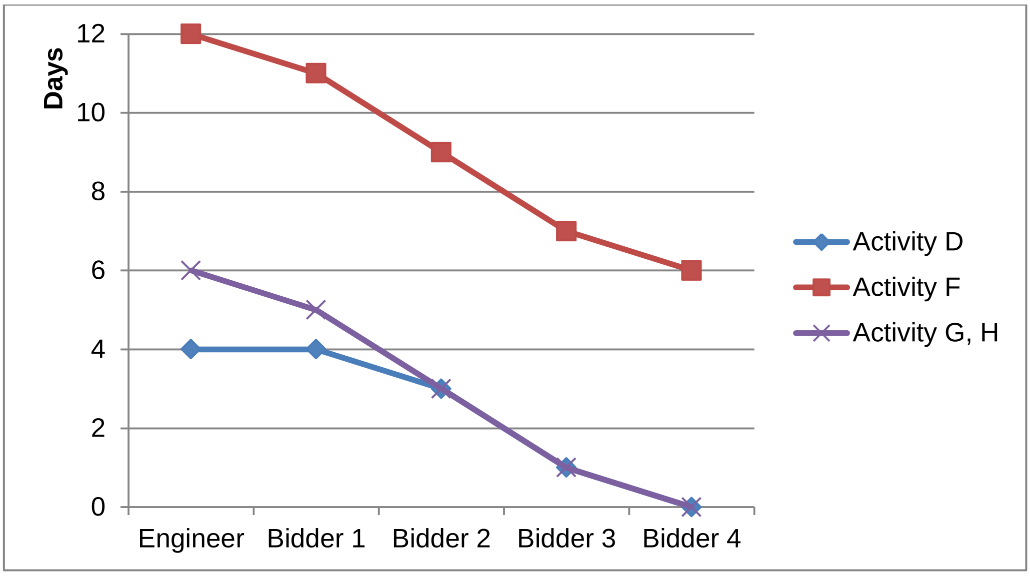


**Figure 4.8: Non-Critical Activities Total Float**

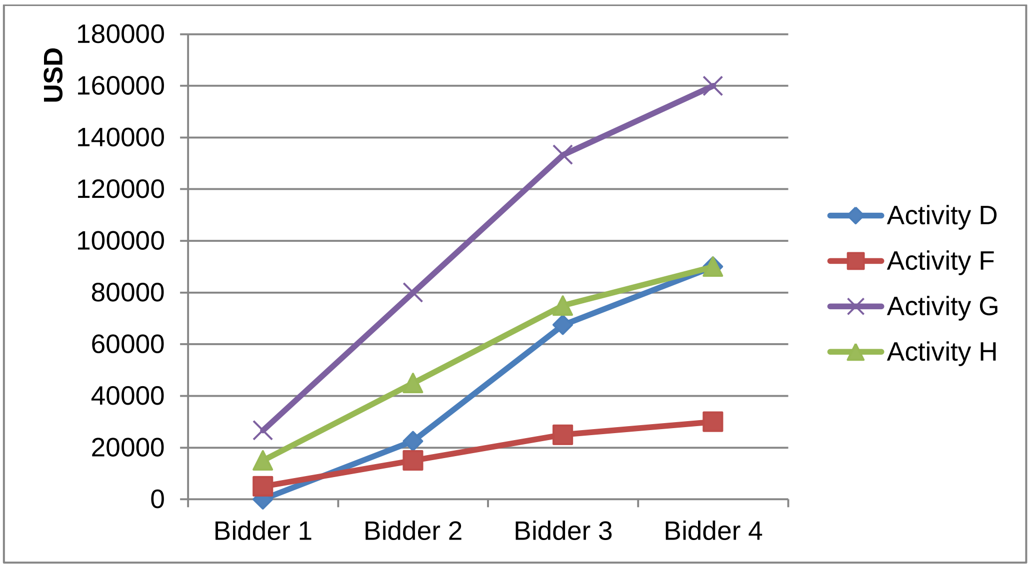


**Figure 4.9: Non-Critical Activities Float Cost**

**Table 4.11: Cost and Risk parameters for all Bidders**

| Bidder ID | A (USD) | R (USD) | R/A |
|---|---|---|---|
| **Bidder 1** | 6,500,000 | 46,667 | 0.72% |
| **Bidder 2** | 6,325,000 | 162,500 | 2.57% |
| **Bidder 3** | 6,525,000 | 300,833 | 4.61% |
| **Bidder 4** | 6,675,000 | 370,000 | 5.54% |

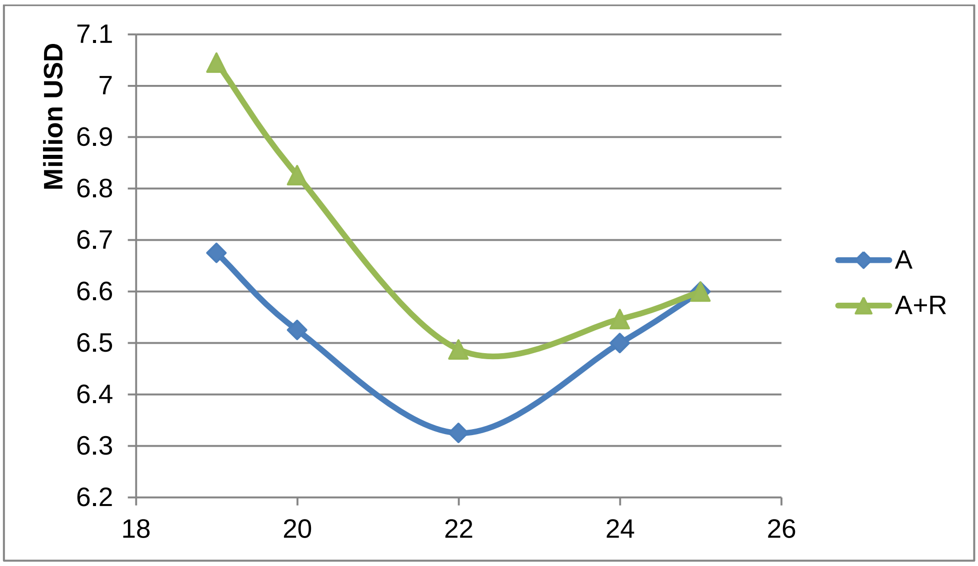


**Figure 4.10: A vs A+R Curves**

The proposed deterministic tri-parameter contracting method (A+B+R) extends the new conception of a three-way tradeoff between cost, time, and risk concurrently as with the first stochastic model. Similarly, clients and owners can define to what extent the risk associated with the schedule have to be mitigated. Consequently, the bid evaluation, which is on the basis of the tri-parameter contracting method, shall determine the most reasonable bid considering a competitive price, duration, and an acceptable level of schedule risk. Moreover, the same expected shift of the original curve of the time-cost tradeoff occurs upon the addition of the Risk parameter. Likewise, as shown in Figure 4.11, the magnitude of the shift increases as the project duration decreases and the schedule becomes more critical due to the consumption of float. Finally, the same idea of determining a new optimum project duration point is applicable in which it represents the lowest combination of actual cost, time, and risk.

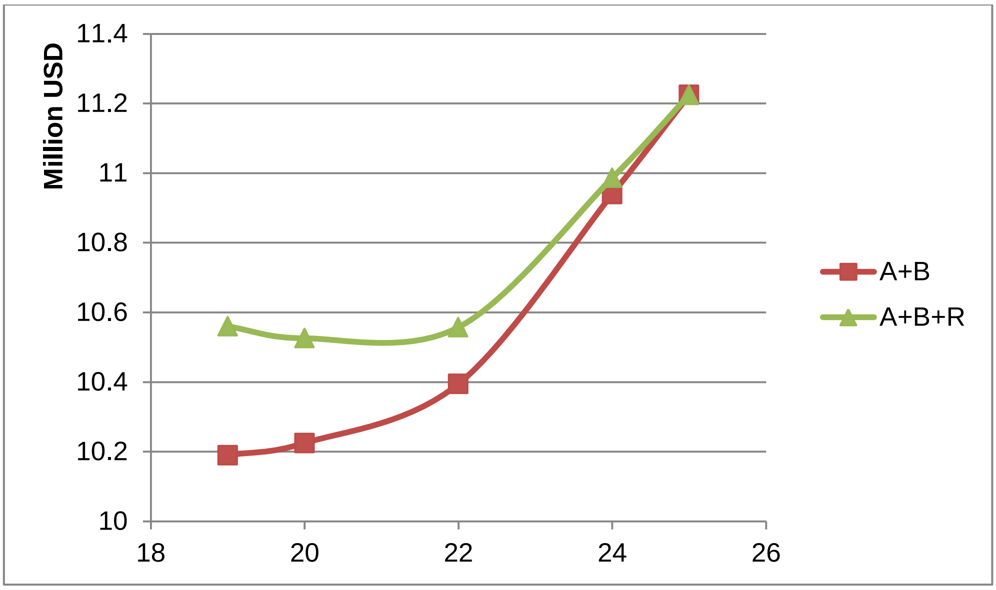


**Figure 4.11: A+B vs. A+B+R Curves**

# Chapter Five: Summary, Conclusions, and Recommendations

## 5.1 Summary

The three pillars of project management determine the success of a project which has to be completed within a certain budget, time limit and quality level. Hence, the awarding criteria in the bid evaluation stage are very essential to ensure that the project has a high chance of meeting the anticipated objectives. Although, the competitive low-bid system has facilitated clients and owners to have lower bid prices from bidders, it neglected the Time parameter which had no weight in the awarding decision. As a result, the award to the winning bidder often would not be the right one especially in the cases of time-sensitive projects. These consequences were the motivation behind the establishment of the bi-parameter bidding system (A+B), which considers the Time parameter in addition to the original Cost parameter. For all the bids, the Time parameter is determined based on a certain weight defined by the client depending on the nature of the project. Bidders started to be keener to have shorter project durations to increase their competitiveness by crashing their activities and compressing schedules. However, such techniques actually consume the float of the non-critical activities, and result in schedules that have less flexibility to accommodate any delay that might occur. Therefore, a new tri-parameter contracting method (A+B+R) is proposed that remains within the principle of the A+B system while integrating a third parameter, which is the Risk parameter (R). Risk management is essential to achieve the project's objective. Thus, the significance of the proposed A+B+R system lies in the consideration and attention given to the schedule Risk parameter which relates to the flexibility of a given schedule or network of activities. The principle of the A+B+R system is the quantification process for the Risk parameter on the basis of the float loss in non-critical activities. The consideration of the Risk parameter shall support clients and owners to anticipate the risks of finishing the project behind the schedule in the case of highly compressed schedules. Therefore, the need relies into modeling appropriate and practical methodologies to quantify the Risk parameter in any given schedule.

## 5.2 Conclusions

The true significance of the proposed tri-parameter contracting method (A+B+R) is that while it remains within the outline of the conventional low-bid system, the bid evaluation also considers two other parameters which is the Time (B) and Risk (R). While the Time parameter (B) is useful for bids evaluation for time-sensitive projects, Risk parameter (R) is even more important for these projects. This is due to the fact that these projects are often associated with highly compressed schedules which consume most of the available float; thus, reducing the scheduling flexibility and the probability of finishing on time. Float results from the Critical Path Method (CPM) calculations representing the duration of delays which the non-critical activities can accommodate without an impact on the final project duration. While contractors often consider the available total float as a time contingency to mitigate the risk of unforeseen circumstances, clients and owners consider float as a practice to accommodate change orders without extending the contract project duration. However, in order to hide the true available total float from the network, contractors tend to create imaginary lags in order to reduce the visible float; hence, clients and owners will be obliged to extend the contract time and compensate contractors in case of change orders.

Float loss and schedule flexibility are important risks that have to be taken into consideration to change the conventional time-cost tradeoff into a three-way tradeoff; time-cost-risk. It is essential to understand the time-cost-risk tradeoff since project stakeholders should always have their decisions at an acceptable level of risk associated with float loss. Therefore, the proposed models of the tri-parameter contracting method (A+B+R) specify the required methodologies to quantify the impact of float loss on both the duration and cost of any project. Ultimately, the A+B+R model would help the clients and owners identify the most reasonable combination of all the three parameters for their projects in which it reduces the risk of awarding the project to the unsuitable contractor. Two proposed models of the A+B+R system are explored and discussed; first one being a stochastic model, and the second based on deterministic equations extended from De La Garza et al. [34]. The application of both systems shows that the final ranking of the bidders in the example has changed when the Risk parameter is considered as part of the bid evaluation process. Moreover, the proposed models of the A+B+R system modify the time-cost tradeoff relationship by adding the third Risk parameter. Such modification to the relationship suggest a new optimum project duration point at which clients and owners shall have the most practical combination of cost, time duration, and risk level.

## 5.3 Recommendations

In reality, where projects are likely to be resource or activity constrained, the available total float in non-critical activities can often be “misleading” with an incorrect measure of flexibility [34]. This principle was further supported by Fondahl’s example [38] in which he explained that consuming float in non-critical activities can cause additional delays on the project completion in the case of resource-constrained schedules. Although these activities remained non-critical in the network after the consumption of float for the change order initiated by the client, they rather became resource-critical, and eventually affected the start dates of the original critical activities in the network. The scenario eventually resulted in delaying the entire project although float consumption was in the free float, not the total float, which theoretically means that there shall be no impact on another activity nor the project duration. Therefore, considering the fact that resource or activity constrained schedules are a reality [39], it is important to have a future work done to incorporate such a principle in order to have a more realistic approach evaluating the real impact of float loss.

Although the previous discussions of the proposed tri-parameter contracting method (A+B+R) reflect the scenario of clients and owners applying specific methodologies to evaluate bids by different bidders, the scenario can be applicable from the bidder’s perspective as well. In reality, each bidder often have several options of different completion durations and its associated cost in which they can finish a project depending on various factors such as the allocated manpower and technical abilities. Hence, bidders can apply the proposed systems to evaluate their own options and find the near-optimum bid choice in which they can be most competitive considering a certain time-cost-risk tradeoff curve determined by historical data. Not only that, but similar to the optimization problems of time-cost tradeoff [40], this application can be investigated further in the future by developing a linear optimization model to find the optimum duration point consider the three parameters all together.

Several other recommendations can be also suggested to improve the accuracy of the Risk parameter quantification process. For instance, since the methodologies depend on many variables obtained from the Engineer's schedule, they should improve their scheduling estimation at which they determine the project duration from the baseline schedule, especially that they often tend to overestimate. Moreover, other factors such as the standard deviation in the stochastic model as well as the Early Finish Cost and Late Finish Cost in the deterministic model, the more reliable these are, the more accurate the Risk parameter presents the true schedule risk in bidders' schedules. Finally, other research [19] has already set recommendations for the original bi-parameter bidding system (A+B) which can still be applicable for the proposed tri-parameter models. For instance, it was recommended that owners and clients do not share the Engineer's estimated duration beforehand so bidders have to rely on their best scheduling practices and techniques. In addition, a more intensive research effort is required to formulate a standardize methodology to determine an accurate Unit Time Value (UTV) for a particular project.

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## Vita

Mohamad Mounzer Rabie was born in 1991, in Abu Dhabi, UAE. After completing his schoolwork in 2008, he was granted a Merit Scholarship to the American University of Sharjah, UAE. In 2012, he graduated Magna Cum Laude with a degree of Bachelor of Science in Civil Engineering and a minor in Engineering Management.

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