Time-Cost Trade-off (TCT) Analysis based Application Framework for Safety Centric Construction Acceleration Planning

by

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Abstract

The purpose of using a Time-Cost Trade-off (TCT) analysis is to account for foreseeable project safety concerns and hazards, speed up activity times, and reduce the overall duration of the project while keeping project cost within a certain budget limit. This type of acceleration planning is common practice in the construction industry and needs to ensure safety in activity execution and take into account multiple dynamic variables, such as changes in crews and work space settings, new hazards and constraints with implications on workers' occupational health and safety. Mitigation measures needs to be taken in acceleration planning to address additional safety constraints, resulting in an inevitable increase on project cost. The application framework established in this thesis can be used specifically for construction activity acceleration planning in order to consider the cost, safety, and time aspects of a project.

This research proposes an application framework for safety centric construction acceleration planning by extending the established TCT analysis in project management. Specifically, the proposed framework can be utilized by project managers to (1) identify relevant factors that shape accidents on typical construction activities; (2) adhere to rules and best practices for schedule acceleration and account for associated costs; and (3) analytically select a subset of activities from the project to shorten activity times so as to minimize project cost in realization of a given target project duration without compromising safety.

The proposed methodology starts by setting all the activities at the shortest "crash"

duration according to the planned “crash” scenario. First, the shortest achievable duration of the project is determined by utilizing the critical path method to analyze the project network model. Then, the goal is to keep the project duration resulting from CPM but lower the project cost to a minimum subject to activity time being adjusted to the best position between crash and normal scenarios along with fixing the associated activity cost, under the same precedence constraints in the project.

To materialize the research objectives, a literature review was performed to identify the major factors related to safety management on construction projects and assess the state of art on TCT analytical methods for project management. The proposed framework was then formed by integrating the appropriate knowledge and technique. Two specific project case studies were conducted to demonstrate applications and benefits in terms of how to plan critical activity acceleration on construction projects. In particular, relevant factors that shape accidents on typical construction activities were identified, while costs in connection with implementing safety measures and adhering to rules and best practices for schedule acceleration were accounted for. Additionally, a 100-acitivty project case study was conducted to contrast the current project scheduling practice (P6 scheduling) against the proposed framework in terms of analytically selecting a subset of activities from the project to shorten activity times so as to minimize project cost in realization of target project duration.

Preface

This thesis is an original work by Samin Mahdavian.

A version of the proposed Safety-Centric Construction Acceleration Planning analysis has been published as a conference paper: Samin Mahdavian, Kumar Subramanian Bellale Manjunatha, Estacio Pereira and Ming Lu (2020). "Safety-Centric Construction Acceleration Planning Guidance for Enabling Time Cost Trade-off Analysis in Project Scheduling. "Construction Research Congress 2020: Project Management and Controls, Materials, and Contracts. The mentioned coauthors were involved with literature review, industry survey, and manuscript composition.

In addition, Samin Mahdavian and Ming Lu submitted a paper in the Engineering, Construction and Architectural Management Journal (ECAM). The title of this paper is: "Application Framework for Safety-Centric Construction Acceleration Planning". Dr. Ming Lu was the correspondence author of and was involved with concept formation and manuscript composition.

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CHAPTER 1: INTRODUCTION

1.1. Background

Satisfying both the cost and time constraints of a project has long been a chief concern for the construction field (Del Pico,2013 – Rasdof and Abudayyeh,1991). When these cost and time goals are not met, it is the job of the project manager to assess the situation and adjust accordingly, in order to minimize the detrimental impacts on project performance. One strategy companies use to prevent issues like time delays, extended project time, and budget overrun, is implementing a Time-Cost Trade-off (TCT) analysis, in order to design or modify the projects resource allocation (Dieckmann and Al-Tabtabai, 1992). The goal of TCT analysis is to limit the overall length of the project based on critical path analysis, in order to meet project deadlines while minimizing cost (Elbeltagi, 2009). To this end, TCT makes use of project schedule compression techniques or ‘crashing’, such as adding equipment or resources, expanding work hours (potentially into holidays) or utilizing overtime, modifying the materials or methods used for construction, and hiring subcontractors (Hocchbaun, 2016; Hegazy, 2002).

At the same time, the construction industry is faced with multiple challenges and safety hazards. The poor statistics on safety for this field are widely recognized, and often attributed to the jobs performed in hazardous work environments. In addition, applying pressure to accelerate a project can cause undue physical and mental stress on workers. According to Mahdavian et al. (2020), using project crashing can have the added effects of 1, increasing safety incidents on a project site; 2, reducing workers health; and 3, poor management of job site safety.

With these safety concerns in mind, the application framework outlined in this thesis is intended to allow project managers in the construction field to account for cost, safety, and time when utilizing acceleration planning for a construction project. The proposed framework provides guidelines and methods to account for safety concerns and their related costs, use hazard mitigation on site at both a local and global level, identify the factors related to shaping accidents, and meet the overall standards and goals of schedule acceleration.

One of the immediate side effects of resolving the safety concerns in a compressed project scenario is the increase of project cost. As a general rule, planning alternatives that significantly increase cost are regarded as unfavorable; thus, a method is needed to control costs associated with acceleration planning without undermining safety. This research presents a solution that includes the best options to execute individual activities without compromising safety requirements, while also controlling the project cost to a minimum.

1.2. Motivation

At this time, the analysis methods utilized for TCT specific approaches do not fully account for workers safety when assessing impacts on project cost and time. This includes newer methods that make use of both the latest optimization software and techniques. These types of acceleration planning strategies as a result, can put undue stress on project workers, adding risk, and increasing the probability of construction site accidents. Project crashing in particular can increase not only the overhead costs related to safety, but occurrences of hazardous activities.

The TCT approach outlined in this thesis is 'safety centric', and takes into account project workers occupational health and safety (OHS) in order to devise an optimized project design for both time and cost; while also putting safety and hazard mitigation on the forefront of project crashing. By applying the research outlined in this paper, construction project managers can better devise strategies for acceleration planning in order to implement policies that emphasize project safety.

The proposed methodology starts by setting all the activities at the shortest "crash" duration according to the planned "crash" scenario. First, the shortest achievable duration of the project is determined by utilizing the critical path method to analyze the project network model. Then, the goal is to keep the project duration resulting from CPM but lower the project cost to a minimum by adjusting activity time to the best position between crash and normal scenarios along with fixing the associated activity cost, under the same precedence constraints in the project.

In this research the TCT optimization method and tool developed by Sasan Nasiri through a MSc thesis is chosen due to its simplicity and cost-effectiveness and hence implemented to define my research and solve the case studies. The manual is presented in Appendix A based on my own user experience and applications needs.

1.3. Objectives

The goal of this research is to design an approach to project crashing that can be applied at both the activity and project level, and includes a safety-centric framework that helps to eliminate workplace hazards and reduce the number of on-site accidents. As a consequence of utilizing a safety-centric approach, the activity costs associated with planning activity acceleration inevitably increase. Therefore, it is important to control costs at the local (activity) level, without sacrificing on project safety. This concern is addressed by approaching project duration and costs at a global level of analysis. The established framework outlined can then be followed by projects management to aid them in selecting a scheduling approach that is best suited to their overall project goals.

The specific objectives of this research are as follows:

- Develop a framework that considers both safety constraints and the potential methods of hazard mitigation in acceleration planning, with critical activities in mind.

- Generalize from the previously published research common sources of safety concerns in the field of construction, and the factors related to accident occurrence.

- Propose a step-by-step method to identify the factors related to construction accidents, while also following time constraints, and considering the budget costs related to hazard mitigation — both on a the local level (activity) and global level (project). More specifically, an analytical model is established that considers project duration, safety, and cost for acceleration planning.

- Given target project duration to complete the project, select which activities are necessary to shorten by how much to result in the lowest total cost at the project level. This is against unnecessarily crashing all activities to their shortest limits at the expense of significant project cost increase. As a result, the solution includes the best options to execute individual activities without compromising safety requirements while controlling the project cost to the minimum. The total cost would be expected to fall within the acceptable budget limit; otherwise, a solid case can be made to increase the cost budget based on safety requirements and optimization analysis. In other words, the methodology introduced in this thesis rises by setting all the activities at the shortest "crash" duration according to the planned "crash" scenario. First, the shortest possible duration of the project is developed utilizing the critical path method to interpret the project network model. Then, the aim is to maintain the project duration resulting from CPM but decrease the project cost to a minimum subject to activity time being adjusted to the best position between crash and normal scenarios and fixing the associated activity cost under the same precedence constraints in the project.

1.4. Thesis Organization

This thesis is divided into six chapters that review the research and methodologies used.

- Chapter 1: Outlines the motivation for this research, and the overall research objectives.

- Chapter 2: A literature review related to safety factors in the construction industry. These factors are grouped into four categories: accident shaping factors, time-cost trade-off, scheduling effects in relation to safety and Streamlined Project TCT Optimization.

- Chapter 3: The proposed application framework is outlined.

- Chapter 4: The framework is applied to construction project analysis, and a step-by-step example of its use is given.

- Chapter 5: The proposed application framework is used for a specific construction project case study to further demonstrate its use.

- Chapter 6: generalization TCT-based construction acceleration problem is presented in this chapter, illustrated with examples.

- Chapter 7: An overall conclusion of the work is given, with the potential limitations and future directions discussed.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

There is currently a well-established foundation of research addressing TCT analysis and its use in the construction industry. In general, most literature has focused on the positive aspects TCT has had on optimizing both project time and costs. When exploring the published literature regarding TCT acceleration planning construction, research can be categorized into three general areas: the time-cost trade-off, accident shaping factors, the effect of scheduling on safety and the streamlined project TCT optimization methodology including its algorithm, automation, and application. In the following chapter, research into each of these areas will be discussed.

2.2. Project Time Cost Trade Off

TCT analysis is a commonly addressed problem in construction planning. By starting with a cost slope approach and a simplified version of critical path scheduling, a new method of analysis is derived in the form of TCT optimization. Critical path scheduling can be further improved by implementing the path-float concept to reduce the critical path cost slope and reduce the overall project duration (Lu et al, 2017). When using a cost-effective approach to project planning, options that lower both the cost and time of the project can be selected, while still considering project safety. While previous research has focused on TCT optimization and methods of safety management, only a limited number of studies have addressed the impact of TCT optimization on safety, and how to find a balance. A study that spearheaded the research on the TCT problem was published by Kelly and Walker (Kelley and Walker 1959). Other foundational studies that attempted to establish tradeoff models for project cost and time duration include Fulkerson (1961), Kelley (1961), Siemens (1971), Robinson (1975), and finally Phillips Jr and Dessouky (1977).

A variety of analytical methods have been proposed as a solution to the TCT problem. These solutions include options such as applying methods of linear programming (e.g., Kelly 1961), genetic algorithms (e.g., Feng et al. 1997), practical heuristic-based solutions (e.g., Hegazi 2002), particle swarm optimization (e.g., Yang 2007), and methods of non-linear programming (e.g., Klansek and Psunder 2008). Studies from the last 10 years have also included methods of ant colony optimization (e.g., Mokhtari et al. 2010), network analysis algorithms (Bettemir and Birgonul 2017), teaching-learning based optimization (Toğan and Eirgash 2019), integer programming — although these methods were also applied (Nasiri and Lu 2019; Jiang and Zhu 2010), and discrete symbiotic organisms search methods (Liu et al. 2020). Each of the aforementioned studies has left a sizable impact on the field and approaches to TCT analysis.

In some of the most recent studies surveyed, select researchers were able to solve the TCT problem by including additional factors in their analysis. The factors included were quality (e.g., Hegazy 1999; Zhang and Xing 2010;Kim et al.2012; Zhang et al. 2015), resource utilization (e.g., Zahraie and Tavakolan 2009), environmental impact (e.g., Ozcan-Deniz et al. 2012), safety (e.g., Mahdavian et al. 2020), quality cost and contract clauses(Akin et al.2021), and risk or uncertainty (e.g., Alzarrad et al. 2020; Sadeghi and Lu 2020).

While safety was mentioned as a factor in some studies, the overall amount of research that takes into account safety in relation to the TCT problem is still lacking. Quality however, as an additional factor, has been given a good deal of consideration (e.g., Hegazy 1999; Zhang and Xing 2010; Kim et al.2011; Zhang et al. 2014; Nguyen et al. 2021). One reason for this, is that the combination of project duration, cost, and quality, are key factors related to the success of projects in the construction field. On a conceptual level, both safety and quality management-based approaches share a good number of similarities (Todd et al. 2006). As the previously cited study states, a primary goal of a construction project is to provide a high-quality product safely. In the remaining portion of this section, research that looks more closely at three-dimensional TCT studies

(TCT/risk, TCT/safety, TCT/quality) will be explored.

In a study by Sadeghi and Lu (2020), researchers presented a model that attempts to address the TCT problem by including accident risk as a factor for analysis. The resulting model provided an optimization based TCT solution. This study illustrates that by including an appropriate method of risk assessment and an analysis of risk penalty cost, the factor of ‘accident risks’ could be successfully included in TCT optimization methods. As a result, the model was able to quantitatively consider multiple risk management strategies.

In research conducted by Koo et al. (2015), an approach based on a Pareto frontier was enhanced to create an integrated multi-objective optimization (iMOO) model for solution set determination. The resulting model can be applied for the following:

- Assessing greater than 2 optimization objects at a time. For example, maintenance and operation cost, CO2 emission cost, and investment cost.
- Appropriately assign weight to related factors.
- Analysis the 4 different fitness functions.
- Include additional factors in the model, such as materials, energy use, and indoor air quality.

Research conducted by Kim et al. (2011) looked at designing particle project schedules by applying a model of mixed-integer linear programming that accounted for a potential quality loss cost (PQLC) when using crash schedules. To adhere to a project deadline and circumvent delays, crash scheduling for critical activities is widely applied in order to minimize the overall project duration. It only makes sense then, to account for PQLC when approaching the TCT problem, because individual activity quality is directly tied to the goal of meeting the requirements of the project’s contractor (Kim et al., 2011).

Ling et al. (2009) took a multifactorial approach by applying both environmental and organization factors with regards to the month, location, time, type of construction, and size of the organization. A study by López et al. (2008) found that both the day of the week and the time were related to the severity of accidents. A follow up study then looked at additional environmental factors related to geography, behavior, and climate, and the effect they had on project accident (López et al., 2011).

To improve safety management, Fung et al. (2010) designed a risk assessment model (RAM) after taking into account the current construction related safety issues and exploring different risk types in other fields of work. When analyzing construction specific hazards, a construction job safety analysis (CJSA) is commonly utilized. A CJSA approach is designed with lean approach to safety management in mind. In order to apply this approach, some level of prediction of the changing project safety risk levels is required. This allows for safety management efforts and safety conscious planning to be performed as needed.

Taking a theory of cost of safety (COS) model, along with an analytic hierarchy process (AHP), Aminbakhsh et al. (2013) developed a framework of safety risk assessment. The approach outlined prioritizes safety in construction projects and performs robustly to set reasonable project goals with a practical budget, all while factoring in project safety.

In a study by Johnson and Liberator (2006), researchers attempted to tackle the TCT problem by applying duration, cost, and quality to each task option by default. This was accomplished by utilizing a mixed-integer linear program to a generalized rendition of the problem.

The general principle behind the study by Deckro et al. (1995), is that a decrease in quality as a result of crash scheduling is not a desirable outcome. If this outcome is predicted to occur, it needs to be circumvented by allowing for additional time to complete the project. Additionally, preventative steps should be taken in order to account for any unexpected reworks or project delays that may occur.

Taking into account differential evolution (DE) and the TCT problem, Tran and Long (2018) outlined a method called the adaptive multiple objective differential evolution for project scheduling with time, cost, and risk trade-off (AMODE-TCR). This method minimizes the possibility of project delay and improves schedule flexibility by utilizing resource control and total float loss. The AMODE-TCR model also eliminates the need for human guidance as it is able to perform automatically.

To explore the source of workplace accidents, Mahdavian et al. (2020) looked at the crucial role of coordination between the work team, the equipment, the materials, and the workplace itself. It is clear from this and multiple additional studies that involving employees directly in project safety programs is critical to their success. Today, scheduling and planning methods have been optimized to incorporation not only resource assessment and cost analysis, but safety considerations for the construction project (Mahdavian et al., 2020).

2.3. What Causes Accidents in Construction Site?

Unsafe conditions at the construction site have been identified as playing a critical role 10% of all construction site accidents, and 90% of all behavioral hazards at the site (Schaufelberger and Lin 2014). Hazardous or unsafe behavior is predicted to increase in workers as a result of project delays (Han et al. 2014). Other studies have found that up to 80% of construction accidents were the result of human attitudes or behavior (Li & Poon, 2013). This type of accident-inducing behavior can result from not devoting enough resources to safety measures for a project or applying safety programs that are ineffective. An example accident-inducing or unsafe worker behavior includes using defective or broken equipment, and can be due to worker stress, drowsiness, or an unfit mental or physical state. According to Peyton and Rubio (1991), construction site accidents primarily occur as a result of either unsafe acts, or unsafe conditions. These two factors can also influence each other. For example, an inexperienced worker can perform unsafe behaviors, resulting in an unsafe workplace condition. In other instances, due to stress or drowsiness, an impaired worker may ignore or disengage with equipment safeguards and ignoring safety conditions can also lead to an accident.

In addition to unsafe site conditions and unsafe behaviors on the part of the worker, research has indicated that accidents may result from the improper use of material or equipment at the construction site. Some of the prime examples include accidents caused by falling objects on the site or crane use (Anumba & Bishop, 1997; OSHA, 2003; NIOSH, 2000). On average, crane incidents result in 71 fatalities in the U.S. every year (OSHA, 2003). As an example, after the disastrous events of September 11th, 2001, up to 151 safety violations results from crane use during the recovery efforts at the World Trade Center (OSHA, 2003).

Material related accidents can include explosive and flammable (fuel) hazards, in addition to toxic hazards from materials like lead, silica, asbestos, or one of the 13 carcinogenic construction materials outlined by OSHA (2003). Explosive or flammable materials for example, can cause accidents or injury if they come in contact with certain electrical equipment (Khaled and Ahmed, 2005); while toxic hazards can cause accident if workers come into contact with the related material.

Construction accidents may also occur due to workplace overcrowding or a lack of site organization. Acceleration planning in particular can result in workers from various trades operating on the site at once, increasing worksite congestion. Alistair et al. (2006) linked workplace layout, problems with space limitation, and bad housekeeping at the site to almost half (49%) of all workplace accidents examined in the study. In particular, low standards for worksite housekeeping or using a poor site layout was found to be highly detrimental in the construction field. Another factor that was found to be highly correlated with construction accidents was the misuse of equipment of a specific task or bad equipment design. Over half of site accidents (56%) were linked to broken or defective equipment like personal protective equipment (PPE). Each task on a construction site is unique, and therefore has customized safety concerns associated with it. In order to account for these specific tasks and their associated risks, factors that affect the overall safety at a worksite such as equipment, weather, behavior, location, and on-site limitations need to be incorporated. Safe work Australia (2019) found that other factors responsible for site injury from 2016-2019 included getting hit by objects (23%), material handling (55%), and falling from a higher level to a lower level (14%).

By utilizing an accident causality model to identify how accidents are caused by poor harmony between the work team, the equipment, the materials, and the workplace, Alistair et al. (2006) developed a model of accident shaping factors. This research identified 11 different factors related to shaping accidents, divided into categories based on 4 sets of criteria. These factors are summarized in Table 1. In the second table column, the related causes for each shaping factor are listed with the appropriate reference.

Table 1. Factors related to shaping accidents, divided into categories based on four sets of criteria (Table 1. in Mahdavian et al., 2020)

Shaping Factors		**Example Direct Causes**	**References**
Worker	Behavior or Attitude	Inadequate Mental capability.	Hosseinian & Torghabeh, 2012
		Disregarding Safety Standards Like Failing to Use Proper PPE.	Zou & Zhang 2009
		Failure to Engage.	Toole 2002
	Lack of Skill	Insufficient Knowledge	Sun et al. 2008
		Inadequate Training.	Alistair et al.2006
		The Decision to Proceed Work in An Unsafe Condition	Rodrigues et al. 2015
		Lack of Experience	Suraji et al. 2001

	Shaping Factors	Example Direct Causes	References
	Fatigue	Physical or Physiological Stress.	Zou & Zhang 2009
		Inadequate Physical Capability.	Alistair et al.2006
		Ergonomic Problems in The Workplace	Mitropoulos et al. 2005
		Overtime	Linda et al. 2003
		Tight Contract Schedule	Mitropoulos et al. 2005
	Supervision	Failure to Monitor Labors	Zou & Zhang 2009
		Failure to Secure	Lee et al. 2012
		Insufficient Experience	Toole 2002
		Inadequate Ratio of Workers to Supervisors	Sun et al. 2008
		Failure to Identify Hazard /Risk	Rodrigues et al. 2015
	Housekeeping	Over Crowding	Spilllane et al. 2011
Site layout	Housekeeping	Overstaffing	Mecca 1999
		Lack of Fall Protection	Reiman & Pietikäinen 2012
		Overlapping of Trades	Fortunato et al. 2012
	Unsafe condition	Hazardous Environment	Hallowell et al.2013
		Inadequate Information Jobsite	Suraji et al. 2001
	Location	Improper Location for The Task	Fortunato et al. 2012
		Improper Position of a Crane Near the Temporary Facility	Khaled & Ahmed 2005
		Worker’s Exposure to Extreme Weather Condition	Lee et al. 2012

Shaping Factors		Example Direct Causes	References
		Improper Location for Storage of Hazardous Materials	Khaled & Ahmed 2005
Equip. and Material	Equipment design / Specification	Equipment Failure	Alistair et al.2006
		Excessive Wear and Tear	Alistair et al.2006
		Defective Equipment	Alistair et al.2006
	Material Suitability / Availability	Hazardous Materials	Hallowell et al.2013
Management	Safety Practice/ Procedure	Inadequate Work Standards	Sun et al. 2008
		Inadequate Monitoring	Brown et al. 2000
		Inadequate Guards or Barriers	Reiman & Pietikäinen 2012
		Unclear Emergency Procedures	Sun et al. 2008
		Failure Safety Equipment	Zou & Zhang 2009

2.4. How Does Schedule Pressure Effect the Safety of Site?

Scheduling can also have a major impact on worksite OHS concerns, as outlined in the literature. Applying the most appropriate method of safety risk management is essential then, to reduce schedule delays in a construction project (Lam & Siwingwa, 2017). Delays or overruns during a construction project can be caused by change orders, work-place injuries, poor site management, and improper project design scope or error analysis (Sacks, Rozenfeld, & Rosenfeld, 2009). Additional factors that can lead to project delays have been identified by Larsen et al. (2016) and are the main reason to prepare an appropriate contingency plan when beginning a project. A study by Mitropoulos, Abdelhamid, and Howell (2005), found that delays could increase the pressure on the workers, causing them to ignore safety protocols or cut corners. More safety also resulted when effectiveness of the worksite supervisor was decreased as a result of increasing the number of workers (Han et al., 2014). Safety concerns can also occur from too many task interactions (Hallowell et al. 2011) or increasing worksite congestion by trying to perform different tasks simultaneously, which leads to more incidences of equipment hitting workers (Zhang et al. 2015). A study by Guo et al. (2018) found that after a project delay, site managers were more likely to lower safety protocols, increasing the possibility of hazards for the workers. For fall hazards, utilizing a control model project schedule in addition to safety monitoring, allowed researchers to pinpoint the most likely location for falls (Navon and Kolton 2006). Additional efforts were made by Yi and Langford (2006) and Wang et al. (2006) to use historical data of worksite accidents to predict the time and location safety concerns would arise. In 2007, a four-dimensional model for construction safety planning was designed by Sooyoung and Fernanda (2017) they incorporated the time and spatial information of the site, along with safety data.

The algorithm adaptive multiple objective differential evolution, proposed by Tran and Long (2018), provides an improved approach for project scheduling with TCT that increases the rate of overall project success. Another noteworthy approach is discussed in a study by Webb et al. (2015), who proposed that using crash project scheduling could result in more safety concerns as measured by the number of injuries or near misses at the site caused by acceleration scheduling. In addition, research by Leigh (2011) suggested that the increased cost related to workplace accidents could be lowered by utilizing health and safety programs in the field of construction. This includes a reduction in the following:

- The project delays that result from stopping work due to accident investigation.
- The cost of replacing and training new workers.
- The damage or loss of workplace equipment.

In general, the indirect costs related to workplace estimates could easily be 2.7x the cost of using preventative measures or better safety protocols (Leigh 2011). Overall, the added pressure of a compressed schedule can place undue physical or mental stress on workers as they struggle to reduce the time it takes to perform tasks. Specifically, using crash scheduling can lead to:

- An increased number of on-site incidents.
- A decrease in worker fitness.
- The implementation of additional safety measures may further increase project time and cost.

The research discussed outlines acceleration planning where the activity cost is only related to the direct cost of accident prevention, as a result of considering safety limitations in the early stages of project planning, before an accident occurs.

2.5. Streamlined Project TCT Optimization Methodology:

In Chapter 6 of this thesis, the streamlined project TCT optimization tool was implemented, which is created by Nasiri and Lu (2019), in this regard, the optimization tool is comprehensively explained in this section. The User's guide of the optimization tool is presented in the Appendix A.

For an activity in a project, multiple alternative modes of execution can be planned, with each mode being associated with a distinct direct cost and duration. Hence, this would potentially result in an exponential explosion of possible combinations in fixing activity modes and determining the lowest cost for a project of practical size and complexity. Despite a significant body of research on TCT optimization methods, TCT has yet to be incorporated in mainstream scheduling software or to be part of project management practice in the real world. As the solution model is more oriented toward exact mathematical optimization, the amount of effort in model formulation along with required computing resource and time in search of solutions would multiply at the expense of model's practical applicability. In practice, applying exact optimization methods can be too complex and practically infeasible for planners and schedulers (Bettemir and Birgönül, 2016); the expertise or time required to implement exact TCT optimization algorithms is generally unavailable to a project team (Moussourakis and Haksever 2004). This partly accounts for why TCT optimization is conceptually appealing but not commonly applied in the real world, resulting in missed opportunities for improving project time and cost performances. Therefore, achieving a balance between optimality versus practicality in connection with TCT optimization methodology is an immediate research need in construction project management.

Heuristic methods, mathematical programming, and evolutionary-algorithms-based methods are the three main categories of solutions for TCT optimization (Ammar 2020; Hegazy 2002; Jiang and Zhu 2010). Heuristics apply simple rules of thumb in optimization (Hegazy 2002), require fewer computing resources than mathematical programming (Liu et al. 1995) and provide fast and reasonable solutions for small and medium sized projects (Menesi et al. 2013). However, heuristics lack mathematical rigor and do not guarantee optimum solution (Hegazy 2002). Mathematical programming can obtain the optimal solution (Ammar,2020) but requires complex formulation [e.g. Zou et al. (2016)] and its solution time would increase exponentially as the problem size increases (Moussourakis and Haksever 2004), limiting applicability to small projects. Evolutionary algorithms are systematic optimization search procedures that mimic natural evolution phenomenon. Such methods can be robust in finding solutions (Menesi et al. 2013). However, evolutionary algorithms generally ignore the inherent structure of time-cost trade-off (Jiang and Zhu 2010); in tackling large scale problems, the optimization time can be non-deterministic (Menesi et al. 2013) while reaching the optimal solution is not analytically guaranteed (Hegazy 2002). In addition, all three categories of TCT solutions normally require repeated use of classic critical path method (CPM) – which entails professional project scheduling software such as Primavera P6 or MS Project.

In short, there is a lack of cost-effective computing methods to enable the TCT optimization analysis on projects of practical size and complexity in the real world, let alone adding safety to the TCT problem.

2.6. Algorithm Description

The presented algorithm is based on curvilinear activity time-cost relationship*,* which represents the most general form of continuous activity time-cost relationship. To handle curvilinear activity time-cost relationships, each activity's time-cost curve is approximated by straight lines for all practical purposes (Ahuja et al. 1994). Each line represents one time-unit, i.e. day or hour (Figure 1). Linear and multilinear time-cost curves are special cases of curvilinear and can be handled as well. The proposed algorithm can handle both convex (increasing cost slope) and concave (decreasing cost slope) or a combination.

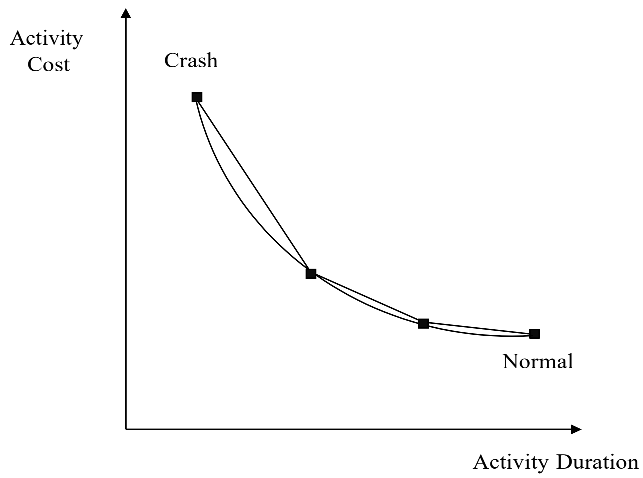

Figure 1. Approximation of curvilinear activity time-cost curve (Nasiri, S. (2019). Integer-Programming-Assisted Path-Float-Based Method for Time-Cost Tradeoff Optimization in Project Planning.)

Figure 2 shows the flowchart of the proposed algorithm, consisting of two main parts. The first part is to find all possible paths from start to finish in the AON network. The routing technique presented by Fratta and Montanari (1975) is embedded for path identification in the project network model. The second part is the iterative cycles. In each cycle, the algorithm provides a feasible solution with new shortened project duration and its corresponding minimized total cost.

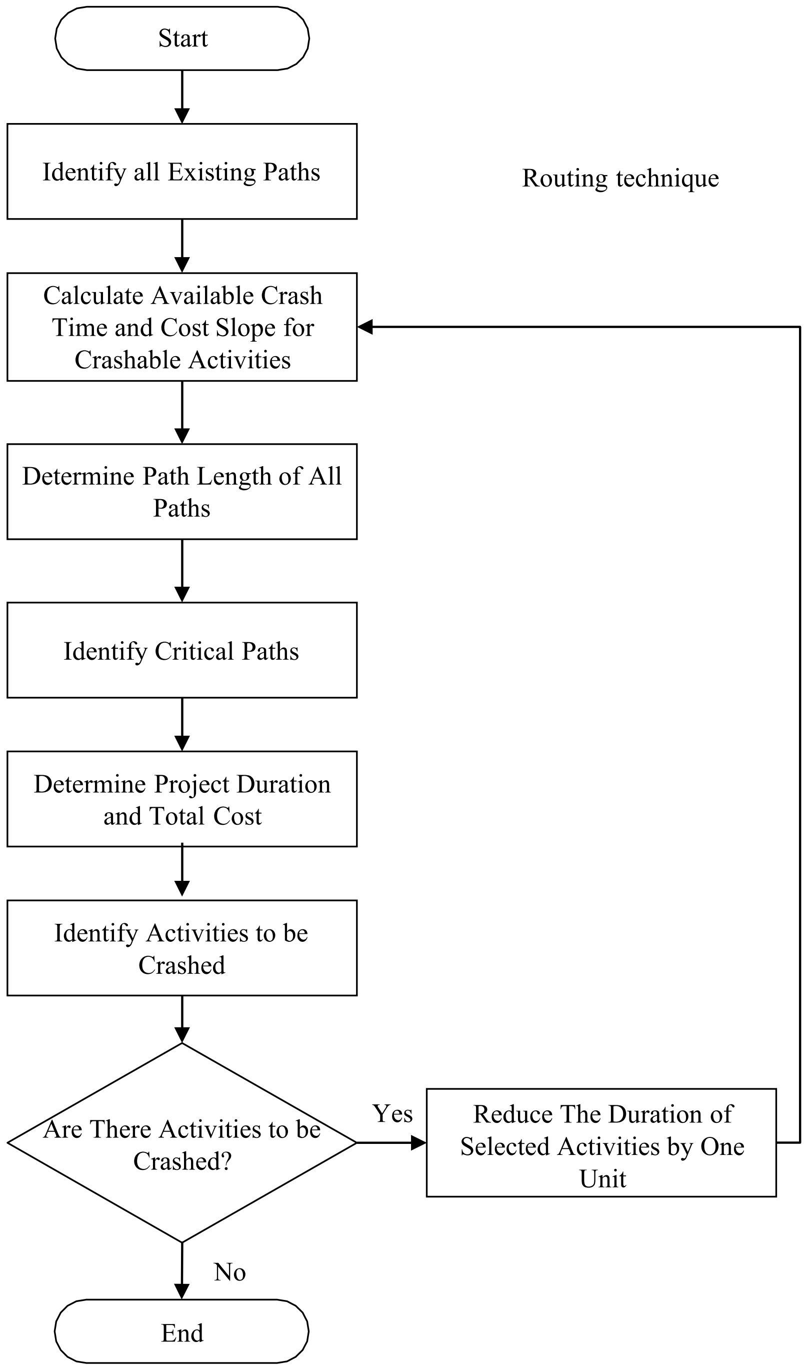

Figure 2. TCT algorithm flowchart (Nasiri, S. (2019). Integer-Programming-Assisted Path-Float-Based Method for Time-Cost Tradeoff Optimization in Project Planning.)

Figure 3 represents a conceptual project-level time-cost curve, generated by the proposed new algorithm. Indirect cost for the project is generally linearly increasing with project duration (constant cost slope); direct cost for the project generally increases in a linear curve (increasing cost slope) as project duration is shortened. The total cost is to combine the direct cost and indirect cost, which generally decreases as project duration is shortened, then it reaches the point with zero slope (i.e. the lowest total project cost solution) before gradually increasing as the project duration is further shortened until reaching the shortest limit (the shortest project duration solution).

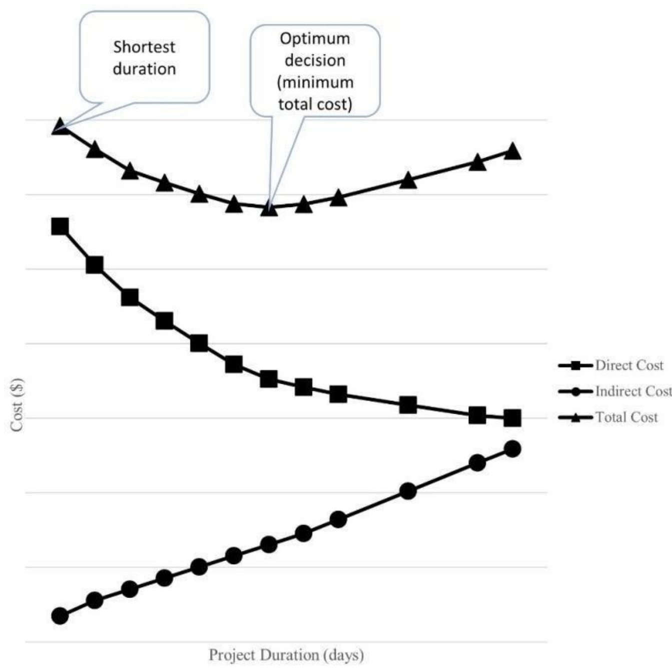

Figure 3. Conceptual project-level time-cost curve

An Excel program was developed by Nasiri (2020) to automate the proposed algorithm. Program description and user guideline are presented in Appendix A.

CHAPTER 3: APPLICATION FRAMEWORK FOR SAFETY-CENTRIC CONSTRUCTION ACCELERATION PLANNING.

The framework discussed in the following chapter outlines steps project managers can take to reduce construction hazards associated with project scheduling.

3.1. Introduction

While models do exist that combine project scheduling with safety management, they do not consider the costs related to hazard mitigation (Pereira et al.,2018). The TCT methods currently utilized may also fail to relate the consequences of crash scheduling to OHS impacts for workers throughout the entirety of the construction project (Mahdavian et al.,2020). By building upon the established models discussed, this thesis aims to develop a model of acceleration planning that addresses these shortcomings by including safety concerns in TCT analysis for the cost and duration of a project. The hypothesis proposed in this thesis is that, if a project schedule is compressed, additional safety measures must be implemented ahead of time; as a result, the overall project cost and duration may increase. The overall result is an increase in the cost slope of schedule crashing when safety concerns have not been successful addressed for cost-time predictions. In the following paragraph, these concepts are explained in further detail.

An activity-on-node (AON) in a method of precedence diagramming in which logical relations and activities regarding safety are assigned boxes or nodes depending on the methods of prevention and specified rules, in order to develop a construction plan. In the case of a ‘normal scenario’, more time is needed to finish an activity, and includes the methods normally used with an average rate of crew production. In the case of a ‘crash scenario’ less time is needed to finish an activity, resulting in higher project costs compared to a normal scenario. Acceleration planning of the normal scenario is often used to generate the crash scenario. The framework outlined in this thesis can be applied to both the normal and crash scenarios but is intended specifically for the crash scenario.

In Figure 4, a graphical representation is provided of factoring in safety to time-cost activities. The solid lines that connect ‘Crash’ to ‘Normal’ and then ‘Safety-Centric Crash’, demonstrate the shift in the activity cost slope that occur when safety protocols are applied to the acceleration planning process on a construction project. In contrast, the dotted line from ‘Crash’ to ‘Safety-Centric’ leads to an increase in both project duration and project cost.

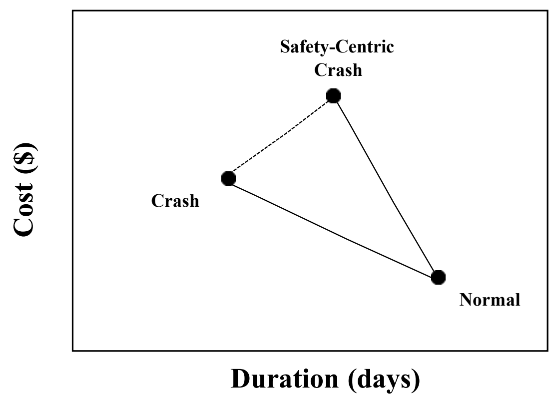

Figure 4. Activity time-cost relationship by factoring safety

In this chapter, the framework for a ‘safety-centric’ form of acceleration planning for use on construction projects is outlined and discussed.

3.2. Development of Framework

As seen in Figure 5, the first step in the framework involves the identification of the factors that shape on-site accidents and safety issues in construction related activities. An extensive literature review of industry best practices, accident causes, and government regulations can be used to identify these shaping factors. Afterwards, rules related to these shaping factors are defined in order to properly utilized TCT analysis features and acceleration planning for a construction project.

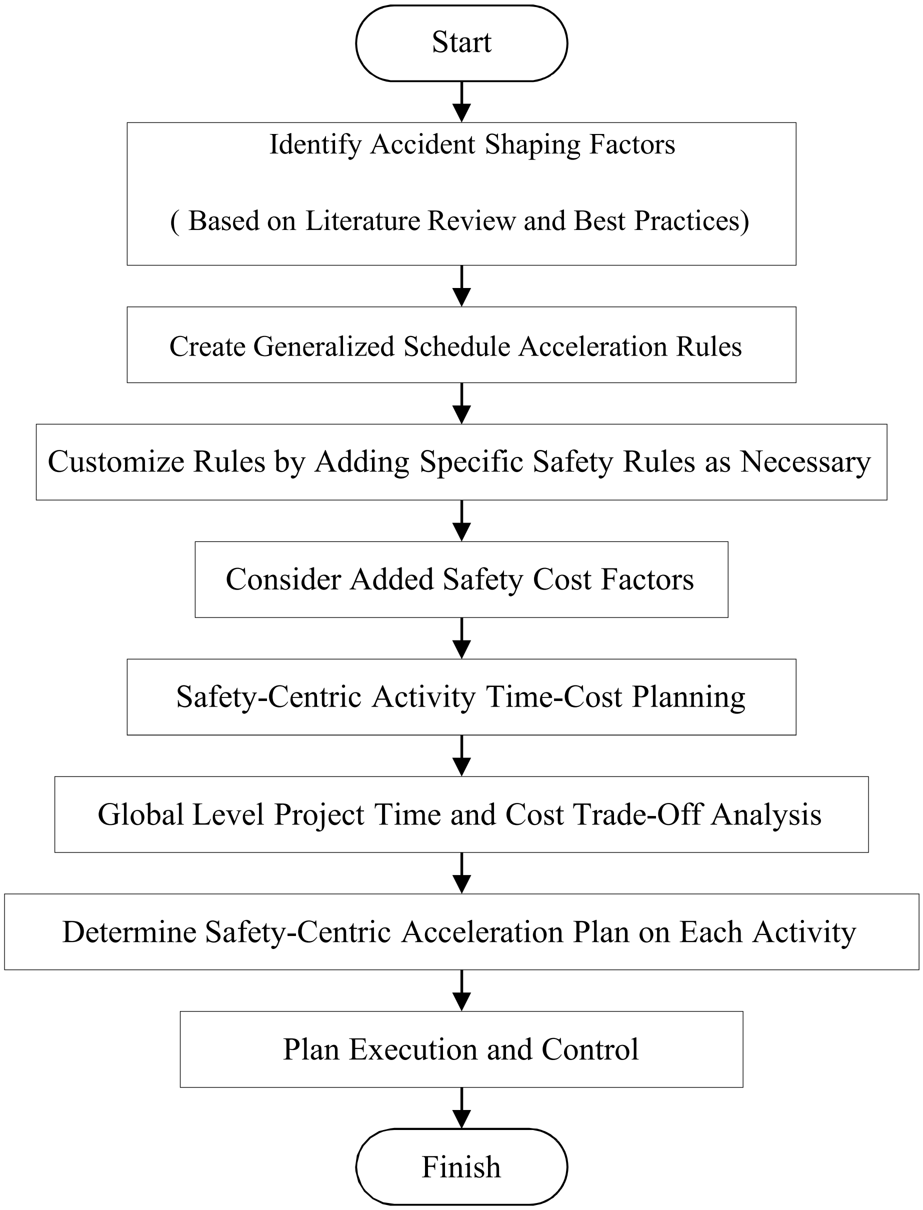

Figure 5. Methodology Flowchart for the proposed framework

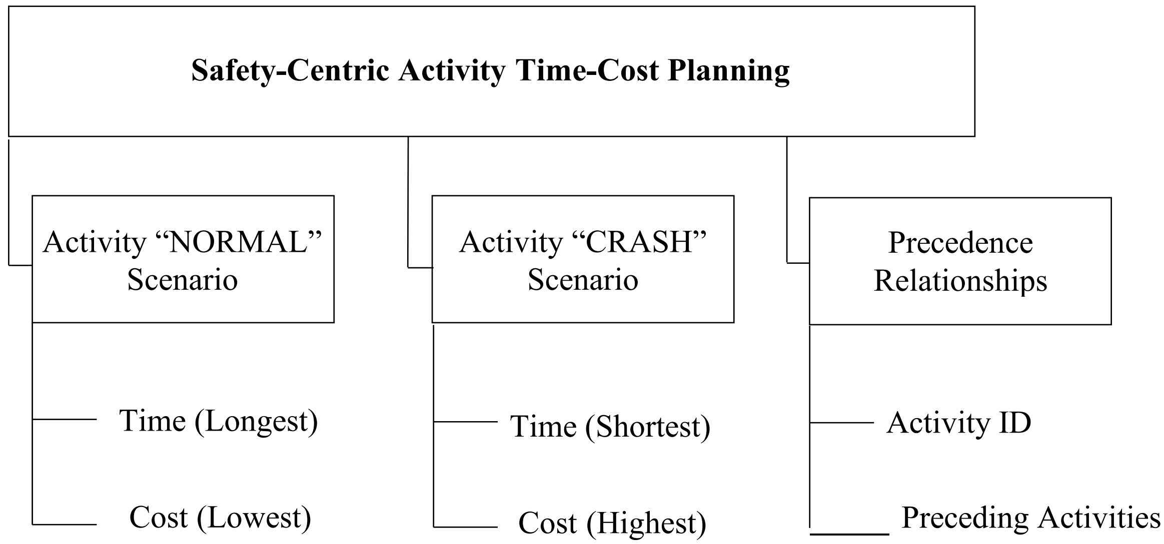

Figure 6**.** Clarification on Step 5 of the flowchart

The intention of Figure 6 is to show how to prepare activity time cost data and define precedence relationships in order to (1) fix the Shortest Project Duration Attainable by applying project scheduling analysis and (2) conduct the ensuing global project time-cost tradeoff optimization analysis. The goal for Figure 7 is how to fix the best positions on each activity's cost slope in global project time-cost tradeoff optimization analysis.

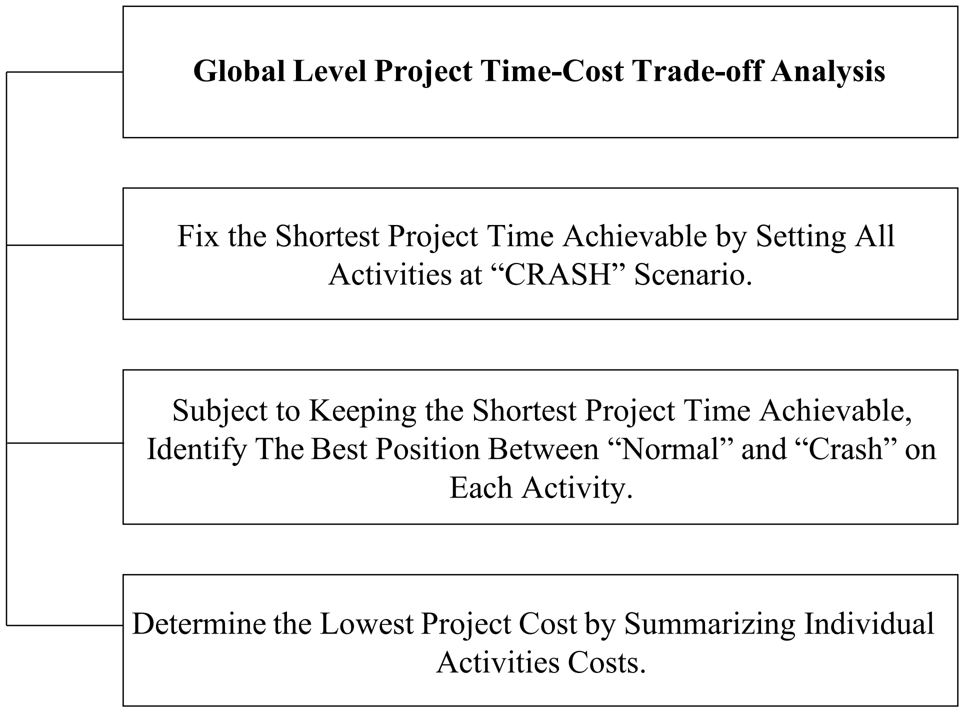

Figure 7. Clarification on Step 6: how to fix the best positions on each activity's cost slope in globalproject time-cost tradeoff optimization analysis

To elaborate on the two main steps of the methodology, Figure 6. And 7 are presented above. This problem definition is relatively similar to the classic project TCT optimization. However, the objective is to meet a more sophisticated goal: determining the lowest feasible cost that lead to the shortest project duration attainable by considering all crash activity scenarios being planned based on the proposed safety-centric construction acceleration planning framework. It is worth mentioning an explicit constraint is imposed to reach this objective, namely: to maintain the shortest project time attainable. Ultimately, the proposed methodology delivers an activity time-cost plan that achieves the shortest project time while resulting in the lowest project cost in terms of aggregated individual activity costs. With the safety sufficiently factored in the activity time-cost tradeoff planning (introducing shaping factors, acceleration rules, and cost factors), the final plan delivered simultaneously satisfies project time, cost, and safety objectives.

Furthermore, to arrive at an optimally crashed project schedule at the global level, it is not necessary to crash each individual activity to its extreme. Only selected activities need to be crashed to meet the optimization objectives in terms of project cost or project duration. As a result, the cost of multiple activities would not necessarily change from the 'Normal' scenario, and only some activities would entail implementation of the'Crash' scenario. In this way, both the desired project safety and cost objectives can be achieved in realization of the shortest project time attainable.

A study by Mahdavian et al. (2020), discusses the shaping factors they identified following a literature review and confirmation of industry regulations, and the related rules. While this is not an all-inclusive list, it does provide a foundation from which to begin any practical applications. In relation to construction acceleration planning, these shaping factors can be divided into 4 sperate categories of site layout, equipment and materials, management, and workers (Gibb et al, 2006). These categories can be used to aid the shaping factor identification as outlined in step one.

After establishing these shaping factors, rules related to each shaping factor are established for the purpose of engaging in TCT analysis and acceleration planning of a construction project. Any proposed steps in the planning process need to consider the relevant safety factors and their related rules, in addition to the resulting increases in project overhead and direct costs at that particular activity level. As an example, looking at COVID-19 specific parameters, accelerating specific construction activities may require providing workers with the appropriate PPE for the accelerated tasks. Additionally, the number of workers per m^2 work area on-site also increases. This higher worker density means physical distances may not be possible, and more expensive N95 masks may be necessary in order adhere to industry and government standards for COVID-19 prevention. Project overhead may also increase due to the additional safety inspectors and site supervisors needed to accommodate the greater number of on-site workers. As another example, if additional cranes need to be operated simultaneously as a result of acceleration planning, the potential for accidents increases and additional monitoring needs to be performed round the clock. The technology itself, and the related labor costs, all add to the overhead costs of the project. In Appendix 1, the safety related cost items for acceleration planning are listed. As before, this list is not all-inclusive, but meant to provide a foundation for future applications.

After acceleration planning is performed for activities at the local level, a global analysis is performed for the project duration and cost. This is needed in order to select which activities to apply crash scheduling to, while still adhering to reasonable project duration and the project's cost objectives.

3.3. Guideline for Automated TCT Excel Program

In this thesis, the TCT optimization method and tool developed by Sasan Nasiri through an MSc thesis is chosen due to its simplicity and effectiveness and hence applied to solve the core problem defined in my research. The application procedure is presented in the following paragraphs, based on my own user experience and applications needs.

3.3.1. Introduction to the Automation Tool:

A Microsoft Excel program for automation and streamlining of TCT optimization is designed to assist in the generally cumbersome and time-consuming TCT modeling and analysis. The program is based on the path-based iterative TCT algorithm reviewed in Section 2.2, which considerably improves the computational efficiency of TCT by breaking down the problem into smaller pieces, thus significantly reducing the number of combinatorial options to be assessed. Furthermore, the path-based approach enables the user to avoid the traditional CPM recalculation for each option and only requires minimal updates in each iteration. The iterative nature of the method provides a feasible solution in each cycle. In light of the methodology's advantages against existing TCT methods, the program can handle large-sized practical networks.

The program assumes each activity's time-cost relationship is curvilinear (the most general case). Thus, if any of the activities has linear or multilinear time-cost relationships, the program is able to handle them easily.

Program inputs include:

- Each activity definition along with its predecessors, sufficient to represent the AON project model.

- Normal, crash, plus any intermediate options in terms of durations and costs for each activity.

- Time-dependent project indirect cost.

The program consists of two main parts:

The initialization: based on the precedence relationships, the program will use the routing technique from graph theory to identify all existing paths in the AON network, from start to finish node.

The iterative cycles: The integer-programming algorithm is coded in Excel to reduce the project's duration in the most cost-effective manner in each cycle, which is automatically performed. Furthermore, activity data (costs and durations) and path lengths are automatically updated in each iteration. It must be noted that for mathematical optimization, Solver, a free add-in of Excel, is used.

The cycles are repeated until no solution can be found to further shorten project duration, and the algorithm is terminated. In the end, a list of valuable information is provided for the user:

- Project duration, direct cost, indirect cost, and total cost for each cycle.

- Activities that were selected to be crashed in each cycle.
- Path lengths in each cycle.
- The minimum project cost and its corresponding project duration.
- The minimum project duration and its corresponding minimum project cost.

3.3.2. Application Guideline based on the Proposed Planning Methodology:

To elaborate on the Figures 6 and 7, the application guideline is divided to two major steps, A and B. Step A is about "Safety Centric Activity Time Cost Planning" with the intention of finding the shortest possible project duration and Step B is about "Global Level Project Time-Cost Tradeoff Analysis". This is done by fixing the shortest project time achievable by setting all the activities at crash scenario. Subject to keeping the shortest project time achievable the best position between normal and crash on each activity is identified. Then, the lowest project cost is determined by summarizing individual activities costs.

In this section, required steps to apply the program are elaborated using a small case study. The AON network and activity time-cost data are given in Figure 8 and Table 2 , respectively.

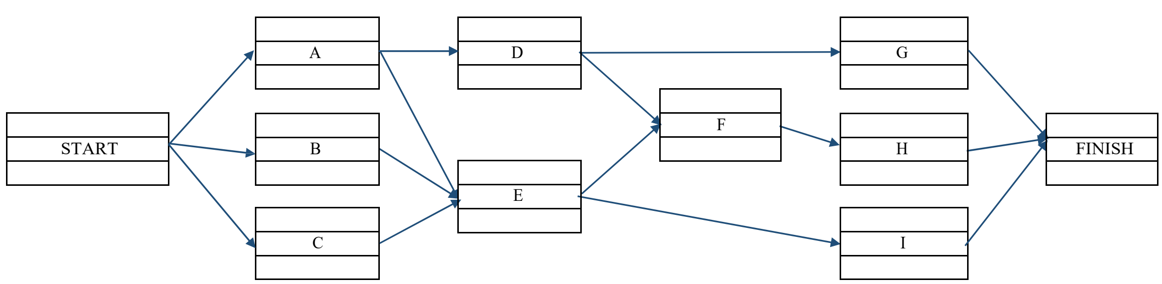

Figure 8. Project Activity on Node

Table 2. Activity duration and cost data

Activity	Normal		Crash		Cost Slope	Crash Available Time
	Duration(d)	Cost ($)	Duration(d)	Cost ($)	($/day)	
A	5	550	3	750	100	2
B	4	400	1	550	50	3
C	2	300	1	400	100	1
D	1	100	1	100	0	0
E	5	450	3	600	75	2
F	3	250	1	400	75	2
G	2	150	1	250	100	1
H	3	400	2	500	100	1
I	4	500	2	600	50	2
	Total	3100	Total	4150		

As previously mentioned, step A is finding the shortest possible duration attainable for the project. Each activity has its possible crashing options defined independently, including the number of crashing options and the cost slopes. Under normal cases on each activity, the total project time and cost were determined to be 16 days and $3100 by applying any professional project management system (e.g. Primavera P6.) It is assumed the total project duration of 16 days exceeds the owner's requirement and needs to be crashed. The proposed solution is to enter all the shortest-possible activity duration for each activity of the project; by running P6, the total project duration is shortened to 10 days at the total cost of $4150. Obviously, the significant budget increase against the baseline budget (34%) is deemed too high by the owner; as such, the new project plan would be unacceptable. Step B is to identify the best position between "normal" and "crash" on each activity, subject to keeping the shortest project time achievable. By implementing the project time-cost tradeoff optimization method proposed by Nasiri and

Lu (2019), the same 10 days project duration is obtained but the total project cost reduces to $3220, which represents a considerable cost saving of $930 (22%) against the solution from P6 in Step A ($4150).

3.3.3. Path finding excel sheet (initialization):

<u>Part 1, finding all the possible paths in the project AON network model:</u>

First, press “Enter AON Data”, and the program asks how many activities are in the AON Including START and FINISH dummy activities (milestones), as shown in figure 9.

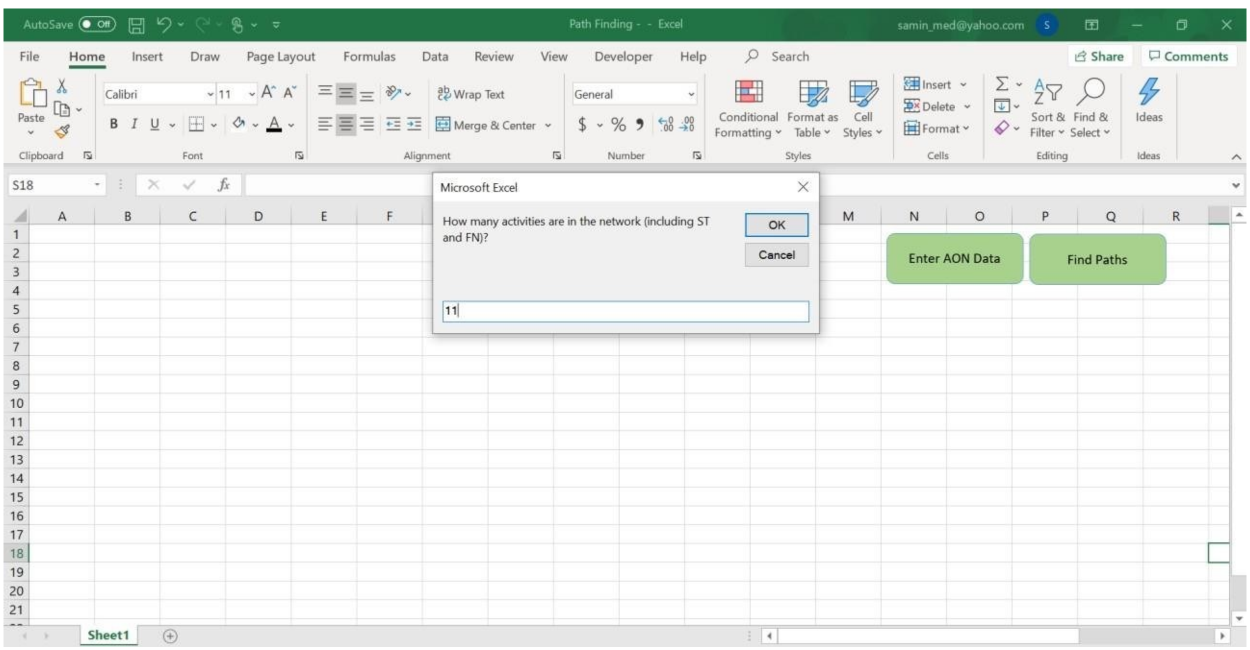

Figure 9. Entering number of activities in a project

Then, user must specify the successors of each activity. If Activity 2 is Activity 1’s successor we put 1 in the spreadsheet table defining precedence relationship constraints, and if it is not, we put 0. Completed succeeding activities’ table is presented below.

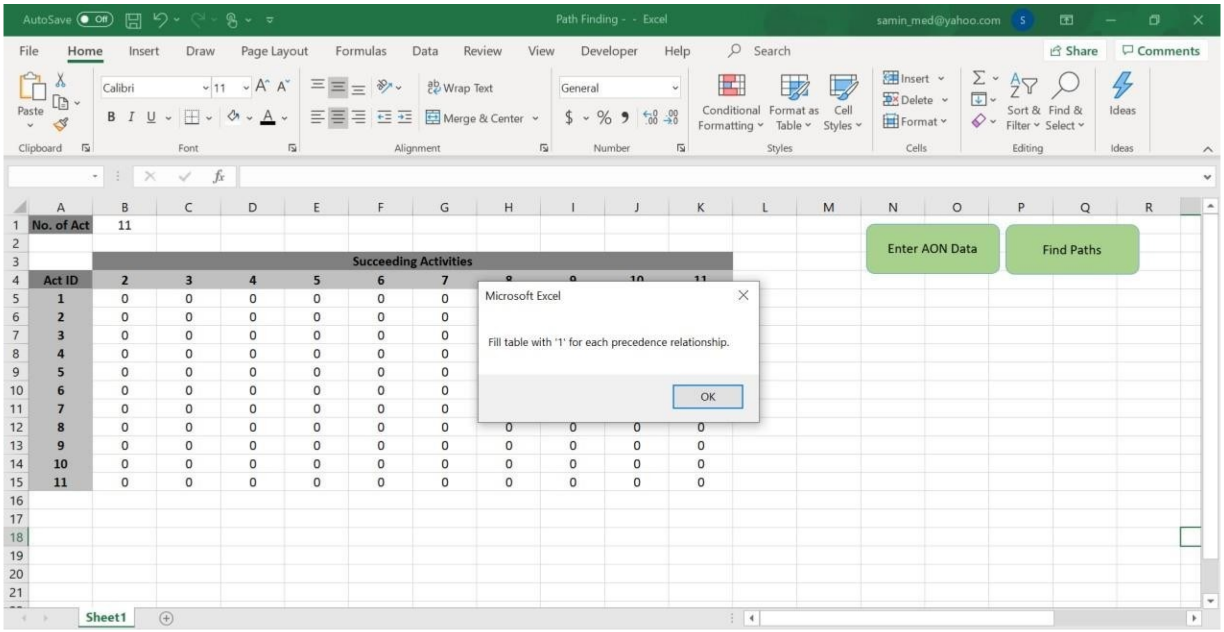

Figure 10. Defining successor activities

Table 3. Successor activities for case study

	Succeeding Activities									
Act ID	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1 (ST)	1	1	1	0	0	0	0	0	0	0
2 (A)	0	0	0	1	1	0	0	0	0	0
3 (B)	0	0	0	0	1	0	0	0	0	0
4 (C)	0	0	0	0	1	0	0	0	0	0
5 (D)	0	0	0	0	0	1	1	0	0	0
6 (E)	0	0	0	0	0	1	0	0	1	0
7 (F)	0	0	0	0	0	0	0	1	0	0
8 (G)	0	0	0	0	0	0	0	0	0	1
9 (H)	0	0	0	0	0	0	0	0	0	1
10 (I)	0	0	0	0	0	0	0	0	0	1
11 (FN)	0	0	0	0	0	0	0	0	0	0

After succeeding activities table is filled, press **Find Paths** to generate path descriptions.

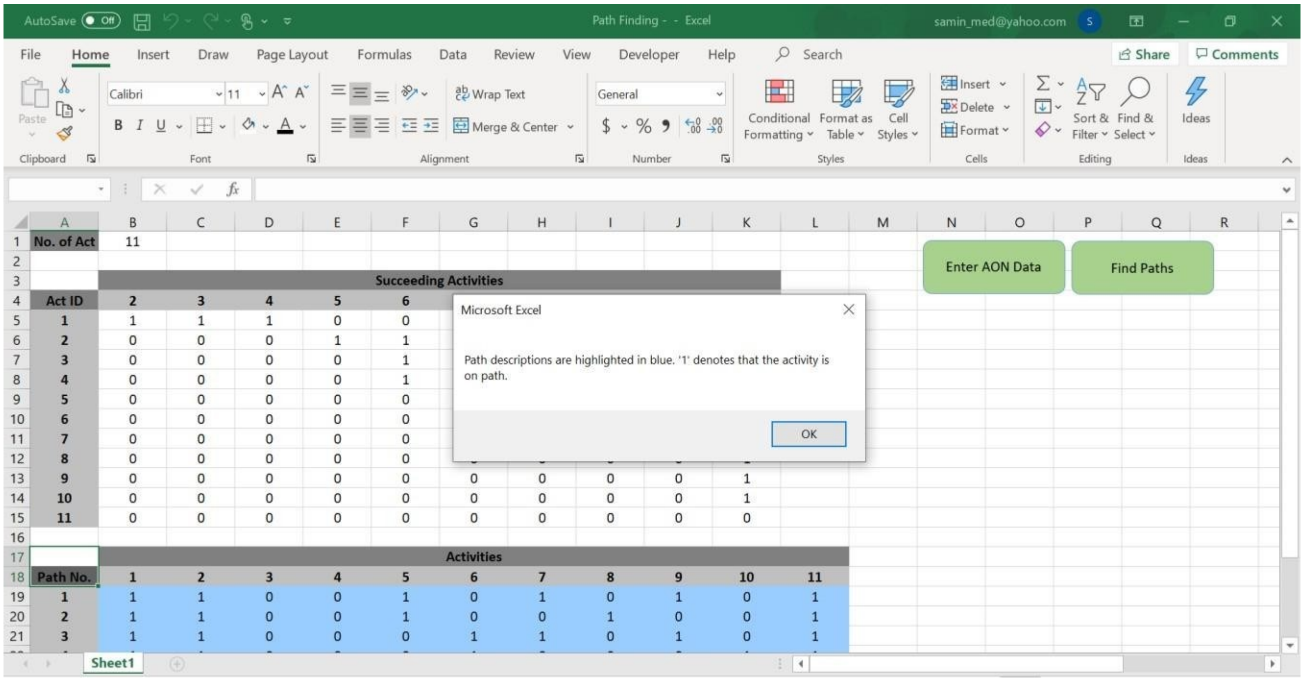

Figure 11. Generating path definitions

Table 4. shows all existing paths from start to finish in the case study.

Table 4. Generated paths for case study.

Path No.	**Activities**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	1	1	0	0	1	0	1	0	1	0	1
2	1	1	0	0	1	0	0	1	0	0	1
3	1	1	0	0	0	1	1	0	1	0	1
4	1	1	0	0	0	1	0	0	0	1	1
5	1	0	1	0	0	1	1	0	1	0	1
6	1	0	1	0	0	1	0	0	0	1	1
7	1	0	0	1	0	1	1	0	1	0	1

Path No.	Activities										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
8	1	0	0	1	0	1	0	0	0	1	1

<u>Part 2. TCT Excel Sheet (Iterative Cycles):</u>

First, press "Enter Data" button. The program will ask:

The number of activities including start and finish.

The number of existing paths in the project AON model, which is obtained in part 1.

- Initial total direct cost denotes the sum of direct costs of all activities under normal settings.

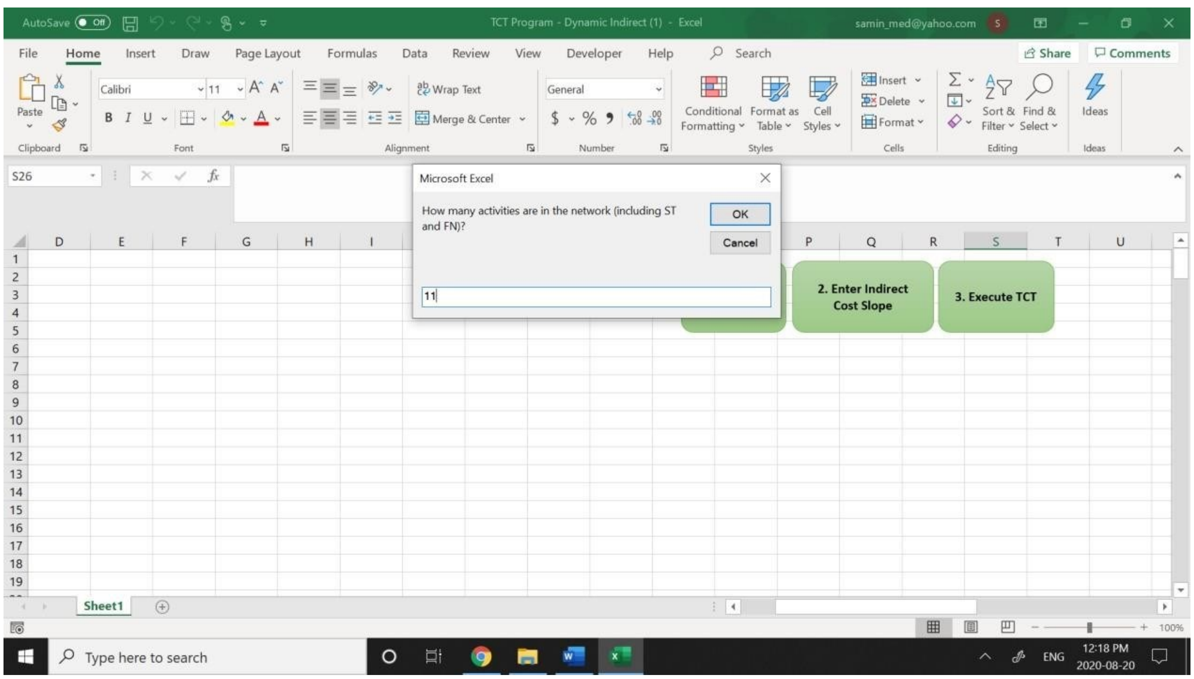

Figure 12. Entering number of activities

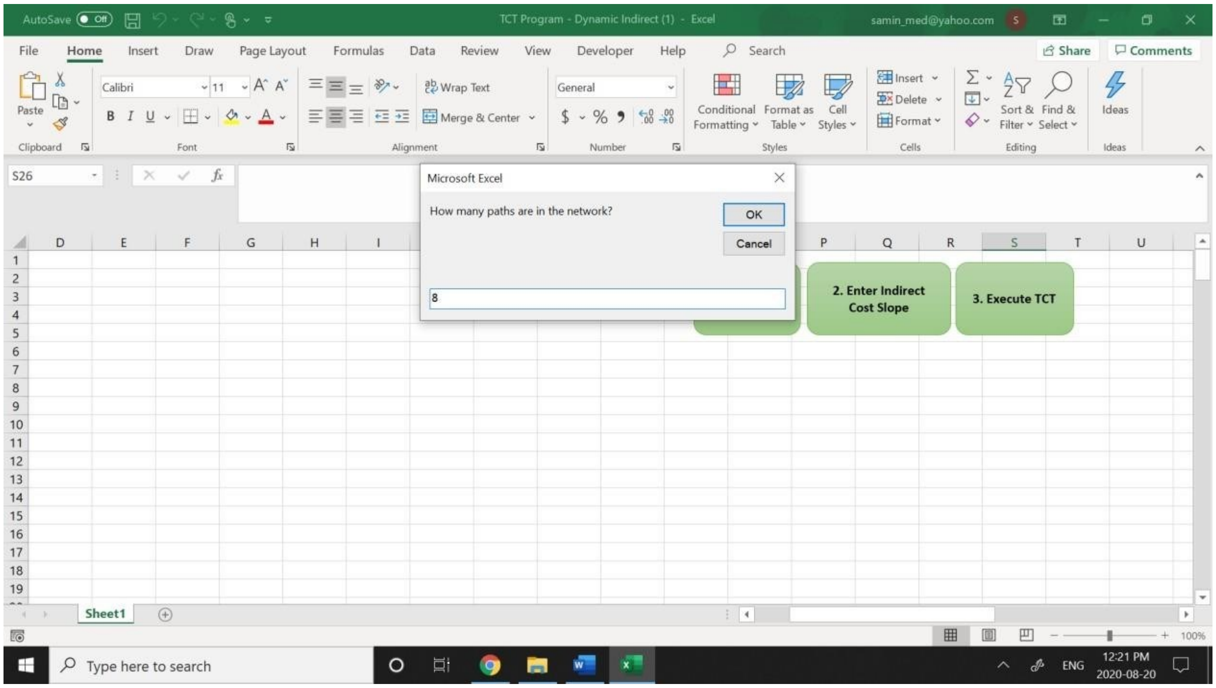

Figure 13. Entering number of existing paths

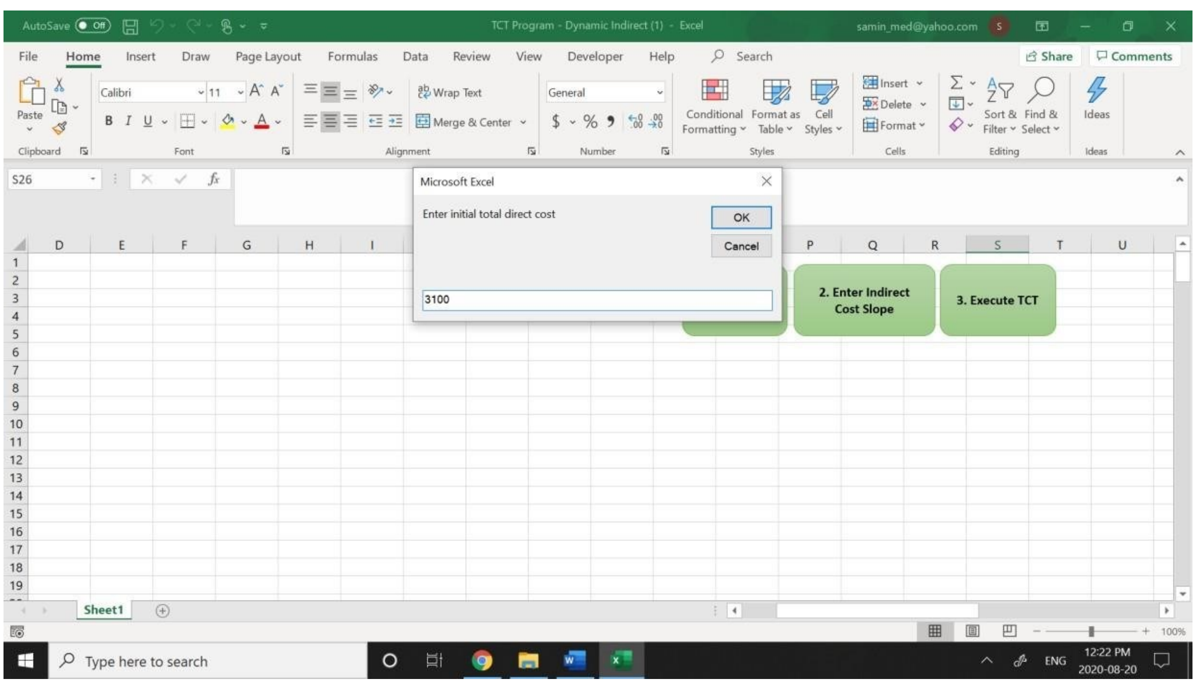

Figure 14. Entering total initial direct cost

Afterwards, three columns of the table in Figure 15 should be entered by user to define activity crashing data including:

Initial AC: initial available crash days for each activity

Norm Dur: normal duration of each activity

S: Direct cost slope of each activity.

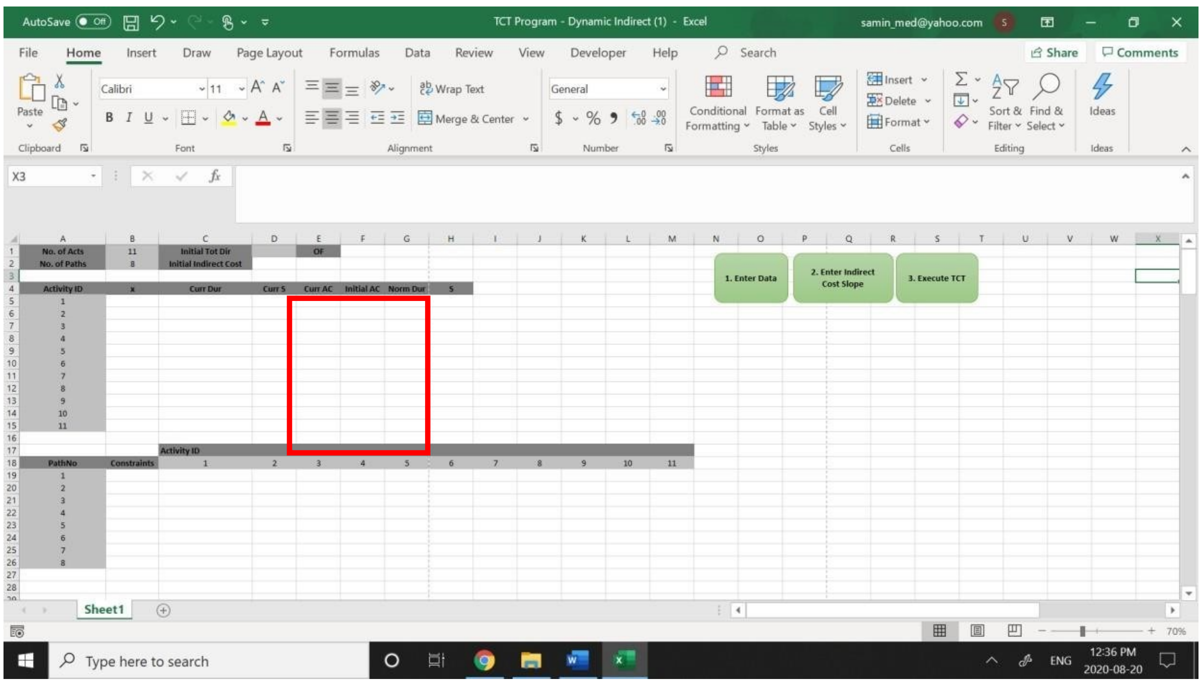

Figure 15. Entering activity cost and duration data

Note that, for each available crash time unit, a direct cost slope must be defined. For instance, if an activity has three available crash time units, one needs to enter the direct cost slope for each of the crashing steps, from left to right, for as many as needed. To better illustrate, take the activity time-cost relationship presented in Figure 16 and note how it is entered in the program.

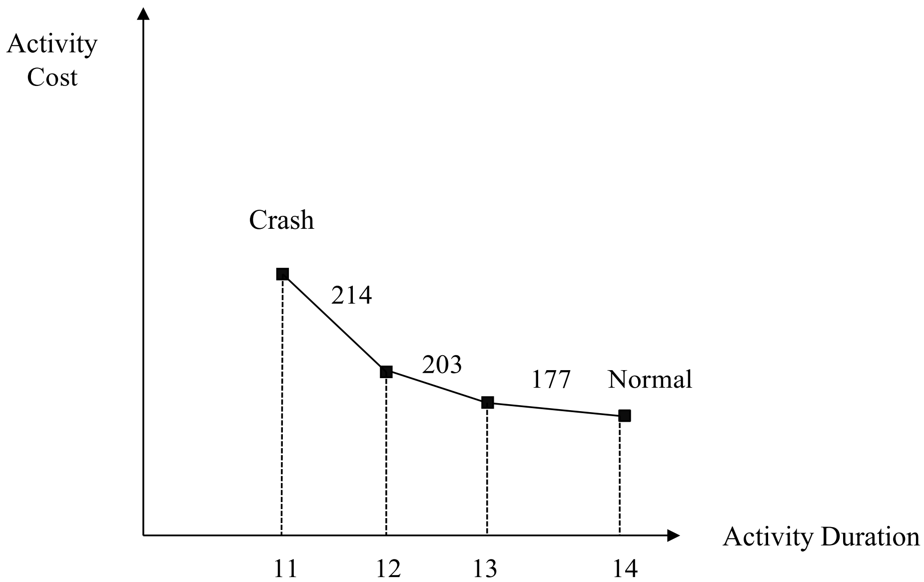

Figure 16. Sample activity time-cost relationship

Activity ID	x	Curr Dur	Curr S	Curr AC	Initial AC	Norm Dur	S		
1					0	0			
2					0	20			
3					2	13	185	203	
4					3	16	186	272	203
5					3	14	177	203	214

Figure 17. Entering time and cost data for the activity presented in Table 2.

Subsequently, the second table should be filled by copy-pasting the path descriptions obtained from **path finding** Excel sheet.

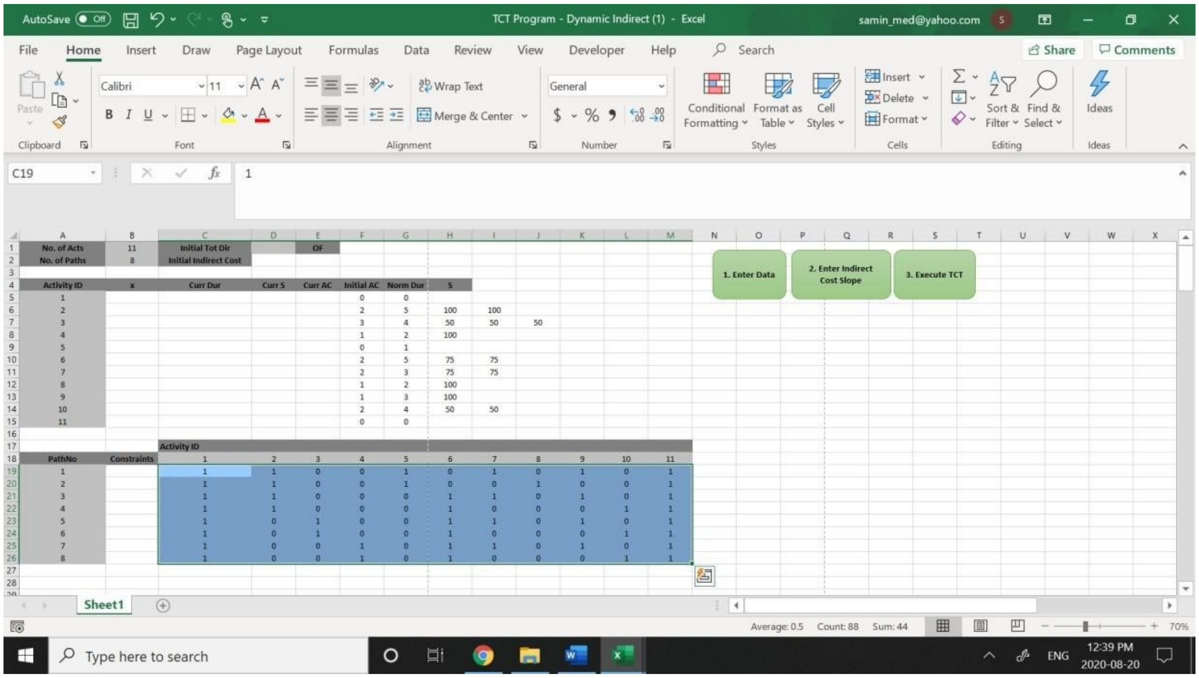

Figure 18. Copying path descriptions from part 1

Afterwards, click **Enter Indirect Cost Slope**. The program will give the initial project duration under normal settings for all activities (Figure 18) and ask the initial indirect cost (indirect cost corresponding to initial project duration) of the project.

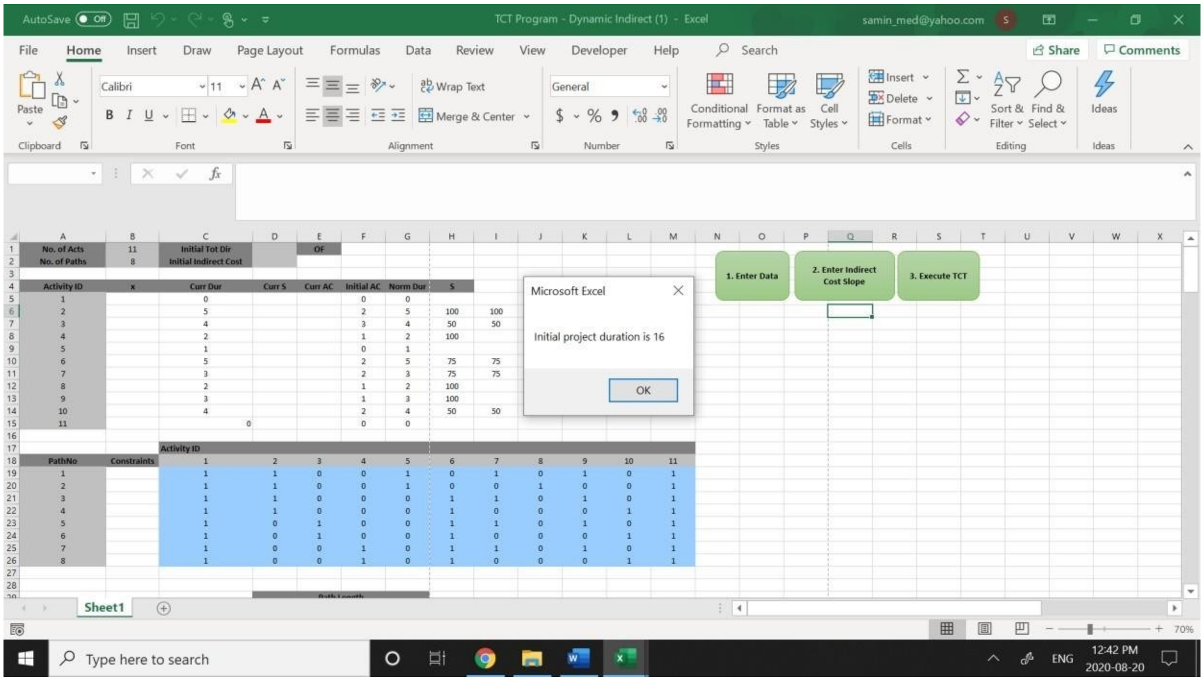

Figure 19. Recording initial project duration (i.e. under normal settings)

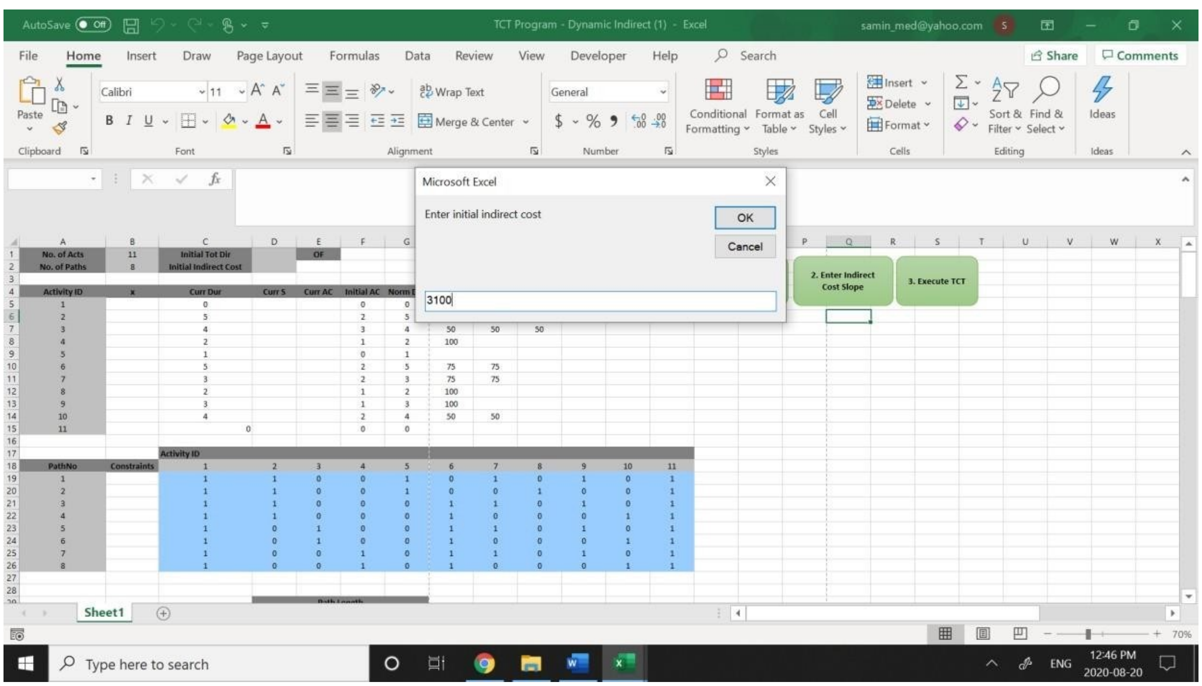

Figure 20. Entering initial project indirect cost

Now, for each project duration, enter the indirect cost slope as illustrated in Fig 20. Note that, depending on the project, we may have a constant or dynamic (changing) indirect cost slope. The designed program can handle both cases. In this small case study, we have a dynamic indirect cost slope that we must enter for each cycle.

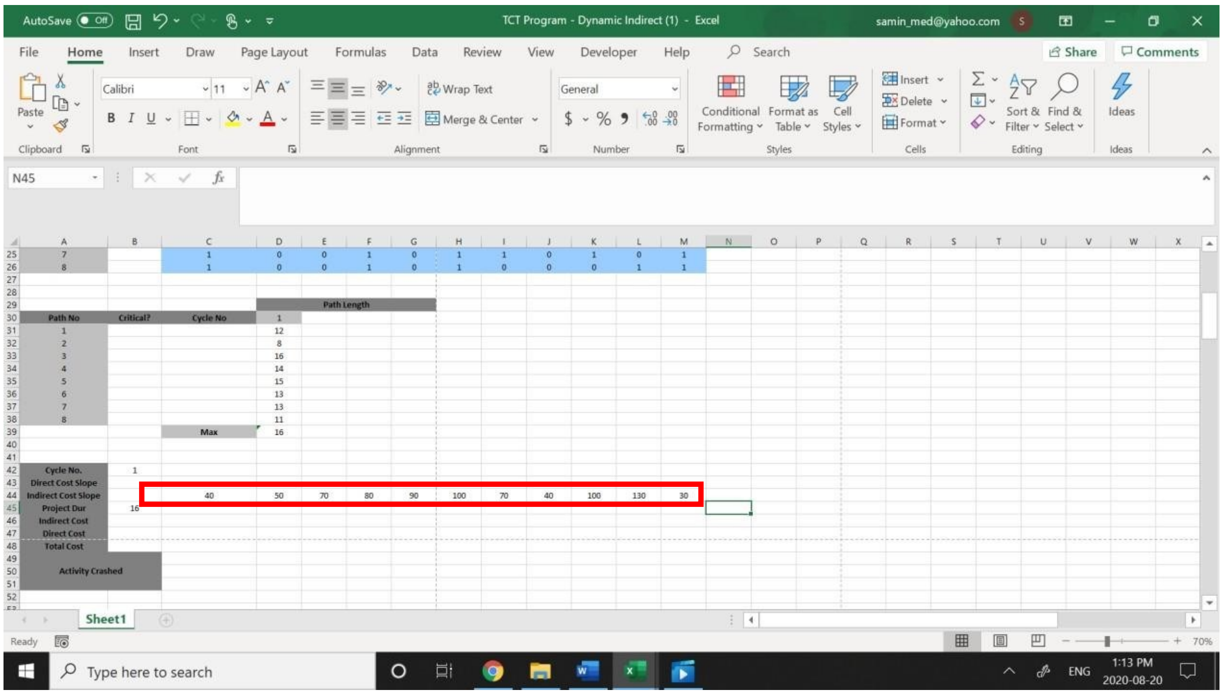

Figure 21. Entering dynamic indirect cost slope for case study

Finally, press “Execute TCT” to generate final results. Figure 22 shows the generated resultsincluding:

- Various project durations with their corresponding minimum total costs.
- Total direct cost slope in each cycle.
- Crashed activities in each cycle. Note that all activities are crashed by 1-time unit in each cycle.
- Overall minimum total cost and its corresponding duration are highlighted in yellow.

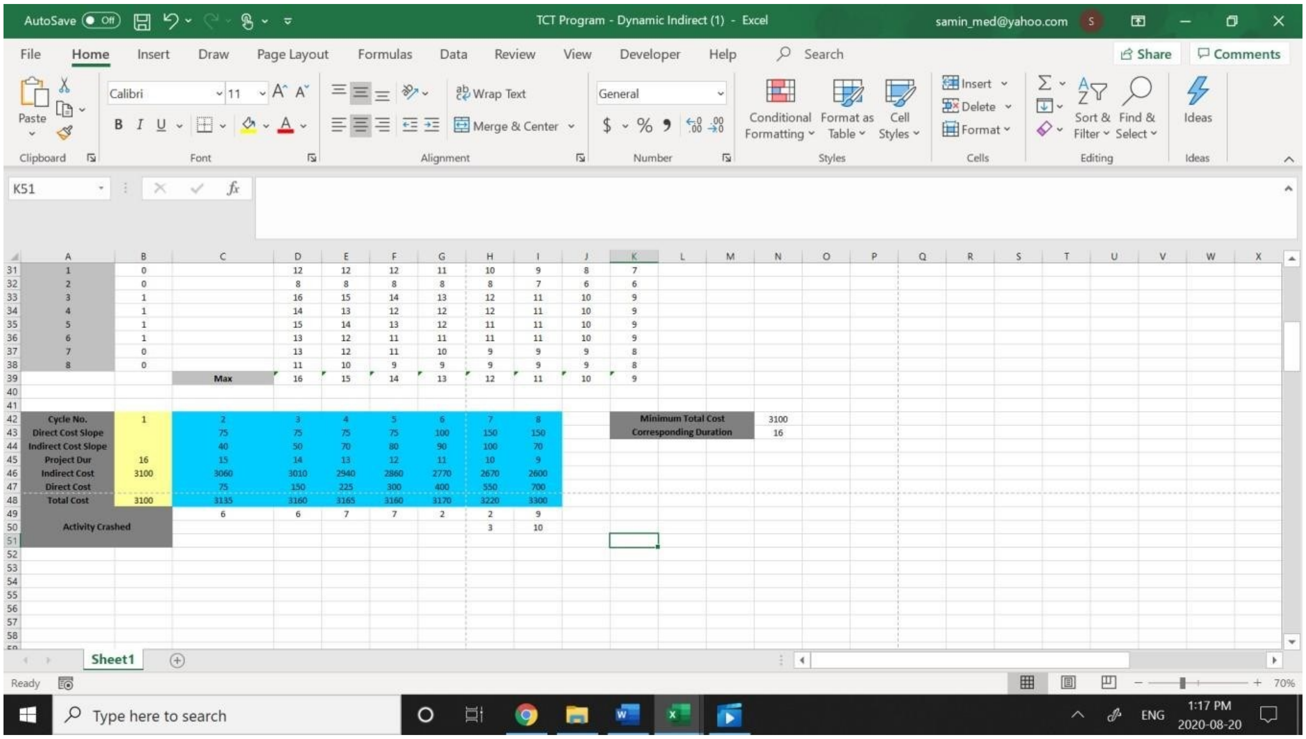

Figure 22. Final results of case study

3.3.4. Program Limitations

It is noteworthy that the Solver's free version (basic solver) is limited to 200 variables and 100 constraints in optimization analysis. As a result, the program may not be able to handle networks with more than 200 activities (depending on the number of activities with available crash time turning critical at the same time), or networks in which the number of simultaneous critical paths are larger than 100. If the problem becomes too large for Solver to handle, an error message will be shown at the end.

The program crashes each activity by one time-unit (i.e. day or hour, depending on user's definition) and handles non-integer available crash times for activities. However, available crash time of less than 1 time-unit is considered as non-crashable. For example, if an activity has 1.8 of available crash time, it can be crashed by 1 time-unit, but the remaining 0.8 is considered as non-crashable.

To ensure that the problem has been properly defined for Solver, it is recommended to check the following:

Check the objective function (set objective) is not empty.

Ensure that the variable cells are defined.

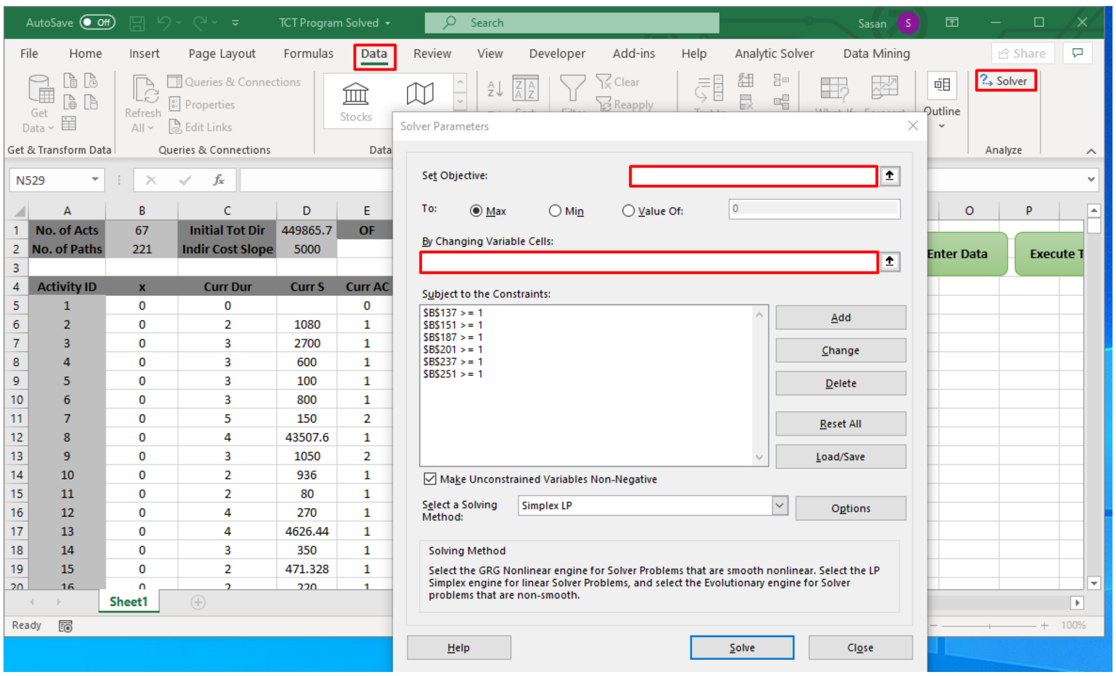

Figure 23. Final check to ensure proper definition of problem in Solver

CHAPTER 4: GENERALIZED SAFETY RULES AND COST FACTORS FOR ACCELERATION PLANNING

In the following chapter, generalized safety rules and cost factors for acceleration planning in connection with the proposed framework are summarized and discussed in further detail.

4.1. Generalized rules for safety centric TCT

The goals of a TCT analysis are to decrease the project duration and the amount of time needed for critical activities. As a result, the number of safety risks may increase from the normal scenario, along with the number of workplace hazards. Due to the dynamic nature of the construction site environment, acceleration planning may fail to account for all the safety issues that may arise during the course of a construction project. The project schedule then, needs to adequately define potential hazards. For the purpose of this thesis, 15 interviews were conducted based on the shaping factors outlined in Table 1. Construction managers who had at least 10-15 years of experience were chosen for the interviews. From these, a list of rules was outlined related to the identified accident shaping factors, for the purpose of TCT analysis and acceleration planning. This list can be seen in Table 5.

Table 5. Generalized safety rules for acceleration planning. (Partially from Mahdavian et al.2020)

No	Shaping Factors	Generalized safety rules for acceleration planning
1	**Site Layout**	Assure that there are appropriate, sufficient vehicle traffic control (flashing lights, Barriers, Warning signs, Lane control device).
2		Ensure that Entrances, Walkways and Stairways are free from obstructions that may restrict their movement.

No	Shaping Factors	Generalized safety rules for acceleration planning
3		Double check facilities like security fences, access roads, storage areas of material and equipment are located at proper place.
4		Monitor position of multiple cranes.
5		Ensure there is no fall object hazards due to parallel activities being performed on top of each other.
6		Ensure there is adequate space around equipment and heavy equipment is on a stable foundation to prevent.
7		Ensure to have an Emergency response plan identifying exit paths, muster points.
8		Cover or guard all the openings on the floor.
9		Ensure that appropriate fall protection systems (perimeter screens/scaffold, guardrails or barriers) are in place around the floor before working at heights.
10		Ensure that work area is even and free from rubbish and slippery agents such as water, grease/oil, snow, etc.
11		Test the atmosphere of confined spaces (Oxygen content between 19.5% and 23%).
12		Identify the amount of toxic, flammable or explosive substance that may be present.
13		Introduce physical barriers and signboards to prevent unauthorized persons form entering the formwork area.
14	**Equip. & Material**	Monitor the number and type of equipment in a work site.
15		Assure employees well known about all hazardous chemicals in the work site.
16		Ensure all the equipment are regularly serviced and maintained according to the manufacturer's instructions.
17		Whenever practicable use mechanical aids such as carts, hand trucks and dollies to move and place large and heavy loads.
18		Have materials placed at the working level and readily accessible to the leading edge.
19		when pushing and pulling are involved, (1) push rather than pull, (2) avoid overloading, (3) ensure the load doesn't block vision and (4) never push one load and pull another at the same time.

No	Shaping Factors	Generalized safety rules for acceleration planning
20	Use of Forklift	Ensure the work areas are continuedly tidy and free of obstructions that may prevent save movement of materials and people.
21		Complete the pre-shift inspection to make sure brake, backup alarm, horn, seatbelt and light are operational.
22		When needed, add proximity sensing and warning devices to avoid collision between cranes.
23		Observe safe operating speeds for conditions.
24		Use smooth and safe turning techniques.
25		Travel in reverse if carrying a load that obstructs forward vision.
26		Keep the load high enough to avoid fetching up on inclines or uneven surfaces. Mast(tilt) the load back as soon as possible after picking up.
27		The parking brake must be set before the operator leaves. If the operator is more than 7.5 m away from the forklift or out of direct sight of it, the engine must be shut off.
28	Use of Crane	All lifting gear such as slings, hooks, shackles, material boxes, straps and lugs should be inspected for damage and wear before lifting.
29		Tag lines should be used to guide, and control suspended loads. Areas beneath suspended loads should be clear of persons.
30		Areas in the vicinity of materials or loads being moved should be clear of persons when moving long materials such as joists, bearers, planks and frames to prevent striking persons nearby.
31		Use the platform to sling materials. The platform should be at least 450 mm wide and have edge protections. There should be a safe means of access to the platform for persons to access the platform. Ladders may be used, and they should be secured at the top to prevent movement.
32	**Worker**	Ensure that workers have sufficient breaks during a shift or between shifts.
33		Review the ratio of number of workers over supervisors.
34		Ensure all workers are utilizing proper PPE for required task.

No	Shaping Factors	Generalized safety rules for acceleration planning
35		Ensure equipment operators being qualified or skilled.
36		Ensure workers are encouraged to identify unsafe conditions.
37	**Management**	Ensure that subcontractors are applying safety procedures.
38		At the right time, Add a safety restraint system instead of the safety arrest system.
39		Employers provide safeguards that eliminate contact by workers with hazards.
40		Ensure proper utilization of labels, signs, floor marking to warn employees about potential hazards.
41		Ensure safety meetings held on a regular basis to address safety performance with field supervisors or foreman.
42		Ensure there is regular inspections on jobsite.
43		Avoid overcrowding by checking the number of workers in a work site.
44		Ensure that OHS policy signed and dated by director/manager.
45		Ensure that OHS roles and responsibilities are allocated and signed.
46		Assure that hazards are identified, and risks are assessed continually.
47		Ensure that periodic workplace inspection checklists are completed.

4.2. Added Cost Factors

The rules outlined in Table 5 require appropriate mitigation strategies, each with associated increases in project overhead or direct cost. These costs include:

- Costs related to additional safety protocols required for accident mitigation. As discussed in the previous example, if additional workers are needed during the COVID-19 pandemic, additional PPE may be required. And as the number of workers on-site increases, physical distancing may no longer be an option, necessitating the more expensive N95 masks. These masks would be necessary in order to meet government or industry standards. The end result is increase in safety-related overhead to account for the additional workers. This overhead may go to adding on-site supervisors or other preventative measures.

- Cost related to additional accident probability. Outlined in the previous section, employing additional equipment like cranes for example, raises the probability of accident occurrence. This results in additional costs for monitoring through more site supervisors or monitoring technology.

These two types of costs must be factored into acceleration planning to provide a safety centric TCT analysis. A summary of these costs is outlined in Table 6.

Table 6. Safety cost factors for safety centric TCT (Partially from Mahdavian et al.2020)

No	Cost Factors
	Protect workers and public from the hazards of site and open excavation:
1	Fencing around the site
2	Standard warning signs
3	Safety tapes
	Protect workers from falls into floor openings, hoist areas and slab edges (Fall Protection):
4	Guardrails
5	Covering with Timbers
6	Safety Nets
7	Safety Tapes
	Prevent workers or public to enter the working radius of cranes, hoists, etc:
8	Fences (hard barrier)
9	Safety Tapes (soft barrier)
	Prevention of tile breaks, fall from edge, fall from skylights:
10	Slide guards on the roof

No	Cost Factors
11	Timbers on skylights
12	Roof ladders
	First Aid and Fire Protection:
13	Fire Protection Tools
14	First Aid Kits
	Personal Protective Equipment (PPE):
15	Face Mask (N95)
16	Equipment driver PPE
17	Excavation Worker PPE
18	Formwork Worker PPE
19	Iron Worker PPE
20	Concrete Worker PPE
21	Roof Worker PPE
22	Bricklayer PPE
23	Painter/Plaster PPE
24	Electrician PPE
25	Mechanics, Plumber PPE
26	Floor Jobs Worker PPE
27	Welder PPE
28	Unskilled PPE
29	Door-Window installation PPE (including screening & pre-approval)
	General Management Prevention programs:
30	Subcontractor management
31	Upper management support (hazard identification & reporting program)
32	Regular Safety Meetings (safety meetings & shift pre-job meetings)
33	Inspections
34	Safety manager
35	Substance abuse programmes

No	Cost Factors
36	Written plan
37	Committees
38	Site Orientation and training
39	Record keeping
40	Emergency response plan
	General Management Prevention programs:
41	Training
42	Breaks
43	Preparation of technical reports
44	Studies of working conditions, questionnaires, workshops, etc.
45	Near-miss reporting and investigation
46	Visits by risk prevention service technical staff
47	Heavy-equipment inspection and approval program
48	Heavy/critical lift plans
49	Behavior based safety program
50	Constructability Review and Action Follow Up
51	Construction Human Factors Analysis
52	Construction Execution risk Assessment

CHAPTER 5: CASE STUDIES FOR ACTIVITY ACCELERATION PLANNING

In the following chapter, the model framework outlined in the previous chapters will be applied to 2 case studies and 1 global project, in order to illustrate its functionality for acceleration planning. In the first case study, the construction of a limited section of a commercial building is planned to use the model framework. For the second case study, an experienced construction manager in the field of road construction and maintenance utilizes the proposed model for the purpose planning the grinding and paving portions of a road rehabilitation project. Finally, the model framework is applied to a global level, 100-activity project, in order to conduct a TCT analysis. The resulting schedule planning allowed for 1, acceleration planning to be performed without drastic increases in project costs or sacrificing the safety of individual activities; 2, the creation of individualized plans for each activity and the associated crash time and activity costs.

5.1. Case 1: Commercial Building Construction

In the following section, the model is utilized for the first case study, the construction of a commercial building. The scope of the project includes the foundation, structure, mechanical and electrical finishes, site construction, and proofing roofing and wood. In Figure 24, the work breakdown structure (WBS) for this case study is outlined. Critical activities are divided into sub-activities, for a cumulative number of 83 different project specific activities.

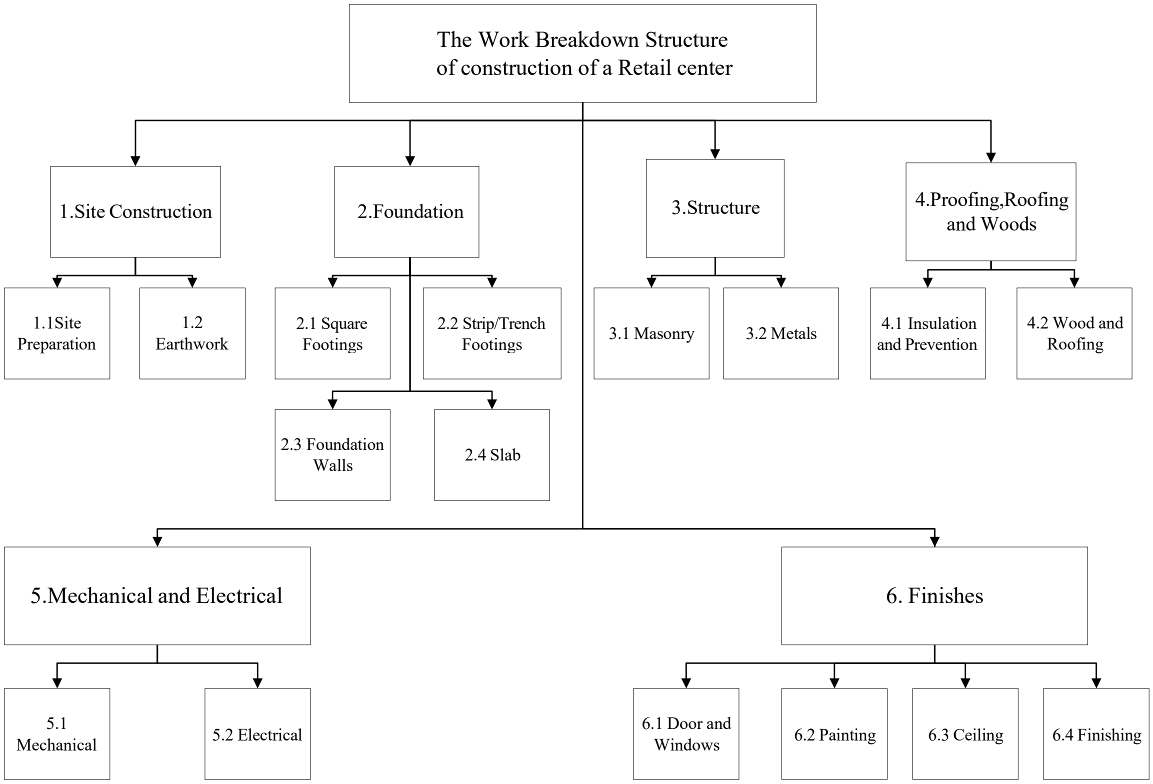

Figure 24. Work Breakdown Structure for case study of the construction of a commercial building

In step one, an AON network for acceleration planning of the project is developed, prior to including safety concerns. For this purpose, the model focused on Activity 4.2 (wood and roofing), due to size limitations. Activity 4.2 is separated into 6 sub-categories of activities, as shown in Table 7.

Table 7. Wood and roofing sub-activities in case study

ID	Activity Name
4.2.1	Installation of Roof Wood Trusses
4.2.2	Installation of Roof Plywood Boards
4.2.3	Installation of Roof Deck
4.2.4	T&G Wood Siding
4.2.5	Trim for Roof and Walls
4.2.6	Installation of Wood Studs for Interior Walls

In order to highlight a safety-centric approach for acceleration planning of a construction project, activity 4.2.1 (installation of roof wood trusses) was selected. The project planner can then assign 4 safety-related activities (S1, S2, S3, S4) to the AON network, based on the accident shaping factors and their related rules specific to the project. For this case study, the accident shaping factors were related to site layout (trips, slips, and falls, working around moving objects), workers (insufficient training for crew members), and equipment and materials (collision between cranes).

To accomplish Activity 4.2.1, 9 days are needed, and 1 crew comprised of a crane, equipment operator, and 4 carpenters. To apply crash scheduling, a second crew is needed. The addition of a crew brings the time needed to 5 days, but increases on-site congestion, leading to a 10% productivity loss. Hence, the crash duration will be reduced to 5 days (i.e. 27,000/ (2*3000*0.9)) instead of 4.5 days. The roof in particular becomes increasingly crowded due to the addition of 5 more crew members. As a result, there is an increase in congestion related hazards (slips, falls, and trips). To give an example, more congestion increases the likelihood that crew members can bump into each other, or trip on another crew members belongings. Employing a second crew also adds a second crane into operation, increase the risk of equipment crashes. Operators of the original crane are now also at a higher risk of hazard exposure due to the additional crane.

If further safety measures are employed, the overall production rate decreases due to work constraints. Now the number of days needed to complete the project rises from 5 to 6, after accounting for the related accident shaping factors and safter rules. Using safety-centric crash scheduling leads to an overall reduction in activity duration but raises the cost. The cost of Activity 4.2.1 in the normal scenario, prior to crash scheduling, is estimated at $77,108.40. The addition of a second crew in the crashed scenario results in direct costs of $79,496. In the case of a safety-centric crash, there are additional costs related to hazard prevention, as seen in Table 8. Increases related to direct cost include additional materials needed to prevent hazards such as sensors and a safety net, and the additional labor (carpenter). When factoring in safety measures related to equipment, material, and labor, the final total direct cost would be $104,775.2

Given the imposed safety hazards, additional mitigation measures must be undertaken: (All the cost are obtained from RS Means and the most updated typical industry cost in Canada)

a. According to Alberta OHS (Section 67, 2018), proximity sensing and warning devices must be installed to avoid collision between cranes.

Alert lighting systems sensor measurement proximity device: $877 × 2 devices = $1752

b. Given the additional risk of falls from the roof, a safety net is to be installed to restrain falls from the roof (OSHA, p. 15, 2015).

Material = 1.59 1.59 ($/Ft^2) * 8150= $ 12,958.5

Labor = 1 Carpenter = $320

c. A safety restraint system (OSHA, 2015) is to be installed instead of the safety arrest system to limit the movement of labourers within a certain area that is not accessible by the other crane. This will protect the workers from the other crane during operation. This system will also provide another level of protection against falls from the roof.

=10 devices * $147 =$1,470

d. Given the newly imposed hazards, additional safety training and supervision must be provided (Alberta Hazard Assessment and Control Handbook, p. 17, 2015).

= 160 hours * 25 $/hour = $4000

Table 8. Safety added cost on Activity 4.2.1 (Installation of Roof Trusses)

Activities to be crashed	**Accident shaping Factor Group**	**Safety Response**	**Cost Estimate**
Installation of Roof Trusses	Site Layout	S1. Add a safety net at a roof top to protect against fall. (OSHA, Page 15,2015)	$13,278.10
	Worker	S2. Provide training and supervision for added crews. (Alberta hazard assessment and control handbook, page 17)	$4,000.00
	Site Layout	S3. Add a safety restraint system instead of the safety arrest system. (Rajendran and Gambatese, 2013)	$1,470
	Equipment and Materials	S4. Add proximity sensing and warning devices to avoid collision between cranes. (Alberta OHS, section 67, 2018)	$1,755.9
		Total Cost	$20,504.00

In conclusion, for Activity 4.2.1 in the first case study, crash scheduling results in an additional crew, leading to an increase in the related accident shaping factors (crane collision, dangers of working around moving objects, slips, falls, and trips). Installing a safety net to project from falls is the first safety activity suggested (S1). The second safety activity (S2) is increasing training and crew supervision. For the third safety activity (S3) a safety restraint system is added in place of the safety arrest system.

Finally, for the fourth safety activity (S4) collision warning devises are added to prevent crane collisions. The final project sub-model at Activity 4.2.1 can be seen in Figure 25.

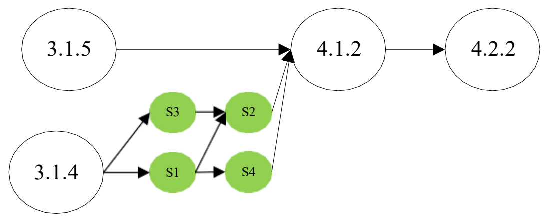

Figure 25. Sub-model of the project network at Activity 4.2.1 updated with additional safety constraints prior to Activity 4.2.1 (installation of roof trusses)

Before crashing, the normal direct cost is \$ 77,108.4, and the indirect cost is \$8,568.72. Adding another crew would increase the direct cost of the activity. The crashing direct cost is calculated as follows.

$$No\ of\ crew \times No\ of\ days \times Daily\ cost + Material\ cost$$
$$= 2 \times 5 \times 2387.6 + 55{,}620 = \$79{,}496$$

For the safety centric crashing scenario, the costs associated with the safety responses are summarized in Table 8. By accounting for safety concerns, the direct cost increases as we have extra material (sensors and safety net) and labor (carpenter) needed to overcome the hazards. In order to calculate the total direct cost, the cost of safety responses is added to the labor, equipment and material cost as follows:

$$Total\ direct\ cost = 20{,}504.1 + 2 \times 6 \times 2387.6 + 55620 = \$104{,}775.2$$

In Table 9 and Figure 26, the total cost and time needed for the 'Normal', 'Crash', and 'Safety-Centric Crash' scenarios are listed. Risk prevention related to crash scheduling raises the project duration and cost related to the activity being crashed. As a result, the direct cost of the 'Safety-Centric Crash' scenario is higher than both the 'Normal' and 'Crash' scenarios.

Table 9. Cost summary of three scenarios - Installation of wood trusses

Normal Scenario		**Crashed Scenario**		**Safety-Centric Crashed Scenario**	
Cost	Duration	Cost	Duration	Cost	Duration
$77,108.40	9 days	$79,496.00	5 days	$104,775. 2	6 days

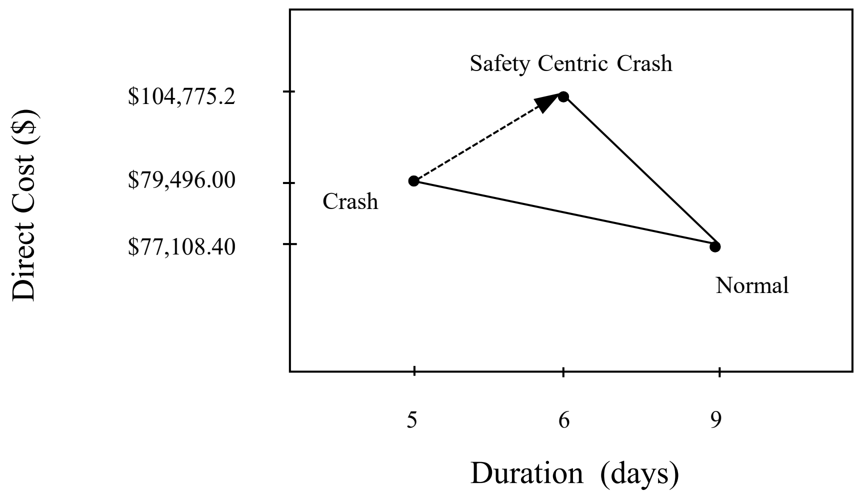

Figure 26. Installation of Roof Wood Trusses – Cost

5.2. Case 2: Urban Road Pavement Rehabilitation

For the second case study, fleet balancing principles are added to the model in order to determine the optimized amount of equipment need for an excavator to function at peak efficiency. The total number of working hours for every piece of equipment can be determined by incorporating the total amount of material handled, and the amount of equipment in the entire system, into simulation modeling. In this way, the total duration of the project can also be determined. In order to validate this framework, the proposed model was applied by an experienced professional in the field of construction managing, in order to develop a plan for the paving and grinding portions of a construction project to repair a city street in Edmonton, Alberta. Due to the practical concerns of this case study, crash scheduling necessitated decreasing the project duration and the length of critical activities. As a result, the number of safety concerns and hazards is greater and in the 'Normal' scenario without crashing.

Work for this construction project can be separated into 2 stages. Firstly, the grinding crew preforms grinding on the required areas. Secondly, the paving crew works in tandem to avoid cold joints. During both stages, the crews are working alongside traffic lanes, increasing safety concerns. A single, high volume lane of traffic is in operation throughout the duration of the project. The actual construction occurs during the night from 9pm – 5am, and clear access needs to be maintained 24/7 for the surrounding businesses.

Accident shaping factors and their related rules specific to this project were selected by the construction manager, and agreed upon by the field crew, including equipment operators and crew supervisors. The selected factors and rules are outlined below:

1. Traffic control for vehicles must be maintained through use of barriers, warning lights and signs, and lane control devices.

2. Locations such as material and equipment storage, security fencing, and access roads must be appropriately placed.

3. Falling object hazards as a result of running activities simultaneously must be accounted for.

4. The worksite must be clean and free of barriers that may impede work or movement.

5. Sufficient time must be allocated for breaks between, or during shifts.

6. The number of workers onsite must be monitored to prevent overcrowding.

7. Workplace inspection checklists must be performed periodically.

The results of applying the proposed framework to acceleration planning of this project can be seen in Figure 27, and validate the original model concept proposed in Figure 27. Taking into account the shaping factors and their related safety rules results in a higher cost slope from the 'Normal' to the 'Crash' scenario. The 'Safety-Centric Crash' scenario, in contrast, has a higher cost and a longer overall project duration. The acceleration plan devised in this thesis robustly incorporates the safety concerns related to crash scheduling, and the steps needed in order to prevent and increase in onsite accidents. Members of the project field staff concluded that the outlined model could be an effective tool to aid members of the construction field such as program coordinators, managers, and field superintendents in identifying and mitigating the hazards related to acceleration planning.

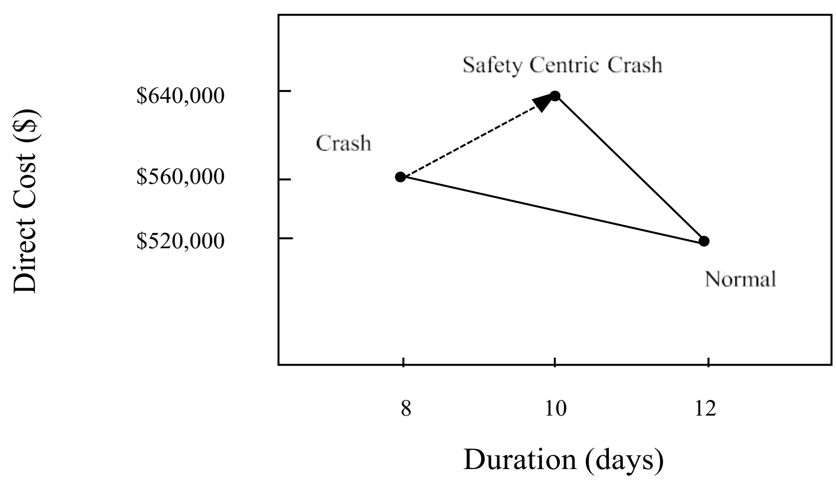

Figure 27. Comparison between total duration and total cost

In conclusion, the outlined safety-centric framework for acceleration planning, and the results for case study 2, were provided to members involved in the project planning, either indirectly or directly. The related effect of the added safety strategies on the overall project duration, and cost for acceleration planning, was then confirmed.

CHAPTER 6: PROBLEM GENERALIZATION AND CASE STUDIES FOR PROJECT ACCELERATION PLANNING

6.1. Total Project Time and Cost Analysis

Through the previous five chapters, the goal was to consider safety through acceleration schedules that haven't been successfully addressed in the past. Meantime, an adverse side effect of safety-centric crash scheduling is a significant increase in project cost. In this chapter, the question becomes how can safety be maintained while also controlling the cost increases? This problem can be solved by applying the simplified TCT optimization tool outlined by Nasiri and Lu (2019). This study utilizes the optimization tool at a global level of project cost and duration analysis. In order to determine the total project cost based on the network model, the total cost of the safety-centric scenario for each activity is combined. It should be noted that the indirect cost is not included in this cost determination.

When applying a crash schedule at the global level, it is not necessary to crash each individual project activity. Only selected activities need to be crashed to meet the proposed cost objectives and project duration. As a result, the cost of multiple activities would not increase from the 'Normal' scenario, and only some would rise to the 'Crash' scenario levels. In this way, both the desired project safety and cost can be achieved. In the following, the proposed model is first applied to a small case study for illustration and then implemented in a fictitious global level 100-activity project consisting of complex precedence relationships for project cost and duration analysis.

Based on the relationship between time and cost outlined in Figure 1, a design is generated that takes into account practical, global level concerns to acceleration planning (as seen in Figure 28). In this more realistic scenario, a single activity may have sub-options that can be executed for two different extremities (e.g., the normal scenario vs the crash scenario show in Plan D). This assumes that each sub-option (including Plans B and C) is possible and is a reasonable crash cash. The resulting time and duration for each plan is then based on the related safety protocol. There is an increase in the cost slope resulting from the additional measures taken to ensure safety, and higher costs occur as the activity duration decreases. This leads to the hypothesis that for a particular project network, under the constraints of project cost and time, crash scheduling (Plan D) does not need to be applied to each activity. Only certain activities require an enhanced level of project crashing. The crashing cushions for the remaining activities are maintained, or even maintaining to the normal scenario, as seen in Plans B and C. This helps to maintain rigorous safety standards in project planning, while still controlling for the overall project cost and duration. The resulting global level analysis of project cost and duration of the discussed case study can then be performed.

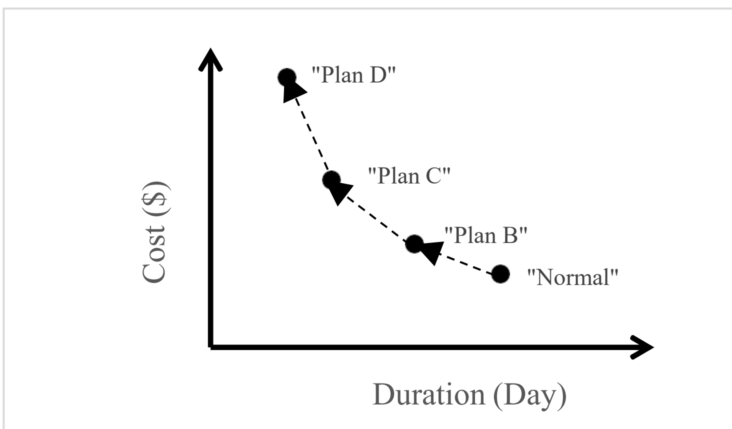

Figure 28. Activity level time and cost relationship in a more practical, general form with more practical options of the crash case

As proposed in chapter three, a step-by-step method is implemented to identify the factors related to construction accidents while following time constraints and considering the budget costs associated with hazard mitigation — both on a local level (activity) and global level (project). More specifically, it established a model that considers project duration, safety, and acceleration planning costs.

In this chapter, given a target project duration to complete the project, select which activities are necessary to shorten by how much to result in the lowest total cost at the project level. This is against unnecessarily crashing all activities to their shortest limits at the expense of significant project cost increase. As a result, the solution includes the best options to execute individual activities without compromising safety requirements while controlling the project cost to the minimum. The total cost would be expected to fall within the acceptable budget limit; otherwise, a solid case can be made to increase the cost budget based on safety requirements and optimization analysis.

6.2. Illustration Case

In this section, an illustration case is presented to clarify the implementation of the proposed method. Project's activity data and AON are given in Table 10 and Figure 29; note this case is based on the example in Hegazy (2002) used to illustrate the classical project TCT analysis. Activity time-cost relationships are assumed to be linear. Any "integer" value for activity time between normal and crash cases is deemed feasible. Note among all the activities, Activity F is not feasible to be crashed, resulting in identical input settings for both cases.

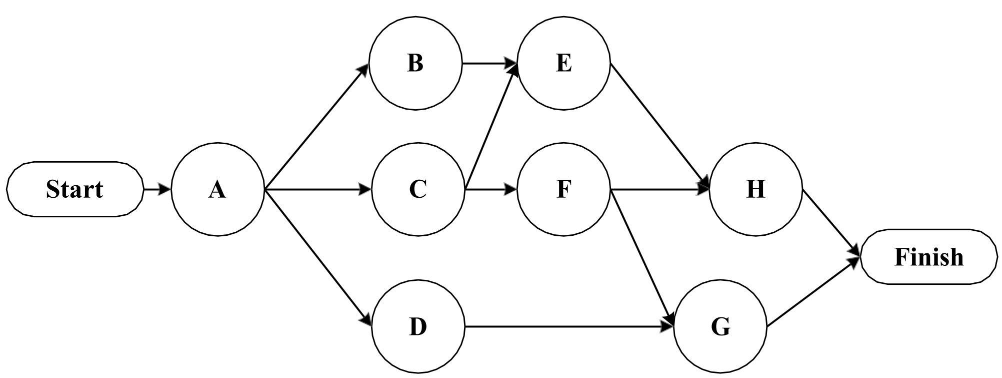

Figure 29. Project network diagram of the demonstration case

Table 10. Activity information on duration, cost and risk index for normal and crash cases

Activity	Duration (day)		Cost ($)	
	Normal	Crash	Normal	Safety-Crash
A	5	4	500	600
B	7	5	350	500
C	8	5	800	920
D	11	7	1200	1400
E	6	4	600	700
F	4	4	500	500
G	7	5	700	1000
H	6	5	300	420

Using the critical path method (CPM), the Normal scenario option was selected for every activity. The resulting project cost $4,950 and took a total of 25 days.

For the purpose of this example, it is assumed 25 days is in excess and requires a crash schedule. If the lower possible time for each activity is assigned, the CPM schedule results in a project cost of $6,040 and a project duration of 18 days. This addition of $1,090 in the budget constitutes a 22% increase and is also assumed to be too significant for the project owner, necessitating a new project plan.

If the TCT optimization method outlined by Nasiri and Lu (2019) is applied to this dataset, the duration of 18 days is generated, but with a final project cost of $5,940. This result is $100 less than the CPM schedule. The revised project scheduling found that activity D did not need crash scheduling at the lowest possible activity time when comparing the two methods. Overall, a safety-centric plan can be used while controlling for cost increase by using a TCT analysis at the global level for project cost and duration.

6.3. 100-Activity Case

This global case study is a 100-activity project with the time and cost of each activity outlined, and the relationship between them .In Appendix B, the specifics of the normal cost and duration, crash cost and duration, percentage of crashing capacity available, and the precedence relationships if listed. For the purpose of creating this test case study, each activity in the Normal scenario is assigned a value of $1,000. The related crash scheduling for each activity is independently assigned, in addition to the cost slope and the crash option number. A randomly generated duration between 10-20 days was assigned for each activity in the Normal scenario. In order to increase the real work applications and network complexity of the model, the precedence relationships between activities were included. Using the project management program Primavera P6, the Normal scenario option was selected for every activity. The resulting project costs$700,000 and took a total of 192 days.

In this example, it is assumed the duration of 192 days is in excess and requires crash scheduling. If the lower possible time for each activity is assigned, the P6 schedule results in a project cost of $772,399, and a project duration of 170 days. This addition of $72,399 in the budget constitutes a 10.3% increase and is also assumed to be significant for the project owner, necessitating a new project plan.

If the TCT optimization method outlined by Nasiri an Lu (2019) is applied to this dataset, the duration of 170 days is generated, but with a final project cost of $713,586. This result is $58,813, or 7.6% less than the initial P6 schedule. When comparing the two methods, the revised project scheduling found that of the 100 project activities, 76 did not need crash scheduling at the lowest possible activity time. As a result, 5-40% of the cost was reserved for other activity crashing, resulting in a substantial cost decrease, while still meeting the 170-day mark for project duration. The results for the top fifteen activities are highlighted in Table 11. Overall, by using a TCT analysis at the global level for project cost and duration, a safety-centric plan can be used while controlling for cost increase.

For a second example, the cost factors outlined in Table 11 were further examined in order to predict the new cost increases related to safety, leading to great costs when activity time is reduced. In order to validate the proposed model for time and cost analysis for acceleration planning of a construction project, the cost slopes of each activity in the project were increased by a factor of 1.5 At the same time, the activity times, both normal and crashed, were kept constant. For the 170-day duration to be maintained with the P6 schedule with each activity set to the highest crash option, the final cost rises to $1,116,000. However, if the optimized TCT method outlined by Nasiri and Lu (2019) is applied, the project can be completed in 170 days, for a cost of considerably less, just $890,000. Compared to the P6 schedule, this is a decrease of $226,000, or a 20% savings in project cost. Figure 30 illustrates the saved cost by using the optimization tool.

Table 11.A glimpse of the results determined for the fifteen activities in terms of crashing plans

Activity ID	Normal Duration (Day)	Crashed Duration at Optimum Solution (Day)	Further Crashing (Day)	Further Crashing (%)
1(Start)	-	-	-	-
2	18	17	0	0%
3	13	13	2	15%
4	16	16	4	25%
5	20	19	0	0%
6	16	16	2	13%
7	16	13	1	6%
8	19	19	2	11%
9	17	14	0	0%
10	17	16	0	0%
11	14	14	3	21%
12	14	14	4	29%
13	17	15	2	12%

Activity ID	Normal Duration (Day)	Crashed Duration at Optimum Solution (Day)	Further Crashing (Day)	Further Crashing (%)
14	10	10	4	40%
15	17	16	0	0%
16	10	10	4	40%

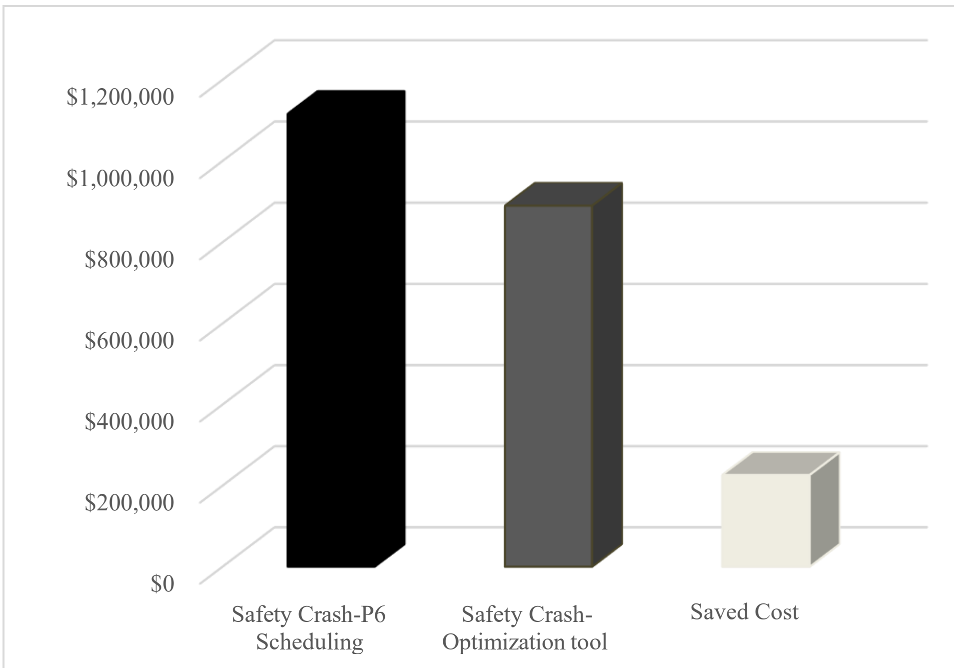

Figure 30. Comparison between Total cost from P6 and Optimization tool

6.4. Detailed Calculations:

6.4.1. Input Data:

The Number of activities used in this study, is 102 (Activity 1 is “Project Start” milestone and Activity 102 is “Project Finish” milestone). The number of paths in this study is 35. The initial total Direct cost is $700000, and the constant indirect cost slope is $1000 per day.

Table 12 depicts activity 1 to 102, with its respective normal duration, crash capacity, cost slopes and succeeding activities.

Table 12. Activity ID, Normal Duration and Direct Cost Slopes

Activity ID	Normal Duration	Available Crash Days	Succeeding Acts	Direct Cost Slope 1	Direct Cost Slope 2	Direct Cost Slope 3	Direct Cost Slope 4
1(Start)			2,52				
2	18	0	3,4,5	369			
3	13	2	6,7	345	673.5		
4	16	4	8	226.5	277.5	438	639
5	20	0	9,10,56	579			
6	16	2	11,12	168	327		
7	16	1	13	222	246	309	582
8	19	2	14	327	340.5		
9	17	0	14,15	324	370.5	465	
10	17	0	16,17	300			
11	14	3	18	586.5	714	715.5	
12	14	4	19	231	243	429	651
13	17	2	19,20	249	256.5	318	655.5

Activity ID	Normal Duration	Available Crash Days	Succeeding Acts	Direct Cost Slope 1	Direct Cost Slope 2	Direct Cost Slope 3	Direct Cost Slope 4
14	10	4	21	192	316.5	535.5	607.5
15	17	0	22	162			
16	10	4	22,23	156	180	450	513
17	17	0	24,25	274.5	436.5		
19	14	4	27	166.5	294	297	610.5
20	14	1	28	714			
21	11	2	29	700.5	720		
22	13	0	30	616.5			
23	19	3	31	360	381	498	
24	19	3	32	457.5	489	538.5	
25	14	1	33,68	178.5	195	729	
26	12	1	34	340.5			
27	20	4	34	411	420	595.5	606
28	18	1	34,35,36	697.5			
29	15	2	36	231	589.5		
30	14	0	36,37	400.5	436.5		
31	13	1	38	336			
32	15	4	39	324	600	615	631.5
33	11	1	39	415.5			
34	19	3	40	271.5	508.5	667.5	
35	10	2	40	480	726		
36	20	0	41	216			
37	17	3	42	459	504	618	
38	12	3	43,44	190.5	487.5	642	
39	15	2	44	169.5	463.5		
40	10	4	45	379.5	550.5	607.5	645
41	19	0	45	187.5	318	370.5	

Activity ID	Normal Duration	Available Crash Days	Succeeding Acts	Direct Cost Slope 1	Direct Cost Slope 2	Direct Cost Slope 3	Direct Cost Slope 4
43	14	1	47	166.5			
44	12	2	48	678	721.5		
45	15	0	49	514.5			
46	13	2	49	274.5	420		
47	19	4	50	414	580.5	679.5	684
48	11	3	50	265.5	364.5	474	
49	19	0	51	192	366	421.5	664.5
50	15	1	51	633			
51	20	0	102	204	526.5	537	657
52	19	0	53,54,55	189			
53	18	3	56,57	288	523.5	543	
54	18	4	58	325.5	657	699	736.5
55	20	0	59,60	234	247.5	343.5	
56	11	4	61,62	270	375	643.5	655.5
57	18	1	63	465			
58	19	2	64	192	459		
59	18	1	65	519			
60	14	3	66,67	189	450	471	724.5
61	19	3	68	150	190.5	253.5	
62	16	1	69	607.5			
63	10	4	70	198	243	508.5	664.5
64	20	3	71	316.5	396	415.5	
65	20	1	72,73	616.5			
66	19	1	73	708			
67	16	1	74,75	381			
68	16	1	76	159	324	528	634.5
69	16	1	77	462			

Activity ID	Normal Duration	Available Crash Days	Succeeding Acts	Direct Cost Slope 1	Direct Cost Slope 2	Direct Cost Slope 3	Direct Cost Slope 4
70	20	3	77,78	178.5	291	333	
71	17	4	78,79	153	294	496.5	676.5
72	17	1	79,80	259.5			
73	12	4	81	276	418.5	721.5	735
74	20	2	82	219	384	393	
75	15	3	83	621	675	739.5	
76	18	0	84	561			
77	15	1	84	352.5			
78	19	4	85	207	309	363	729
79	12	1	86	657			
80	10	1	87,88	516			
81	17	3	88	378	619.5	738	
82	19	2	89	190.5	301.5	699	
83	10	3	89	309	324	561	
84	14	2	90	177	690	711	
85	10	3	90	244.5	337.5	729	
86	15	3	91	376.5	601.5	685.5	
87	19	3	92	340.5	397.5	450	
88	11	1	93	649.5			
89	10	0	94	235.5			
90	20	1	95	543	568.5	603	
91	11	4	95	181.5	249	327	535.5
92	16	4	95,96	241.5	352.5	439.5	519
93	13	3	97	195	271.5	564	
94	20	3	98	252	360	616.5	723
95	13	0	99	264	409.5	526.5	
96	17	0	99	162	217.5		

Activity ID	Normal Duration	Available Crash Days	Succeeding Acts	Direct Cost Slope 1	Direct Cost Slope 2	Direct Cost Slope 3	Direct Cost Slope 4
97	12	3	100	360	453	604.5	
98	16	1	100	297	300	640.5	
99	13	0	101	175.5	474		
100	19	0	101	154.5			
101	11	0	102	430.5	442.5		
102(Finish)							

6.4.2. Output Data:

presents the final results.

Cycle No.	1	2	3	4	5	6	7	8	9	10	11	12
Project Dur	192	191	190	189	188	187	186	185	184	183	182	181
Indirect Cost	192000	191000	190000	189000	188000	187000	186000	185000	184000	183000	182000	181000
Direct Cost	700000	700162	700508.5	700876	701245	701626	702020.5	702533.5	703112.5	703855	704651.5	705464.5
Total Cost	892000	891162	890508.5	889876	889245	888626	888020.5	887533.5	887112.5	886855	886651.5	886464.5
Activity Crashed		15	41	49	2	51	25	25	5	9	49	41
			68	99		84	36	41		95	101	101
										100		

Cycle No.	13	14	15	16	17	18	19	20	21	22	23
Project Dur	180	179	178	177	176	175	174	173	172	171	170
Indirect Cost	180000	179000	178000	177000	176000	175000	174000	173000	172000	171000	170000
Direct Cost	706349.5	707353	708394	709559.5	710822.5	712178.5	713609.5	715054	716626	718367.5	720379
Total Cost	886349.5	886353	886394	886559.5	886822.5	887178.5	887609.5	888054	888626	889367.5	890379
Activity Crashed	17	10	51	51	7	7	51	49	13	9	7
	49	45	68	74	9	30	55	68	30	13	22
	52	60	82	95	17	89	95	94	55	76	90
					55	99			90	96	96
										98	98

Figure 31. Final results of case study

Table 13. shows the activities and how much of the crashing capacity has been used. To clarify, applying an optimally crashed project schedule at the global level, it is not necessary to crash each individual activity to its extreme. Only selected activities need to be crashed to meet the optimization objectives in terms of project cost or project duration. As a result, the cost of multiple activities would not necessarily change from the 'Normal' scenario, and only some activities would entail implementation of the 'Crash' scenario. In this way, both the desired project safety and cost objectives can be achieved in realization of the shortest project time attainable.

Table 13 .Activity Normal, Crash and Further Crashing% Duration

Activity ID	Normal Duration (Day)	Crashed Duration at Optimum Solution (Day)	Further Crashing (Day)	Further Crashing (%)	Succeeding Acts
1(Start)					2,52
2	18	17	0	0%	3,4,5
3	13	13	2	15%	6,7
4	16	16	4	25%	8
5	20	19	0	0%	9,10,56
6	16	16	2	13%	11,12
7	16	13	1	6%	13
8	19	19	2	11%	14
9	17	14	0	0%	14,15
10	17	16	0	0%	16,17
11	14	14	3	21%	18
12	14	14	4	29%	19
13	17	15	2	12%	19,20
14	10	10	4	40%	21
15	17	16	0	0%	22
16	10	10	4	40%	22,23
17	17	15	0	0%	24,25
18	12	12	4	33%	26
19	14	14	4	29%	27
20	14	14	1	7%	28
21	11	11	2	18%	29
22	13	12	0	0%	30
23	19	19	3	16%	31
24	19	19	3	16%	32
25	14	12	1	7%	33,68

Activity ID	Normal Duration (Day)	Crashed Duration at Optimum Solution (Day)	Further Crashing (Day)	Further Crashing (%)	Succeeding Acts
26	12	12	1	8%	34
27	20	20	4	20%	34
28	18	18	1	6%	34,35,36
29	15	15	2	13%	36
30	14	12	0	0%	36,37
31	13	13	1	8%	38
32	15	15	4	27%	39
33	11	11	1	9%	39
34	19	19	3	16%	40
35	10	10	2	20%	40
36	20	19	0	0%	41
37	17	17	3	18%	42
38	12	12	3	25%	43,44
39	15	15	2	13%	44
40	10	10	4	40%	45
41	19	16	0	0%	45
42	16	16	3	19%	45,46
43	14	14	1	7%	47
44	12	12	2	17%	48
45	15	14	0	0%	49
46	13	13	2	15%	49
47	19	19	4	21%	50
48	11	11	3	27%	50
49	19	15	0	0%	51
50	15	15	1	7%	51
51	20	16	0	0%	102
52	19	18	0	0%	53,54,55

Activity ID	Normal Duration (Day)	Crashed Duration at Optimum Solution (Day)	Further Crashing (Day)	Further Crashing (%)	Succeeding Acts
53	18	18	3	17%	56,57
54	18	18	4	22%	58
55	20	17	0	0%	59,60
56	11	11	4	36%	61,62
57	18	18	1	6%	63
58	19	19	2	11%	64
59	18	18	1	6%	65
60	14	13	3	21%	66,67
61	19	19	3	16%	68
62	16	16	1	6%	69
63	10	10	4	40%	70
64	20	20	3	15%	71
65	20	20	1	5%	72,73
66	19	19	1	5%	73
67	16	16	1	6%	74,75
68	16	13	1	6%	76
69	16	16	1	6%	77
70	20	20	3	15%	77,78
71	17	17	4	24%	78,79
72	17	17	1	6%	79,80
73	12	12	4	33%	81
74	20	19	2	10%	82
75	15	15	3	20%	83
76	18	17	0	0%	84
77	15	15	1	7%	84
78	19	19	4	21%	85
79	12	12	1	8%	86

Activity ID	Normal Duration (Day)	Crashed Duration at Optimum Solution (Day)	Further Crashing (Day)	Further Crashing (%)	Succeeding Acts
80	10	10	1	10%	87,88
81	17	17	3	18%	88
82	19	18	2	11%	89
83	10	10	3	30%	89
84	14	13	2	14%	90
85	10	10	3	30%	90
86	15	15	3	20%	91
87	19	19	3	16%	92
88	11	11	1	9%	93
89	10	9	0	0%	94
90	20	18	1	5%	95
91	11	11	4	36%	95
92	16	16	4	25%	95,96
93	13	13	3	23%	97
94	20	19	3	15%	98
95	13	10	0	0%	99
96	17	15	0	0%	99
97	12	12	3	25%	100
98	16	14	1	6%	100
99	13	11	0	0%	101
100	19	18	0	0%	101
101	11	9	0	0%	102
102(Finish)	0	0	0	0	0

CHAPTER 7: CONCLUSION

7.1. General Findings

In summary, the method outlined in this thesis addresses the practical need for a TCT analysis that appropriately considers safety management in project scheduling and cost budgeting. The developed safety-centric application framework can be used to aid project managers in construction acceleration planning, while controlling the associated increases in project cost in connection with resolving safety concerns and mitigating workplace hazards. By following this framework, managers identify accident shaping factors and apply relevant rules related to their project, in order to factor in the associated safety costs for hazard mitigation. A side effect of including safety concerns in the acceleration planning process can be a significant increase in the project cost. How to control the project cost increment while not compromising on safety places considerable pressure on the project manager, as increasing total cost budget may not be realistic for a real-world project. As a general rule, planning options that significantly increase cost are deemed unfavorable; thus, a method is needed that controls cost increases associated with acceleration planning, without compromising on safety. This research attempts to solve this problem by utilizing a global level analysis of project cost and duration. The results suggest that depending on the project network and the cost and time requirements, the most extreme crash option may not be necessary on each activity. In reality, only a set of certain activities require this level of crash scheduling, while the remaining activities maintain at normal scenarios or at a point between normal and crash scenarios on the activity cost slope. This allows both the project cost and duration to be maintained alongside resolving safety concerns when developing a **practically feasible acceleration** plan for the construction project. In other words, given target project duration to complete the project, how to select which activities are necessary to shorten by how much in order to result in the lowest total cost at project level. This is in contrast with unnecessarily crashing all of the activities to their shortest limits at the expense of significant project cost increase. As a result, the final planning solution includes the best options to execute individual activities without compromising safety requirements, while controlling the project cost to the minimum. The total cost would be expected to fall within the acceptable budget limit; otherwise, a solid case can be made to increase the cost budget based on safety requirements and optimization analysis.

The conceptualized methodology initiates by arranging all the activities at the shortest "crash" duration according to the planned "crash" scenario. Then, the shortest plausible duration of the project is developed employing the critical path method on the project network model. Then, the objective is to maintain the shortest project duration resulting from CPM while reducing the project cost to a minimum, by adjusting activity times to the best positions between crash and normal scenarios under the same precedence constraints in the project. The associated activity costs can be derived as a result.

7.2. Limitations

Due to limitations in the categorization of construction activities, there is no all-inclusive model for acceleration planning that exists, based on an entirely objective dataset. Therefore, the methods utilized in this thesis still require human input to select the appropriate accident shaping factors and rules that apply to their specific project planning needs. New Shaping factors and safety rules should be identified due to the changing nature of a particular activity or project. The proposed shaping factors and safety rules presented in this thesis are a reliable starting point and serve only as guidance for construction executives. Despite this, the framework outlined in this research offers a real-world, systematic method for safety-centric acceleration planning in the construction industry.

In this thesis, the straight-line model is assumed for the activity cost slope. Any point between crash and normal scenario is considered feasible. While, in the industry practices, this relationship may not be linear or continuous.

Furthermore, this thesis considers no uncertainty in time/cost for the normal and crash scenarios (Similar to PERT). This research solely addresses the most likely estimates, similar to the traditional CPM and TCT methods defined on deterministic terms. To add, the AON project network is assumed fixed in the proposed methodology and case studies.

7.3. Future Study

Future studies are needed that integrate more detailed risk analysis into the TCT optimization of the proposed model outline. Additionally, newly developed AI may be available at this time, allowing for a refined selection of the related project variables, such as accident shaping factors and the associated rules, based on cognitive analysis of the historical data available. As a result, the safety regulations and factors could be determined automatically, allowing acceleration planning to be performed for time and cost analysis more intelligently, without the need for extended human input.

As mentioned in the limitations, this study focuses on the linear cost slope relationships. Future research can focus on non-linear relationships that reflect a more realistic perspective of the first-hand construction practice. Furthermore, future studies can concentrate on adding uncertainties to cost and time estimates.

REFERENCES

Abdi, A., & Taghipour, S. (2018). An optimization model for fleet management with economic and environmental considerations, under a cap-and-trade market. *Journal of Cleaner Production, 204*, 130-143.

Gibb, A., Haslam, R., Gyi, D., Hide, S., & Duff, R. (2006, November). What causes accidents? In *Proceedings of The Institution of Civil Engineers-Civil Engineering* (Vol. 159, No. 6, pp. 46-50). Thomas Telford Ltd.

Alkaissy, M., Arashpour, M., Li, H., Alaghmand, S., & Nezamian, A. (2021). Quantitative analysis of safety risks and relationship with delayed project completion times. *Risk analysis*.

Alzarrad, M. A. (2020). Fuzzy Monte Carlo Simulation to Optimize Resource Planning and Operations. In *Concepts, Applications and Emerging Opportunities in Industrial Engineering*. IntechOpen.

Anumba, C., & Bishop, G. (1997). Importance of safety considerations in site layout and organization. *Canadian Journal of Civil Engineering*, *24*(2), 229-236.

Ammar, M. A. (2020). Efficient modeling of time-cost trade-off problem by eliminating redundant paths. International Journal of Construction Management, 20(7), 812-821.

Aminbakhsh, S., Gunduz, M., Sonmez, R. (2013). Safety risk assessment using analytic hierarchy process (AHP) during planning and budgeting of construction projects. *Journal of Safety Research*, 46(2013): 99–105.

Ahuja, H. N., Dozzi, S. P., & Abourizk, S. M. (1994). *Project management: techniques in planning and controlling construction projects*. John Wiley & Sons

Bettemir, Ö. H., & Birgönül, M. T. (2017). Network analysis algorithm for the solution of discrete time-cost trade-off problem. *KSCE Journal of Civil Engineering*, 21(4), 1047-1058.

Brown, K. A., Willis, P. G., and Prussia, G. E. (2000). "Predicting safe employee behavior in the steel industry: Development and test of a sociotechnical model." *Journal of Operations and Management*, 445–465.

Choe, S., & Leite, F. (2017). Construction safety planning: Site-specific temporal and spatial information integration. *Automation in Construction*, *84*, 335-344.

Deckro, R. F., Hebert, J. E., Verdini, W. A., Grimsrud, P. H., & Venkateshwar, S. (1995). Nonlinear time/cost tradeoff models in project management. *Computers & Industrial Engineering*, *28*(2), 219-229.

Del Pico, W. J. (2013). *Project control: Integrating cost and schedule in construction*. John Wiley & Sons.

Diekmann, J.E. and Al-Tabtabai, H., 1992. Knowledge-based approach to construction project control. *International Journal of Project Management*, 10(1), pp.23-30.

Elbeltagi, E., Ammar, M., Sanad, H. and Kassab, M., 2016. Overall multiobjective optimization of construction projects scheduling using particle swarm. *Engineering, construction and architectural management.* Vol. 23 No. 3, pp. 265-282

Feng, C. W., Liu, L., & Burns, S. A. (1997). Using genetic algorithms to solve construction time-cost trade-off problems. *Journal of computing in civil engineering,* 11(3), 184-189.

Fortunato, B. R., Hallowell, M. R., Behm, M., and Dewlaney, K. (2012). "Identification of safety risks for high-performance sustainable construction projects". *Journal of*

Construction Engineering Management, 499-508.

Fratta, L., & Montanari, U. (1975). A vertex elimination algorithm for enumerating all simple paths in a graph. *Networks*, 5(2), 151-177.

Fung, I. W., Tam, V. W., Lo, T. Y., & Lu, L. L. (2010). Developing a risk assessment model for construction safety. *International Journal of Project Management*, 28(6), 593-600.

Fulkerson, D. R. (1961). A network flow computation for project cost curves. *Management science*, 7(2), 167-178.

Gibb, A., Haslam, R., Gyi, D., Hide, S. and Duff, R., 2006, November. What causes accidents? *In Proceedings of The Institution of Civil Engineers-Civil Engineering* (Vol. 159, No. 6, pp. 46-50). Thomas Telford Ltd.

Guo, B. H., Goh, Y. M., & Wong, K. L. X. (2018). A system dynamic view of a behavior-based safety program in the construction industry. *Safety science*, *104*, 202-215.

Hallowell, M. R., Hinze, J. W., Baud, K. C., and Wehle, A. (2013). "Proactive construction safety control: Measuring, monitoring, and responding to safety leading Indicators". *Journal of Construction Engineering and Management*.

Han, S., Saba, F., Lee, S., Mohamed, Y. and Peña-Mora, F., 2014. Toward an understanding of the impact of production pressure on safety performance in construction operations. *Accident analysis & prevention*, *68*, pp.106-116.

Hegazy, T. (1999). Optimization of construction time-cost trade-off analysis using genetic algorithms. *Canadian Journal of Civil Engineering*, *26* (6), 685-697.

Hegazy, T. (2002). "Resource management: Part 2 - Time-Cost Tradeoff." Chapter 8 in

Computer-Based Construction Project Management, T. Hegazy, Prentice Hall, Upper Saddle River, New Jersey, 211-236.

Hosseinian, S. S., & Torghabeh, Z. J. (2012). Major theories of construction accident causation models: A literature review. *International Journal of Advances in Engineering & Technology*, *4*(2), 53.

Hochbaum, D. S. (2016). A polynomial time repeated cuts algorithm for the time cost tradeoff problem: The linear and convex crashing cost deadline problem. *Engineering, Computers and Industrial,* 95, 64-71.

Jiang, A., & Zhu, Y. (2010). A multi-stage approach to time-cost trade-off analysis using mathematical programming. *International Journal of Construction Management*, 10(3), 13-27.

Kelley Jr, J. E., & Walker, M. R. (1959, December). Critical-path planning and scheduling. In *Papers presented at the December 1-3, 1959, eastern joint IRE-AIEE-ACM computer conference* (pp. 160-173).

Kelley, J. E. (1961). "Critical-Path Planning and Scheduling: Mathematical Basis." *Operations Research,* 9(3), 296-320

Khaled El-Rayes, & Khalafallah, a. A. (2005). Trade-off between Safety and Cost in Planning Construction Site Layouts. *Journal of Construction Engineering and Management*, 1186-1195.

Klanšek, U., & Pšunder, M. (2008). Cost optimal project scheduling. *Organizacija*, *41*(4).

Kim, J., Y., Kang, C., W. and Hwang, I., K. (2012). A practical approach to project scheduling: considering the potential quality loss cost in the time–cost tradeoff problem.

International Journal of Project Management, Vol.30, pp. 264–272.

Koo, C., Hong, T., & Kim, S. (2015). An integrated multi-objective optimization model for solving the construction time-cost trade-off problem. *Journal of Civil Engineering and Management*, 21(3), 323-333.

Lam, T. Y., & Siwingwa, N. (2017). Risk management and contingency sum of construction projects. *Journal of Financial Management of Property and Construction*.

Larsen, J. K., Shen, G. Q., Lindhard, S. M., & Brunoe, T. D. (2016). Factors affecting schedule delay, cost overrun, and quality level in public construction projects. *Journal of management in engineering*, *32*(1), 04015032.

Lee, H., Kim, H., Park, M., Teo, E. A. L., and Lee, K. (2012). "Construction risk assessment using site influence factors." *Journal of Computing of Civil Engineering*, 319-330.

Leigh, J. P. (2011). Economic burden of occupational injury and illness in the United States. *The Milbank Quarterly*, *89*(4), 728-772.

Linda M.G, steven H, et al. (2003). "The "Goldilocks Model" of overtime in construction: not too much, not too little, but just right." *Journal of safety research*, 215-226

Li, R. Y. M., & Poon, S. W. (2013). Workers' Compensation for Non-fatal Construction Accidents: Review of Court Cases in Hong Kong. *Construction Safety*, 123-135.

Ling, F. Y. Y., Liu, M., & Woo, Y. C. (2009). Construction fatalities in Singapore. *International Journal of Project Management*, 27(7), 717-726.

Liu, L., Burns, S. A., & Feng, C. W. (1995). Construction time-cost trade-off analysis using LP/IP hybrid method. *Journal of construction engineering and management*, 121(4), 446-454.

López-Alonso, M., Ibarrondo-Dávila, M. P., & Rubio, M. C. (2016). Safety cost management in construction companies: A proposal classification. *Work*, 54(3), 617-630.

Lu, M., Liu, J., and Ji, W. (2017). "Formalizing a path-float-based approach to determine and interpret total float in project scheduling analysis." *International Journal of Construction Management,* 17(4), 251-263

Mahdavian, S., Bellale Manjunatha, K. S., Pereira, E., & Lu, M. (2020, November). Guidance to Safety-Centric Construction Acceleration Planning in the Context of Project Time-Cost Tradeoff Analysis. In *Construction Research Congress 2020: Project Management and Controls, Materials, and Contracts* (pp. 1186-1193). Reston, VA: American Society of Civil Engineers.

Mecca, S. (1999). "As sequences flow: proposal of organizational rules for 'Lean Construction" management." *The International Group for Lean Construction (IGLC)* (pp. 399-410). Berkeley: Univ. of California.

Menesi, W., Golzarpoor, B., & Hegazy, T. (2013). Fast and near-optimum schedule optimization for large-scale projects. *Journal of construction engineering and management*, 139(9), 1117-1124.

Mitropoulos, P., Abdelhamid, T. S., and Howell, G. A. (2005). "Systems model of construction accident causation." *Journal of Construction engineering Management*, 816-825.

Mokhtari, H., Kazemzadeh, R. B., & Salmasnia, A. (2010). Time-cost tradeoff analysis in project management: An ant system approach. *IEEE Transactions on engineering management*, *58*(1), 36-43.

Moussourakis, J., & Haksever, C. (2004). Flexible model for time/cost tradeoff problem. *Journal of Construction Engineering and Management*, 130(3), 307-314.

Nasiri, S. (2019). Integer-Programming-Assisted Path-Float-Based Method for Time-Cost Tradeoff Optimization in Project Planning.

Nasiri, S., & Lu, M. (2019). Path-Float Based Approach to Optimizing Time-Cost Tradeoff in Project Planning and Scheduling. In Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation (pp. 585-592). Reston, VA: American Society of Civil Engineers, https://doi.org/10.1061/9780784482421.074

"National Institute for Occupational Safety and Health (NIOSH)." (2000). Worker health chartbook. Atlanta: Worker health chartbook. (Rosa, R. R. Worker health chartbook, 2000; Nonfatal illness.)

Navon, R. and Kolton, O., 2006. Model for automated monitoring of fall hazards in building construction. *Journal of Construction Engineering and Management*, 132(7), pp.733-740.

Nguyen, D. T., Le-Hoai, L., Tarigan, P. B., & Tran, D. H. (2021). Tradeoff time cost quality in repetitive construction project using fuzzy logic approach and symbiotic organism search algorithm. *Alexandria Engineering Journal*.

Occupational Safety and Health Administration (OSHA).,2003. "Washington: Safety and health regulations for construction" 29 Code of federal regulation.

Ozcan-Deniz, G., Zhu, Y., & Ceron, V. (2012). Time, cost, and environmental impact analysis on construction operation optimization using genetic algorithms. *Journal of management in engineering*, *28*(3), 265-272.

Pereira, E., Han, S. and AbouRizk, S., 2018. Integrating case-based reasoning and simulation modeling for testing strategies to control safety performance. *Journal of Computing in Civil Engineering*, *32*(6), p.04018047.

Peyton, R.X. and Rubio, T.C., 1991. *Construction safety practices and principles.* Van Nostrand Reinhold Company.

Phillips Jr, S., & Dessouky, M. I. (1977). Solving the project time/cost tradeoff problem using the minimal cut concept. *Management science,* 24(4), 393-400.

Pollack-Johnson, B., & Liberatore, M. J. (2006). Incorporating quality considerations into project time/cost tradeoff analysis and decision making. *IEEE Transactions on Engineering Management*, *53*(4), 534-542.

Reiman, T., and Pietikäinen, E. (2012). "Leading indicators of system safety Monitoring and driving the organizational safety potential." *Journal of Safety Science*, 1993-2000.

Rasdorf, W. J., & Abudayyeh, O. Y. (1991). Cost-and schedule-control integration: Issues and needs. *Journal of construction engineering and management*, 117(3), 486-502.

Robinson, D. R. (1975). A dynamic programming solution to cost-time tradeoff for CPM. *Management Science*, *22*(2), 158-166.

Rodrigues, F, et al. (2015). "Correlation of causal factors that influence construction safety performance: A model." *Work*, 721-730.

Sacks, R., Rozenfeld, O., & Rosenfeld, Y. (2009). Spatial and temporal exposure to safety hazards in construction. *Journal of construction engineering and management*, *135*(8), 726-736.

Sadeghi, M., & Lu, M. (2020, August). Time-Cost Trade-off Optimization Incorporating

Accident Risks in Project Planning. *In International Conference on Computing in Civil and Building Engineering* (pp. 643-653). Springer, Cham.

Schaufelberger, J. and Lin, K.Y., 2013. *Construction Project Safety* (Vol. 93). John Wiley & Sons.

Siemens, N. (1971). "A Simple CPM Time-Cost Tradeoff Algorithm." *Management Science,*17(6), B-354-B-363.

Spilllane John, P., et al. (2011)."Confied site construction: a qualiative investigation of critical issues affecting management of health and safety." *Journal of civil engineering and construction technology*, 138-146.

Sun, Y., Fang, D., Wang, S., Dai, M., and Lv, X. (2008). "Safety Risk Identification and assessment for beijing olympic venues construction." *Journal of Management in Engineering*, 40-47.

Suraji, A., Duff, A. R., and Peckitt, S. J. (2001). "Development of causal model of construction accident causation." *Journal of Construction Engineering Management*,337-344.

Todd W. Loushine, P. L. (2006). Quality and Safety Management in Construction. *Total Quality Management and Business Excellence*, 1171-1212. doi: 10.1080/14783360600750469.

Toğan, V., & Eirgash, M. A. (2019). Time-cost trade-off optimization of construction projects using teaching learning-based optimization. *KSCE Journal of Civil Engineering*, *23*(1), 10-20.

Toole, T. (2002). "Construction site safety roles." *Journal of Construction Engineering Management*, 203-210.

Tran, D.H. and Long, L.D., 2018. Project scheduling with time, cost and risk trade-off using adaptive multiple objective differential evolution. Engineering, Construction and Architectural Management. Vol. 25 No. 5, pp. 623-638.

Webb, C., Gao, L., & Song, L. G. (2016). Schedule compression impact on construction project safety. *Frontiers of Engineering Management*, *2*(4), 344-350.

Yang, I. T. (2007). Using elitist particle swarm optimization to facilitate bicriterion time-cost trade-off analysis. *Journal of construction engineering and management*, *133*(7), 498-505.

Yi, K.J. and Langford, D., 2006. Scheduling-based risk estimation and safety planning for construction projects. *Journal of construction engineering and management*, 132(6), pp.626-635.

Zahraie, B. and Tavakolan, M. (2009), "Stochastic time-cost-resource utilization optimization using nondominated sorting genetic algorithm and discrete fuzzy sets", *Journal of Construction Engineering and Management*, Vol. 135 No. 11, pp. 1162-1171.

Zhang, S., Teizer, J., Pradhananga, N. and Eastman, C.M., (2015). Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning. *Automation in Construction*, 60, pp.74-86.

Zou, P. X., and Zhang, G. (2009). "Comparative study on the perception of construction safety risks in China and Australia." *Journal of Construction Engineering and Management*, 620-627.