Methodology for Project Schedule Acceleration Integrated with Energy Source-Based Assessment of Occupational Health and Safety Risks

by

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Abstract

There will always be uncertainties and hazards involved with project activities in the construction industry. Both long-term and short-term safety events reported to occupational health and safety authorities are impacted by the practice of schedule compression by crashing the project activities. Project activities with high occupational health and safety risks, such as tunnel construction projects, are subject to considerable uncertainties as it includes many hazardous and risky tasks.

This research proposes a measure of risk indexing based solely on the energy sources associated with particular project situations and construction processes being planned. Identifying and assessing risks in planning construction activities is to anticipate and prevent potential problems from manifesting at the worksite. It is often far less expensive to eliminate problems at the construction planning stage than to modify the work site later to eliminate or mitigate a hazard. The method developed in this thesis is associated with the related risk factors of ten significant types of energy release categorized by the American Society of Safety Professionals (namely, Mechanical, Biological, Temperature, Chemical, Pressure, Electrical, Radiation, Sound, Gravity and Motion).

As the concern for occupational health and safety in construction increases, a variety of preventive measures have been implemented to mitigate risks associated with hazardous activities. The current practice of project acceleration planning would result in increased vulnerability regarding occupational health and safety (OHS) risks, especially on projects susceptible to high-level hazards in construction. The proposed research defines a new project planning problem termed “minimizing project schedule at lowest safety risks" and develops generic solutions based on a structured risk analysis methodology.

In planning construction activities, risk identification and assessment are essential to anticipate and prevent potential problems from manifesting on site. Often, it is much more cost-effective to eliminate issues at the planning stage of construction than to modify the work site later to eliminate or mitigate hazards. The energy source-based risk indexing method developed in this research serves as a breakdown structure of risks in order to quantify the risk index value. Based on the construction process design, risk indexing is performed by evaluating the probability and severity of associated risk factors. Analyses of energy source-based safety risk indexes offer a valuable method of scientific inquiry that has predictive validity, contributing to our understanding of hazards and risks that may cause accidents and injuries. Furthermore, the developed computerized technique can be used by the project managers to determine (i) the method of risk mitigation during project planning and scheduling; and (ii) the individual activity times along with assessed risk indexes that result in the shortest project time at the lowest total risk index. Additionally, the proposed method is formulated to mitigate the substantial increment of OHS-related risks due to accelerating construction progress on projects by avoiding the incurrences of unnecessary activity time crashing and associated OHS-related risks.

A practical case in the context of planning a tunnel construction project is presented to demonstrate the complete application of the proposed research. In addition, another 100-activity case was conducted in order to validate the potential benefits and applicability of the developed methodology for planning critical activity accelerations in the construction industry. Conclusions are drawn to summarize the contributions of the present research and identify opportunities to pursue in the near future.

Preface

This thesis is an original work by Ayesha Siddika.

A version of the proposed Methodology of Energy Sources based Risk Indexing has been published as a conference paper titled "Evaluating Risk Indices for Execution Plans of Construction Activities: Energy Sources Approach" on "CSCE 2021: Construction Track Volume 2" authored by Ayesha Siddika and Ming Lu (2021). The mentioned coauthor was involved with all the supervision related to conceptual research methodology development and manuscript composition.

In addition, Ayesha Siddika and Ming Lu are planning to submit a paper to the ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems. The title of this paper is: "Methodology for Project Schedule Acceleration Integrated with Energy-Source-Based Assessment of Occupational Health and Safety Risks." Dr. Ming Lu is the correspondence author of that paper. He was involved with the concept formation and manuscript composition.

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Table of Contents

Abstract i

Preface iv

Acknowledgments v

Chapter 1: Introduction 1

- 1.1 Background 1
- 1.2 Research Motivation 2
- 1.3 Objectives 5
- 1.4 Rationale of the Study 7
- 1.5 Scope of the Research 8
- 1.6 Thesis Organization 9

Chapter 2: Literature Review 11

- 2.1 Introduction 11
- 2.2 Health and Safety Related Terminologies 11
- 2.3 OHS Risks in Construction Industry 14

2.4 Importance of Safety in Tunnel Construction Projects 15

2.5 Risk Analysis in Safety Management 16

2.6 Energy- Based Risk Indexing 20

2.7 Project MPSLSR Operation 23

Chapter 3: Energy Source-Based Risk Indexing 27

3.1 Introduction 27

3.2 Risk Factor Identification 27

3.3 Risk Index Calculation Methodology 33

3.3.1 Calculation of Risk Index for Each Individual Factor 34

3.3.2 Calculation of Risk Index for Each Type of Energy Release 37

3.3.3 Calculation of Risk Index for Each Activity 37

3.3.4 Risk Slope Calculation 39

3.4 Example Case 40

3.4.1 Project Description 40

3.4.2 Work Breakdown Structure 41

3.4.3 Risk Indexing 50

3.4.4 Results and Discussion 52

Chapter 4: Generalized MPSLSR Operation for Acceleration Planning 53

4.1 Introduction 53

4.2 Concept of CPM-Based Model Formulation 56

4.3 Time-Risk Trade-off Methodology 58

4.3.1 Calculation of Project Duration 59

4.3.2 Calculation of Project Risk Index 60

4.3.3 Logical Precedence Constraints 61

4.3.4 Objective Function 62

4.3.5 Normalization of Objective Functions 62

4.4 MPSLSR Model Validation 63

Chapter 5: Case Studies on MPSLSR Operation for Activity Acceleration Planning 65

5.1 Case 1: TBM Tunnel Construction 65

5.1.1 Elaboration of Objective Function and Constraints for Tunneling Case Study 80

5.1.2 Computerized Program Results for Tunneling 82

5.2 Case 2: 100 Activity AON Network ... 87

5.3 Automated Computerized Engine Performance ... 97

Chapter 6: Conclusion ... 100

6.1 General Findings ... 100

6.2 Limitations ... 101

6.3 Future Study ... 102

References ... 103

Appendix ... 112

Input Data Preparation ... 112

Computerized MPSLSR Program User Guideline ... 112

Part 1: Path Finding Program (Initialization) ... 113

Part 2: MPSLSR Operation Sheet (Iterative Cycles) ... 118

Automated Computerized Engine Program Limitations ... 124

Results from Computer-based MPSLSR Program for 100-activity Case ... 126

List of Tables

Table 1: Definition and example of the ten hazardous energy sources in the wheel (source: Hallowell, 2020) 22

Table 2: Checklist to assess safety risks on construction activity by energy sources for injuries and loss 28

Table 3: Severity Index Scale to assign risk points for each factor (source: ACS, 2020) 35

Table 4: Probability Scale to assess the risk of each factor (source: MITRE, 2020) 36

Table 5: Interpretation of risk index value (source: NIST, 2012) 38

Table 6: Activity details for the bridge construction project example 42

Table 7: Risk factors associated with painting operation 47

Table 8: Risk index calculation of painting operation 51

Table 9: Hazard and risk data for TBM tunnel construction project 70

Table 10: Activity details with normal duration and different acceleration duration 74

Table 11: Risk index value of each activity for normal and accelerated scenarios 77

Table 12: Example project input data 78

Table 13: Activities' acceleration data 79

Table 14: Network paths of example project 79

Table 15: Risk index value at the normal, accelerated and optimized scenario for tunneling

construction 83

Table 16: Activity time and risk index in the near optimum scenario against the normal scenario and the accelerated scenario for tunneling case study 84

Table 17: Normal vs. accelerated scenarios of automated prototype program 85

Table 18: Activity ID, normal duration and risk slope 88

Table 19: Risk index value at normal, accelerated and near optimum scenario for 100 activity case 95

Table 20: Detailed results of MPSLSR operation 96

Table 21: Case characteristics and computing times (source: Nasiri and Lu, 2022) 98

Table 22: Generated paths for case study 117

Table 23: Activity ID with possible acceleration time and risk slopes for 100 activity case 130

Table 24: Comparison of results for normal scenario, accelerated scenario and optimized scenario for 100 activity case 134

List of Figures

Figure 1: Flowchart of risk index calculation methodology 33

Figure 2: Project work breakdown structure 41

Figure 3: Flowchart of the stepwise methodology of risk evaluation 55

Figure 4: Sample AON 57

Figure 5: Activity's time-risk relationship 59

Figure 6: AON network model for the TBM tunneling case study 66

Figure 7: Screenshot of results generated from the automated prototype program 86

Figure 8: Results for 100 activity case study 94

Figure 9: Entering the number of activities in a project 114

Figure 10: Defining successor activities 115

Figure 11: Successor activities for tunneling case study 116

Figure 12: Generating path definitions 117

Figure 13: Entering the number of activities 118

Figure 14: Entering the number of existing paths 119

Figure 15: Entering total initial risk index for normal scenario 120

Figure 16: Entering activity risk index and duration data 121

Figure 17: Entering available acceleration time and risk slope data for the activity presented in

tunneling case study 122

Figure 18: Copying path descriptions from part 1 for tunneling case study 122

Figure 19: Result of tunneling case study 123

Figure 20: Final check to ensure proper definition of the problem in Solver 125

Figure 21: Preceding relationship for 100 activity case study 126

Figure 22: Results from Path Finding Program for 100 activity case study 127

Figure 23: Possible path lengths for 100 activity case study 128

Figure 24: Results from MPSLSR automated program for 100 activity case study 128

List of Abbreviations

AON: Activity on Node
CPM: Critical Path Method
ES: Early Start
EF: Early Finish
EPBM: Earth Pressure Balance Machine
HSE: Health, Safety and Environment
LS: Late Start
LF: Late Finish
MPSLSR: Minimizing Project Schedule at Lowest Safety Risks
NP: Non-deterministic Polynomial-time
OHS: Occupational Health and Safety
OSHA: Occupational Safety and Health Administration
RI: Risk Index
TBM: Tunnel Boring Machine
TCT: Time Cost Trade-off
TF: Total Float
WBS: Work Breakdown Structure
PQLC: Potential Quality Loss Cost
TCST: Time Cost Safety Trade-off
PFCPM: Path Float-based Critical Path Method
PQLC: Potential Quality Loss Cost

Chapter 1: Introduction

1.1 Background

Occupational health and safety risks are inherent to construction work due to the nature of the activity operations, construction methods and materials, heavy equipment and physical environment of the construction project (Laryea and Mensah, 2010). Hazard and risk factors in construction projects are assessed to determine the possible effects they may have on a specific part of the project (Salah and Moselhi, 2016). The responsible management of risk should therefore be a critical component of the decision-making process during any construction project that impacts the workers' health and safety (Ebrat and Ghodsi, 2014).

In recent days construction projects have become riskier and more complex due to the various forms of activities involved (Chatterjee et al., 2018; Bahamid and Doh, 2017; Wang et al., 2004). With the rapidly increasing construction projects in the last few decades, occupational health and safety in the construction industry have become more significant. Sharp objects, heavy loads, high places, and emphasis on production all provide opportunities for accidents. However, the most recognized occupation safety and health hazards on construction sites have been working at height, working underground, working in confined spaces and in proximity to falling materials, handling load and hazardous substances, noises, dust, using plants and equipment, fire, exposure to live cables, poor housekeeping and ergonomics (Okoye, 2018). For OHS-related risks, injuries resulting from project execution in the construction industry are incredibly costly. It is estimated that the direct cost of accidents accounts for 15% of the total cost of a project (Agarwal and Everett, 1997). Hence, managing risk is considered one of the most critical aspects of the construction project as it affects the project outcomes (Watt, 2014).

Besides, critical path method (CPM) based project planning requires decreasing the duration of specific activities to complete a project before a specified deadline. So, it is necessary to either increase some resources or change the execution methods of the activities, which would consequently result in increased vulnerability of the project regarding occupational health and safety, especially on projects susceptible to high-level safety-related risks in construction (i. e., tunneling). The proposed research defines this new project planning problem as “minimizing project schedule at the lowest safety risks" and develops generic solutions using a structured risk analysis methodology. The OHS risks associated with planning activity methods will be adequately assessed in a consistent, systematic manner based on energy sources formalized within the safety management domain. To structure the risk evaluation, this research follows the approach proposed by Siddika and Lu (2021), which is based on the assessment of the potential release of energy sources formalized by the American Society of Safety Professionals (ASSP, 2018); thus, the risk index of a particular activity execution plan can be systematically determined on a 100-point scale. Further, the MPSLSR program copes with the substantial increment of safety-related risks due to accelerating construction progress on projects subject to high-level OHS-related risks, avoiding unnecessary activity time crashing and associated safety-related risks.

1.2 Research Motivation

Construction work is inherently dangerous. Hence, better planning and the implementation of a structured safety program are necessary for a safe project. A recent study has proposed a matrix of shaping factors that explains how accidents arise from a failure in coordination between the workplace, work team, equipment and material (Mahdavian et al., 2020). Modern planning and scheduling methods include advancements in cost analysis, resource assessments, and the incorporation and consideration of project planning safety. Numerous studies have shown that employee involvement in a safety program is essential to safety performance.

Identifying and assessing the hazards and risks in construction operations is an essential step in safety management (Brown, 1976; Goetsch, 1996; Holt, 2001). Hazard assessment attempts to anticipate and prevent potential problems at the worksite. It is often far less expensive to prevent problems at the construction planning stage than to modify the work site later to eliminate or mitigate a hazard. The risk index is calculated by assessing the likelihood and severity of a risk entered subjectively by an experienced safety officer. Conventional project risk management approaches in the project feasibility stage emphasize managing business risks and often ignore operational risks. However, there are instances of project failures because of operational risks such as technical complexities, contractors' and suppliers' incapability, government red tape etc., which remain unidentified until they occur. Previous studies have analyzed accident causation in construction and most followed statistical approaches based on historical accident data. Nonetheless, such data are often scant, ill-structured, and unsuitable for computing the risk index at activity levels. To address this issue and reduce the bias of experts’ judgment, a more systematic guideline needs to be formulated to allow for consistency and reduce subjectivity in evaluating the risk index value.

Risk analysis and management in construction depend mainly on intuition, judgment and experience (Akintoye and MacLeod, 1997). It is always tricky to predict the outcome of construction projects, and there are always risks and uncertainties involved. In particular, the uncertainties related to the project activities are more severe for projects like tunneling or underground construction, where occupational health and safety risks are high. These risks directly affect the health of the worker. In such a situation, the project managers and schedulers focus more on reducing the OHS-related risks affecting the function, construction productivity and environment.

Accelerating project activity duration is a commonly used method to expedite the construction process to save time and money. If a client, for example, requires their project to be completed earlier, a contractor may provide additional resources to shorten the duration of designated activities. As previously explained, for this to occur, the associated risks of the project activity will be increased. In practice, this assumption is often deemed to be unrealistic, as construction projects are subjected to constraints that play a crucial role in determining their schedule, for example, activity dependency, limited working area and availability of information (Sriprasert and Dawood, 2003).

Competence with a detail view of the risk situation is mandatory for successful handling of the risks while fast-tracking the activity duration. A few studies are available in the literature on the problem related to accelerated time-risk balance. This type of optimization problem is classified as an NP-hard problem with a large number of variables and constraints (Elbeltagi et al., 2005). In NP-hard problem, a computer algorithm that verifies a solution can be created in a polynomial time where NP-hardness stands for Nondeterministic Polynomial time hardness. Traditionally, mathematical modeling and heuristic methods are used to solve these problems. Mathematical methods convert the problem into standard mathematical programming models and then use linear, integer, or dynamic programming to obtain the optimal solution for the problem. However, formulating bi objective or multi-objective function as well as required constraints is time-consuming and prone to errors (Liu et al., 1995).

Heuristic methods provide a way to obtain reasonable solutions but do not guarantee optimality. However, they require less computational effort than mathematical methods. On the other hand, strategies that do not ensure optimal solutions, i.e., heuristic methods (Liu et al., 1995), lack mathematical rigor and can result in missing the optimal solution by a large margin. By relaxing some non-realistic assumptions, more practical methods must be presented to develop an efficient model for solving traditional time risk problems considering only necessary decision variables and only dominant paths (critical path).

Based on that context, an efficient mathematical model is required to be developed to minimize the project schedule at the lowest safety risks, followed by a structured risk index quantification method.

1.3 Objectives

To materialize the research objectives, a detailed study was performed to identify the major factors related to the OHS-related risks of construction projects and assess the time-risk trade-off methods for project planning and management. In construction, it is a common practice that the potential accident risk assessment for individual activities is performed independently by the safety officer, while the time and cost estimate of the project is estimated by a project planner who applies established planning methods (Microsoft Project or Primavera P6). A new risk indexing approach needs to be developed to structure the risk evaluation and reduce the bias of experts' judgments. Furthermore, to address the risk indexing concept in the scheduling and planning of the project for accelerated conditions, a multi-objective problem solution needs to be formulated.

This research is framed to focus mainly on the-

i. identification of the critical accident risk factors along with their probability and severity of occurrence based on the ten categories of energy sources for individual activities of a construction project; and

ii. development of a new mathematical model framework to determine a feasible schedule of project activities to achieve a specific predefined objective, for example, the shortest project duration with the lowest risk index value subject to the project constraints or limitations.

In the current practice of critical path method (CPM) based project planning and control, there is a need to accelerate a delayed project in an attempt to complete the project before the specified due date. Hence, the duration of performing certain activities must be shortened. To achieve this goal, it is necessary to either increase some resources or change the execution methods of critical activities. Nonetheless, this would consequently result in increased project vulnerability regarding OHS risks, especially on projects susceptible to high-level hazards in construction (such as tunneling and underground construction). Therefore, having identified the tradeoff between time and risks, this research aims to provide an automated prototype program for problem solutions.

The specific objectives of this research are as follows:

- To propose a structured scientific method of OHS risk index assessment of the activities of a project associated with the significant types of energy sources addressed by the American Society of Safety Professionals (ASSP, 2018).

- To conduct structured research on risk management of construction projects, mainly focused on the definition, formulation, and application in minimizing risks of the projects disposed to high-level vulnerability.

- To establish a methodology for achieving the objective of minimizing total project risk while reducing the duration of individual activities within the project.

- To develop case studies in the context of high OHS risk projects to demonstrate the complete application and benefits in planning critical activity acceleration on construction projects.

The risk index value and the mathematical modeling outcome will ensure the project's overall goals. Through the developed methodology, the risks of individual activities are assessed in light of systematic identification of risk factors associated with the individual activities and minimizing total project risk to achieve the target duration.

1.4 Rationale of the Study

The risk indexing criterion is a critical factor considered when implementing the project activities within the project deadline. In the construction industry, there is always a need to minimize or accelerate the project duration to obtain the project goal within the planned period. For example, they may ‘accelerate’ a project’s duration (i.e., the shortest possible time for which an activity can be scheduled) by allocating more resources (if sufficient resources are available) to expedite construction activities. However, accelerating a project’s duration invariably increases the risk of the project, as additional resources are required, which increases the project's vulnerability.

In the construction industry, safety risk practices present a similar set of shortcomings as those of past hazard recognition techniques. There are several limitations of the risk analysis method in the diverse portfolio of projects in the industry, but the most significant is the subjectivity of data. There is no scientific method available to calculate risks. By introducing the concept of energy into safety risk analysis within the construction industry, the goal and intention would be to introduce a scientific risk analysis method.

To address this ongoing concern, this research has focused on risk-based approaches to proactive safety management. Although the quantity and quality of safety risk data have improved in recent years, available data do not link directly to natural principles and are, therefore, limited in their application and scientific extension. This study offers a new explanation of safety risk using the concept of energy, where the underlying proposition is that all hazards are truly defined by exposure to one or more of ten distinct forms of energy. This research is intended to investigate the impact of the safety risk index on the high OHS risk-prone project’s duration connected with the critical path method. Moreover, this research tried to ensure that the results from the MPSLSR operation must be “optimal enough” to provide the best possible solutions for the schedule compression of a high occupational health and safety (OHS) risk endured project.

1.5 Scope of the Research

This study will address the current limitations of a structured safety risk quantification methodology by offering a new energy source-based approach to characterizing the potential severity of injuries. As mentioned earlier, the potential factors of health and safety in a construction project can be addressed and the mathematical modeling can be done by developing a new methodology for the acceleration duration of the project. Therefore, solutions to occupational health and safety problems in one construction project may not readily be adapted to other projects to generate further improvements. This research aims to introduce a more fundamental and systematic approach to characterizing and measuring OHS risks of construction projects.

Compared to advances in general risk analysis techniques, the development of safety risk analysis methods has lagged due to the limited amount of reliable data sources. Besides, all these data sources have inherent limitations that reduce the validity and reliability of safety risk assessments due to subjectivity. Opinion-based data acquired by industry professionals have traditionally relied primarily on qualitative risk estimates using numerical or subjective scales (Baradan and Usmen, 2006; Brauer, 2005; Everett, 1999; Shapira and Lyachin, 2009).

1.6 Thesis Organization

The present thesis is divided into six major chapters that review the research and methodologies used, along with case studies and a conclusion.

- Chapter 1: The first chapter provides relevant background information, the rationale of the study, objectives, scope and limitations of the study. This chapter outlines the motivation for this research and the overall research problem. In addition to its introduction, this research has been organized in another three chapters.

- Chapter 2: This chapter deals with the relevant literature review related to the OHS safety risk indexing methodology of a construction project and the MPSLSR modeling process. The risk factors are grouped into ten significant types of energy release categories namely, Mechanical, Biological, Temperature, Chemical, Pressure, Electrical, Radiation, Sound, Gravity and Motion. This chapter also focuses on the detailed literature review for the MPSLSR problem.

- Chapter 3: The third chapter deals with the energy source-based risk index quantification methodology with an example case study to show the applicability of the proposed risk index calculation method for the painting activity of a bridge construction project.

- Chapter 4: This chapter illustrates the methodology of a mathematical model solution for multi-objective problems dealing with a construction project's time and risk trade-off. This chapter also describes the necessity and applicability of the computer-based modeling solution to save the time of hand calculation for large-scale and complex construction projects.

- Chapter 5: In this chapter, two case studies from two different construction projects are solved to show the applicability and validation of the proposed research methodology. The first case study is a simple and small one based on the demo data of the partner industry's TBM tunnel construction project. This one is developed to adequately illustrate and validate the steps and features of the proposed methodology. The second case is developed to demonstrate the implementation of the proposed automated prototype computerized program on a large and complex project network with curvilinear time-risk relationships on activities. This case consists of one hundred and two activities, with fifty of them having acceleration options.

- Chapter 6: The last chapter provides the overall conclusion of the thesis along with the summary of potential advantages of the research work, limitations of the methodology and future research directions.

Chapter 2: Literature Review

2.1 Introduction

With stratified activities, dynamic project environments, and complex construction activities, the construction industry is known for its high level of risk (Renault and Agumba, 2016). The presence of sharp objects, heavy loads, working on heights as well as a focus on productivity make construction work inherently dangerous (OHS, 2009). The critical path method (CPM) is a mathematical algorithm for scheduling a set of activities within a construction project. A well-planned safety program and detailed planning are prerequisites for a safe project (Bonyuet, 2001).

The published literature concerning minimizing project acceleration planning in construction can be divided into several categories. Applying the concept of energy to explain safety risk requires a detailed understanding of the concepts of both safety risk analysis and safety management. To better illustrate how this study seeks to advance the cause of safety within the construction industry, a review of relevant literature is conducted in three general areas: risk index quantification of the construction activities, the effect of scheduling on the safety of the project and the MPSLSR methodology including its algorithm, automation, and application. In this chapter, there will be a discussion of the research conducted in each of these areas.

2.2 Health and Safety Related Terminologies

At the beginning of the study, a literature review on health and safety in the construction industry is conducted, focusing first on how the construction industry operates and its most dangerous activities. A substantial portion of the literature on construction risk management is devoted to empirical studies on risk management practices in the construction industry and conceptual frameworks for managing risks using multiple tools and techniques.

Understanding some basic occupational health and safety definitions is essential before engaging in a detailed discussion of the issues related to health and safety in the construction industry (Alhajeri, 2011). The following section provides a brief definition of some basic terms associated with the OHS risk management in construction:

Health is the protection of the bodies and minds of people from illness resulting from the materials, processes, or procedures used in the workplace.

Safety is the protection of people from physical injury. The concept of safety encompasses a set of principles and rules that must be followed to protect labor and capital from risks encountered in industrial environments, such as effective and efficient maintenance, which leads to a healthy and safe working environment that enables employees to perform at their best.

Health and safety are often used together to indicate concern for the physical and mental well-being of employees at the place of employment. The line between them is ill-defined, and the words are commonly used together to indicate this concern.

Welfare is the provision of facilities to maintain the health and well-being of individuals at the workplace.

Construction safety means the condition or state of being protected from or unlikely to cause danger or risk at the construction involving people, machinery or equipment, management, method and environment at the project site. A strong safety program is one of the essential steps in preventing construction-related accidents. Safety programs are developed by the Occupational Safety and Health Administration (OSHA) to ensure construction site safety. For a site safety program to be successful, a strong safety program must be in place.

Environmental protection is the arrangements to cover those activities in the workplace which affect the environment (in the form of flora, fauna, water, air, and soil) and, possibly, the health and safety of employees and others. Such activities include waste and effluent disposal and atmospheric pollution.

An accident is defined by the Health and Safety Executive (HSE, 2003) as "any unplanned event that results in injury or ill health of people, or damage or loss to property, plant, materials or the environment or a loss of a business opportunity."

Hazard and Risk are the potential of a substance, activity, or process to cause harm. Hazards take many forms, including chemicals, electricity, and working from a ladder. A hazard can be ranked relative to other hazards or a possible level of danger (Keng, 2004).

A **Risk** is the likelihood of a substance, activity or process causing harm. In the US, the Department of Homeland security defines risk as the potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences.

A risk can be reduced and the hazard controlled by good management. It is essential to distinguish between hazard and risk as the two terms are often confused and activities such as construction work are called high risk when they are high hazard. The level of risk remaining when controls have been adopted is known as the residual risk. There should only be a high residual risk where poor health and safety management and inadequate control measures exist.

Thus, it can be seen that health and safety are far more than a worker wearing a safety helmet on construction sites. Health and Safety is a philosophy that identifies and eliminates job site hazards throughout the lifecycle of a work project. It is a philosophy that discourages work practices that place individuals at risk of injury and the integration of Health and safety into the daily work process. Risk has been defined in several ways. The health and safety executive (HSE) explained risk as the chance high or low that somebody will be harmed by the hazard (HSE, 1998). Hertz and Thomas (1983) defined risk taken from the Random House College Dictionary as exposure to the chance of injury or loss. The Health and Safety Commission (1995) defined risk as the likelihood that harm will occur (Jannadi and Bu-Khamsin, 2002).

According to Lim (2003), risk can be defined as either the probability of an unwanted event, a combination of hazard, unpredictability, and partiality of the actual result differing from the expected result, loss uncertainty, or likelihood of loss. However, risk in this study is defined as the chance or probability, high or low, of harm being done. Risk will be apparent at all stages of the life cycle of a construction project at appraisal, sanction, construction, and operation (Perry and Hayes, 1985). One of the most severe risks in the construction industry is the safety and health aspect. It also promotes an environment where each person in the project construction hierarchy has a role and responsibility for safety and health.

Since the construction industry is one of the most employment-generating industries, it is essential to pay attention to the occupational health and safety of the workers and employees. Considering the diversity and complexity of construction activities, it may be dangerous for workers. Therefore, the effects and consequences of noncompliance incidents for event safety and interest groups would be costly and irrecoverable.

2.3 OHS Risks in Construction Industry

Health and safety issues have always been a significant problem and concern in the construction industry. Wherever reliable records are available, construction is among the most dangerous on health and safety criteria, particularly in developing countries. Efforts have been made to address this problem, but the results have been far from satisfactory, as construction accidents continue to dominate the overall construction industry.

In the United States, according to the Bureau of Labor Statistics, 13,502 construction workers died due to work-related injuries from 1992 through 2003, while the construction industry accounts for 19 percent of all workplace injuries and fatalities. Work-related severe injuries cost employers almost $1 billion per week in 2002 in payments to injured workers and their medical care providers, growing to $49.6 billion from $46.1 billion in 2001 (Blotzer, 2005).

Due to the high number of accidents that occur in construction and their consequences to workers, organizations, society and countries, occupational health and safety (OHS) have become a significant issue for employers to take care of the workers. In construction, workers perform a great diversity of activities, each one with a specific associated risk. Building design, materials, dimensions and site conditions are often unique, which requires adaptation and a learning curve from site to site. Injuries may occur in many ways and at every juncture of the process (Grant and Hinze, 2014).

The health and safety of the workers are relevant to all branches of the industry, and it is vital for the construction industry. It has always been a significant issue as it is considered among the most exposed sectors concerning occupational health and safety-related incidents. As a result of this situation, there is a high frequency of accidents, which makes it an unsafe industry. The degree of safety in this selected sector is not indicated by a single accident but by a set of accidents within a specified time interval. Knowledge about the noticeable trends in accidents is required to assess the level of safety and directions for changes (Hola and Szóstak, 2014).

Occupational health and safety is an area concerned with the development, promotion, and maintenance of the workplace environment, policies and programs that ensure the mental, physical, and emotional well-being of employees, as well as keeping the workplace environment relatively free from actual or potential hazards that could injure employees (Nyirenda et. al, 2015).

An occupational health and safety (OHS) management system is a process to identify and control hazards on an ongoing basis and protect the health and safety of workers, aimed at minimizing the incidence of injury and illness at the workplace (Work Safe Alberta, 2022). Lingard and Rowlinson (2005) maintained an effective OHS management system is conducive to designing and performing productive work with workers' occupational health and safety in mind.

A workplace risk assessment is one of the critical tools for improving occupational health and safety conditions at work. Sousa et al. (2014) state that several tools and methods exist to investigate and understand occupational accidents in the construction industry.

Zhou et al. (2015) systematically analyzed construction safety studies. They discovered that of all the research themes, 33.03% were related to accident data, 20.27% to the impact of person and group/organizational characteristics, and 44.65% to the safety management process. Safety planning, monitoring, assessment, measurement, and performance are all included in the corpus of studies on the safety management process (Zhou et al., 2015).

2.4 Importance of Safety in Tunnel Construction Projects

Tunneling projects are complex as they differ from on-ground structures and design conditions vary case by case (Siang et al., 2017). Tunneling projects find themselves in a situation where unexpected conditions threaten the continuation of the project. The health risks associated with tunnel construction can impact the community and workers who build these tunnels. There are various risks related to tunneling construction, such as exposure to harmful substances, tunnel cave-ins, flooding, fires, and explosions. Tunnel construction imposes risks on all parties involved and those not directly involved in the project (Eskesen et al. 2004).

Tunnels are artificial underground spaces that provide a capacity for particular goals such as storage, underground transportation, mine development, power and water treatment plants, and civil defense (Yazdani-Chamzini, 2013). Tunnel construction is a critical activity in developing infrastructure projects. In many situations, tunneling projects involve problems where unexpected conditions threaten the project's continuity. Such issues can arise from prior knowledge limited by unknown underground conditions. Therefore, a risk analysis that can take into account the uncertainties associated with the underground projects is needed to assess the existing risks and prioritize them for further protective measures and decisions to reduce, mitigate and even eliminate the risks involved in the project. Yazdani-Chamzini (2013) proposed a risk assessment model based on the concepts of fuzzy set theory to evaluate risk events during tunnel construction operations.

Lu et al. (2020) developed a web-based professional training platform that provides information on occupational health and safety in the tunneling industry based on the Alberta OHS and British BS 6164 codes. It exclusively focuses on sharing knowledge on the best safe work practices in a tunnel under construction or in service.

In the modern era, tunnel construction conditions are getting more complex. Since it generates more risks, more stringent criteria must be placed during the design, construction and exploitation phase (Zafirovski et al., 2019).

2.5 Risk Analysis in Safety Management

Risk in the context of occupational health and safety refers to measuring the possibility of harm and the related effects of a hazard present in a particular circumstance (Baradan and Usmen, 2006; Jannadi and Almishari, 2003). In risk management, vulnerability results from an object's inherent qualities that make it susceptible to danger.

This definition is simply associated with the definition of sensitivity in physics. Of a large number of similar occurrences, the majority do not cause significant damage, while some lead to major injuries or damages (incident pyramid of Heinrich). In general, Risk (R) can be presented conceptually with the basic equation:

$$Risk\ (R) = Hazard\ (H) \times Vulnerability\ (V) \times\ Amount\ of\ elements\ at\ risk\ (A) \quad (1)$$

In 1984, system safety engineers in the United States military first applied the energy source-based risk quantification method for the risk assessment associated with an event as the product of the probability and the severity of an outcome (Quality, 1984). This definition of the safety risk, shown in Eq. (1), has remained consistent since its indoctrination and will be the premise for the energy source-based safety risk concept.

$$Unit\ Risk = Frequency\ \times\ Severity \quad (2)$$

It should be noted that the probability that a hazard will cause an injury is analogous to the frequency of events within a given period. Typically, frequency is expressed in terms of incident rates, whereas severity is defined as the impact on the work or firm (Hallowell and Gambatese, 2009).

Risk assessment techniques are central to understanding what is most uncertain about a project and are the foundation for risk management (Kendrick, 2003). There are several methods to assess the risks imposed by construction project activities. Probability-impact (P-I) function, a branch of the traditional risk assessment methods, is one of the most popular techniques for assessing the risk level. Based on the basic concept of conventional risk assessment, risk is defined as a function of probability and impact of different accident scenarios (Heldman et al. 2007). This approach applies a risk matrix, well-known as the probability-impact (P-I) matrix, to assess the level of risk for different scenarios.

Numerous safety risk quantification methods have been developed over the past 15 years, varying in complexity and application. According to Everett (1999), injuries are causally related to various trades based on the frequency of particular overexertion injuries sustained while performing work tasks. Similarly, Huang and Hinze (2003) quantified the risk of fall accidents using statistical data from OSHA and the Bureau of Labor Statistics. Several additional studies have since contributed to the advancement of safety risk analysis, quantifying risk for such categories as struck-by accidents (Hinze et al., 2005), fatalities between construction trades (Baradan and Usmen, 2006), and tower crane activities (Shapira and Lyachin, 2009). All those researchers focused on analyzing the frequency of event occurrences to quantify risk. The proposed energy source-based safety risk concept would address this significant deficiency and serve as a means to reliably quantify the severity based on the physical environment of the project site.

Very recently, Desvignes (2014) and Villanova (2104) explored attribute level risk analysis, which allows one to evaluate risk independent of specific tasks and environments by focusing on fundamental characteristics (e.g., uneven surfaces, work at height, etc.). Alexander et al. (2015) introduced the energy-level risk analysis strategy by building upon the new attribute-level theory to predict the injury severity of the workers.

Construction Job Safety Analysis (CJSA) is a structured method for hazard analysis and assessment of construction activities. It was developed within the framework of research toward a lean approach to safety management in construction, which required the ability to predict fluctuating safety risk levels to support safety-conscious planning and pulling of safety management efforts to the places and times where they are most effective. The method involves identifying potential loss-of-control events for detailed stages of the activities commonly performed in construction and assessing the probability of occurrence for each event identified. The CJSA process comprises three significant steps: hazard identification, probability assessment and severity assessment (Rozenfeld et al., 2010).

Fung et al. developed a Risk Assessment Model (RAM) to assist the decision of safety professionals on safety management by examining the current safety problems in construction and investigating the various types of risks that occur in different work trades. The model is verified by reliability checking through a case study. The model consists of three main parts: the data input section, data analysis section and result section. RAM principle includes the stages of collection of historical accident data, risk assessment model and identification of risk level.

Aminbakhsh et al. proposed a novel framework based on the theory of cost of safety (COS) model and the analytic hierarchy process (AHP) to facilitate safety risk assessment. This framework presents a robust method for prioritizing safety risks in construction projects to create a rational budget and set realistic goals without compromising safety. According to the COS model, there is a theoretical equilibrium point at which the total costs of prevention and detection are equal to the total costs of injuries, and this point reflects the best possible investment. The COS model also supports the presumption that some level of safety risk must be considered acceptable to maintain an organization's financial stability. The framework first divides the decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The hierarchy elements are set in accordance with the construction safety risk problems. Once the hierarchy is built, experts assign a numerical scale to each pair of alternatives by making a pairwise comparison concerning their impact on the element placed at the higher level in the hierarchy. A priority index for each expert's judgment is determined by converting evaluations of risks into numerical values. Then, using the processed weights of the AHP, numerical values are compared and risk items are prioritized.

Tian et al. (2012) proposed the fuzzy analytic hierarchy process (AHP) method to evaluate work safety in hot and humid environments. It is difficult for crisp numbers to measure the behavioral factors and qualitative factors, such as safety training and personal protection. The human assessment of qualitative attributes is always subjective and thus imprecise. Therefore, conventional AHP seems inadequate to capture decision-makers’ requirements explicitly (Ayag and Ozdemir, 2006). To model this kind of uncertainty in human preference and capture the human reasoning, the principle of fuzzy logic was introduced. Trapezoidal fuzzy numbers are adopted to handle inherent uncertainty and imprecision of the data involved in the decision process. Within the proposed methodology, a decision group is firstly established. A safety evaluation framework containing three factors (work, environment, and workers) and ten sub-factors are established. The fuzzy weights of the factors and sub-factors are calculated based on pair-wise comparisons. Then the fuzzy evaluating vectors of the sub-factors and factors can be calculated according to the initial evaluation data. Therefore, the safety risk index, safety grade and early warning grade can be determined. An example is given to demonstrate the proposed method. The results illustrate the engineering practicability and effectiveness of this method in extreme environment evaluation.

Applying the concept of energy to explain safety risk requires understanding the concepts of both safety risk analysis and safety energy. According to ASSP (2018), the Energy Wheel is a simple but effective way to improve worker hazard recognition. This method focuses the worker's attention on the various types of energy present in the workplace rather than randomly attempting to identify workplace hazards. Hazard recognition in the construction industry rises significantly by using this energy source-based risk assessment technique. By applying this method, workers can recognize hazards which helps to reduce or mitigate accident potential through appropriate interventions.

2.6 Energy- Based Risk Indexing

A risk assessment is simply a careful examination of what, in the workplace, could cause harm to people. It enables a weighing up of whether enough precautions are in place or whether more should be done to prevent injuries related to those at risk, including workers and public members.

The impetus for an energy source-based safety approach is the concept of energy source-based hazard recognition (Albert et al., 2014). According to Carter and Smith (2006), construction workers are customarily poor at identifying hazards during construction because of the industry's diverse, fragmented, and dynamic nature. The inability to identify risks results in construction workers being exposed to unanticipated dangers or engaging in unsafe work practices without understanding the severity of adverse consequences (Wilson, 1989). Taking inspiration from William Haddon's work (Haddon, 1973) on safety energy, Fleming (2009) sought to improve worker hazard recognition by categorizing hazards based on the primary energy source that could cause the injury (e.g., motion, gravity, electricity, etc.). Fleming's (2009) principal theory is that all construction accidents originate from a specific energy source that is identifiable before work. When an energy source is released outside the work plan, the unexpected loss of control over the energy source creates the potential for injury.

Principles of energy source-based safety were soon implemented for hazard recognition by an expert team sponsored by the Construction Industry Institute (CII), which identified and predefined ten energy sources relevant to construction to serve as cognitive cues (Albert et al., 2014). Using a multiple baseline intervention research method with six construction crews, Albert et al. (2014) demonstrated a significant 31% improvement in hazard recognition skills amongst workers. Unfortunately, existing literature detailing the use of energy in construction safety is very sparse as the concept of energy source-based safety within the construction industry remains in its infancy. However, the initial research results indicate significant promise in using the concept of energy to identify and rank safety hazards encountered in the construction industry.

An energy wheel is a virtual tool to identify the ten primary energy sources. The energy source-based risk indexing method is developed here in this research to assess the hazards associated with the energy forms explained in the energy wheel. According to Haddon (1973), the energy theory is based on the observation that all injuries result from undesirable contact between a person and one or more energy sources.

The energy wheel has ten icons, each representing a different type of energy. Although not strictly scientific, the energy icons represent the most common ways energy manifests at work.

The word hazard is simply defined by Merriam-Webster (2015) as, "a source of danger." Hazards have been conceptualized according to the type of energy they represent (e.g., gravity, motion, mechanical, electrical, pressure, and so on). The concept of energy offers a new perspective that enables a more scientific understanding of hazards.

According to the energy theory, a hazard is a source of energy that could cause injury, illness, or death. The concept of energy, however, offers a new perspective that enables a more scientific understanding of hazards. In an occupational setting, energy is required to lift, transport, and assemble materials, and it can be stored or transferred by hoists, cranes, cables, equipment, and tools. Additionally, several materials possess stored energy in their natural state that may be released in the act of performing work (e.g., excavating a trench), and workers have energy under their elevated center of gravity when upright (Hallowell, 2020).

The following table (Table 1) provides a definition and example of the ten energy sources in the wheel. The illustrations are intended to be practical interpretations of each energy source rather than a precise scientific meaning.

Table 1: Definition and example of the ten hazardous energy sources in the wheel (source: Hallowell, 2020)

Energy Category	Definition	Examples
1) Gravity	The attraction of mass causes force on the earth	Uneven work surface, work at height, unsure materials, overhead support structures
2) Motion	Change in the physical position or location of objects or substances	Traffic, mobile equipment, projectiles, dust particles
3) Mechanical	Working parts of a machine or assembly, including rotation, vibration, tension, or compression	Auger, cable, chain fall, angle grinder, gears, pullies
4) Electrical	Presence of an electrical charge or current	Wires, power lines, power tools, extension cords, transformer, relay
5) Sound	Audible vibration caused by the contact between two or more objects	Heavy machinery, pile driving, power tools, nail gun
6) Pressure	Liquid or gas compressed or under vacuum	Pneumatic tire, piping system, tank, hydraulic lines
7) Temperature	The intensity of heat in an object or substance	Friction, engines, sudden pressure change, steam
8) Chemical	Toxic objects or substances that pose health risks	Solvents, engine exhaust, silica, wood dust, liquid concrete

9) Radiation	Objects or substances that emit electromagnetic waves or subatomic particles	Welding, sun exposure, x-ray testing, radioactive waste
10) Biological	Living organisms or viruses	Viruses like Covid-19; living organisms like bees, snakes, alligators, bears, restrooms etc.

2.7 Project MPSLSR Operation

Optimizing construction project scheduling has received a considerable amount of attention over the past 20 years (Zhou et al., 2013). Decision-making under uncertainty constitutes a broad and popular area of operations research and management sciences. A large number of studies can be found on project Time Cost Tradeoff analysis, whereas a few studies are available in the literature for the problem of MPSLSR. However, the MPSLSR modeling operation is somehow related to the concept of TCT optimization problem definition. The MPSLSR analysis does not include the cost in the problem formulation. It deals with risks and project duration only and the trade-off between them. The higher the schedule compression is required; the associated risk of any project activity increases accordingly, and so does the cost; notably, the cost dimension (activity or project levels including direct and indirect costs) is taken out of the MPSLSR problem definition to confine the complexity; project time-cost-risk further integration in optimized project planning will be worthy of pursuit in the future.

The MPSLSR operation identifies the best possible duration of any project with a manageable limit of the risk index value. The MPSLSR mathematical model consists of three things:

- A target or goal to minimize the accident risk index value with minimum project duration.
- A set of adjustable values of project duration and risk index that may be changed to improve the target.

- A set of constraints that need to be satisfied (i.e., activity duration to be accelerated on the critical path).

Mahdavian et al. (2020) analyzed how accidents would develop when work teams, equipment, and materials failed to work in coordination. Several studies demonstrate the importance of employee involvement in safety programs. As a result, modern planning and scheduling methods consider cost analysis, resource assessment, and the consideration of safety within a project.

Time-cost trade-off (TCT) analysis is a classic planning problem that appeals to construction management. Sadeghi and Lu (2021) developed a model that factors accident risks in the classic time-cost trade-off problem definition. It results in the best possible solution for the time-cost-safety trade-off (TCST) problem. It is noteworthy that a risk index is developed to add safety assessment to the decision-making process based on the conventional critical path method. Here the TCST problem was formulated as a nonlinear programming model, further demonstrated and validated by a case study with a few hypothetical what-if scenarios. This study revealed that the imposition of a risk index would markedly affect the resulting TCST problem's optimum solution.

Regarding safety-related risks, the activity time-risk relationship can be categorized as continuous vs. discontinuous, similar to activity time-cost relationships defined in TCT. Activity-level Time-Cost relationships can be linear, multilinear, or curvilinear (Ahuja et al., 1994). Hence, the discontinuous time-risk relationship can be discrete points or linear with gaps in between. The risk curve can be divided into many small, straight-line sections for a continuous curvilinear time-risk relationship to improve practicality.

Krokhmal et al. (2011) researched the most recent advances in the context of decision-making under uncertainty which emphasized the modeling of risk-averse preferences using the apparatus of axiomatically defined risk functionals.

Cooke and Pinter (2007) conducted research to indicate how mathematical programming (MP) techniques can be combined with probabilistic risk analysis (PRA) to structure and solve problems in risk management. This research aimed to illustrate how the modeling concepts and techniques can be combined with probabilistic risk analysis to structure and solve risk management problems.

They formulated cost-optimal and risk-minimizing models in both deterministic and stochastic settings.

Expediting critical activities to shorten the project completion time is commonly applied to mitigate delays and maintain the original project schedule. Kim et al. (2012) proposed a mixed-integer linear programming model to develop practical project schedules that consider the potential quality loss cost (PQLC) for excessive expediting activities. Since individual activity quality is defined by conformance to project contractor requirements, implementing project scheduling that considers the potential quality loss cost in the time-cost trade-off problem is practical (Kim et al., 2012).

Tran and Long (2017) applied the adaptive multiple objective differential evolution (AMODE) for simultaneously optimizing project time, cost and risk. They developed an equation to evaluate the minimization of total project risk, including two different elements. The first one is the ratio of current and maximum total float; the second one is the required resources for the project. As the total float is mainly resulting in more reserved time for activities. It increases the probability of completing the project on time and decreases the risk of schedule delay.

In replacing project costs with risks in MPSLSR, it is beneficial to know how to assess a risk index in a generic method, considering the relative range of risk and time values at the activity level. The importance of incorporating risk assessment by independent safety officers in safety-centric time-cost trade-off analysis has been highlighted in previous research (Mahdavian et al., 2020; Siddika and Lu, 2021).

Ling et al. (2009) emphasized organizational and environmental factors relating to time, month, location, size of the organization, and construction type to identify the proximal causes and contributory factors related to the fatality of the accidents. He adopted the induction approach to analyze the worker's behavior, what they were doing at the time of the accident and what time of the day the fatal accident was likely to occur etc.

Tunnel construction is becoming increasingly difficult nowadays. It creates more risks, stricter criteria must be applied during the design, construction, and operation phases. Structured or formalized methodology to assess risks of project activities and scheduling compression are lacking based on the literature review. Along with filling that particular gap, this research will address the importance of putting MPSLSR in the context of evaluating the risk of schedule for the project with high risks and claim contributions to optimize the project risk in the accelerated situation.

Chapter 3: Energy Source-Based Risk Indexing

3.1 Introduction

According to the literature review, all of the input information used for the various methods of Risk Index analysis is derived from qualitative surveys of industry experts or from historical data analysis, which is too subjective. The main disadvantage of this procedure is that the extracted information may differ from person to person and industry. A standard categorization of risk factors is needed to avoid this bias, which will help increase the consistency and reduce the subjectivity of data extraction from industry personnel. The intended concept of energy source-based safety risk indexing would address this significant shortcoming and serve as a means to reliably quantify the risk index value followed by the physical characteristics of the hazard.

The framework discussed in this chapter outlines the steps project managers can take to calculate the risk index values of associated construction project activities. The method developed in this section is associated with the related risk factors of ten significant types of energy release categorized by the American Society of Safety Professionals. These are Mechanical, Biological, Temperature, Chemical, Pressure, Electrical, Radiation, Sound, Gravity and Motion.

This study is intended to identify any energy category responsible for susceptibility to potential hazards on the project. The calculation of the risk index includes the assessment of the probability and severity of each associated factor. The risk indexing is based on an analysis of the construction process design associated with energy release resulting in occupational health and safety hazards. An example demonstration case is described in this chapter to show the method's applicability.

3.2 Risk Factor Identification

Ten significant categories of energy sources are responsible for injuries and loss in the construction industry (ASSP, 2018). As a first step of the energy source-based risk indexing methodology, related risk factors of these energy releases need to be addressed for the safety risk assessment of a construction project. This method will help to identify hazards, assess risk, and then implement the appropriate controls to prevent incidents in the construction project site. This process becomes even more essential for critical risk activities.

When a new project begins, the first step is to review the overall scope of work for the project to identify the potential hazards encountered during each work task and that are present on the project site. The first stage of an energy source-based risk indexing strategy is identifying the energy sources or other hazards that might exist during the project lifecycle or in the work environment. A checklist has been prepared considering these factors to address all the possible risks of the activities of a construction project (Table 2).

Table 2: Checklist to assess safety risks on construction activity by energy sources for injuries and loss

Serial No.	**Type of Factors**	**Related Risk Factors**	**Description**
1	Mechanical	Rotating equipment	It has to be checked whether there are any guards and devices to prevent access to dangerous areas.
		Compressed springs	
		Drive belts	
		Conveyors	
		Motors	
2	Motion	Vehicle speed, collisions and sudden stops	A wide variety of mechanical motions and actions are hazardous to workers. So, it has to be checked whether there are any mechanical motions and movements.
		Vessel or equipment movement	
		Flowing water	
		Wind action	

		Body positioning Lifting Straining Bending	
3	Gravity	Falling object Collapsing roof Body tripping Falling from a considerable height	It has to be checked whether there is any measure to control gravitational hazards by understanding the magnitude of forces.
4	Sound	Impact noise Vibration High-pressure relief Equipment noise	As there is no effective treatment for hearing loss, it has to be checked whether there are any hearing aids and scope to avoid exposure to loud continuous noise; workers are wearing hearing protection, reducing the time around loud noises.
5	Radiation	Lighting issues Welding arc X-rays Solar-rays	The sources of energy emitted from radioactive elements and naturally occurring radioactive materials must be identified to address the risks.

		Naturally occurring radioactive materials	
		Non-ionizing sources	
6	Electrical	Power lines	It has to be checked how vulnerable the site is to the presence and flow of electric charge.
		Transformers	
		Static charges	
		Drive belts	
		Conveyors	
		Motors	
7	Pressure	Pressure piping	It has to be checked whether there are any regular monitoring and maintenance to identify the leaks from high-pressure hydraulic lines, hoses, tanks, etc.
		Compressed cylinders	
		Control lines	
		Vessels	
		Tanks	
		Hoses	
		Pneumatic and hydraulic equipment	
8	Chemical	Flammable vapors	

		Reactive hazardous materials	Chemical hazardous materials should be handled carefully. So, the potential of hazardous chemical reactions should have been checked to assess this risk.
		Carcinogens or other toxic compounds	
		Combustibles	
		Corrosives	
		Pyrophoric materials	
		Inert gas	
		Welding fumes	
		Dust	
9	Temperature	Open flame and ignition sources	The temperature of the worksite has to be checked to assess the risks associated with it.
		Hot or cold surfaces	
		Liquids or gases	
		Friction	
		Bad environmental condition	
		Steam	
		Extreme or changing weather conditions	

10	Biological	Bacteria	Any risks that come from the biosphere should have been considered. It has to be checked whether the employees are working around other people who may have diseases or around animals and insects or working around potentially hazardous pathogens or sewers etc., or any sharp materials that need to be cleaned regularly.
		Animals	
		Viruses	
		Insects	
		Bloodborne pathogens	
		Contaminated water	
		Any other risks that come from the biosphere- like people, plants, or animals	

When using energy to identify risk factors, the energy wheel serves as a set of reminders to scan for hazards associated with each form of energy. The energy wheel can be used as a reminder to consider hazard categories that may have been overlooked. As an example, a crew may use the mechanical icon as a prompt to identify rotating machinery, the tension in cables, the vibration caused by the automated tools, and other hazards that may arise during the work.

Once the associated hazard risk factors have been identified, the next step is to calculate the risk index value by assessing the probability and severity of that specific risk event. The following sections of this chapter describe the risk index quantification method by using the energy source-based approach.

3.3 Risk Index Calculation Methodology

The evaluation of hazards and risks can be conducted by implementing a system of risk assessment, inspection, and field-level surveys aligned with the checklist. While collecting data, it needs to be confirmed whether the project plan considers the associated tasks or scopes of work relevant to the risk factors mentioned above. If the answer is ‘Yes’, the magnitude of the factors should be scaled up. Figure 1 illustrates the stepwise procedure of risk index calculation by following the energy-source based approach.

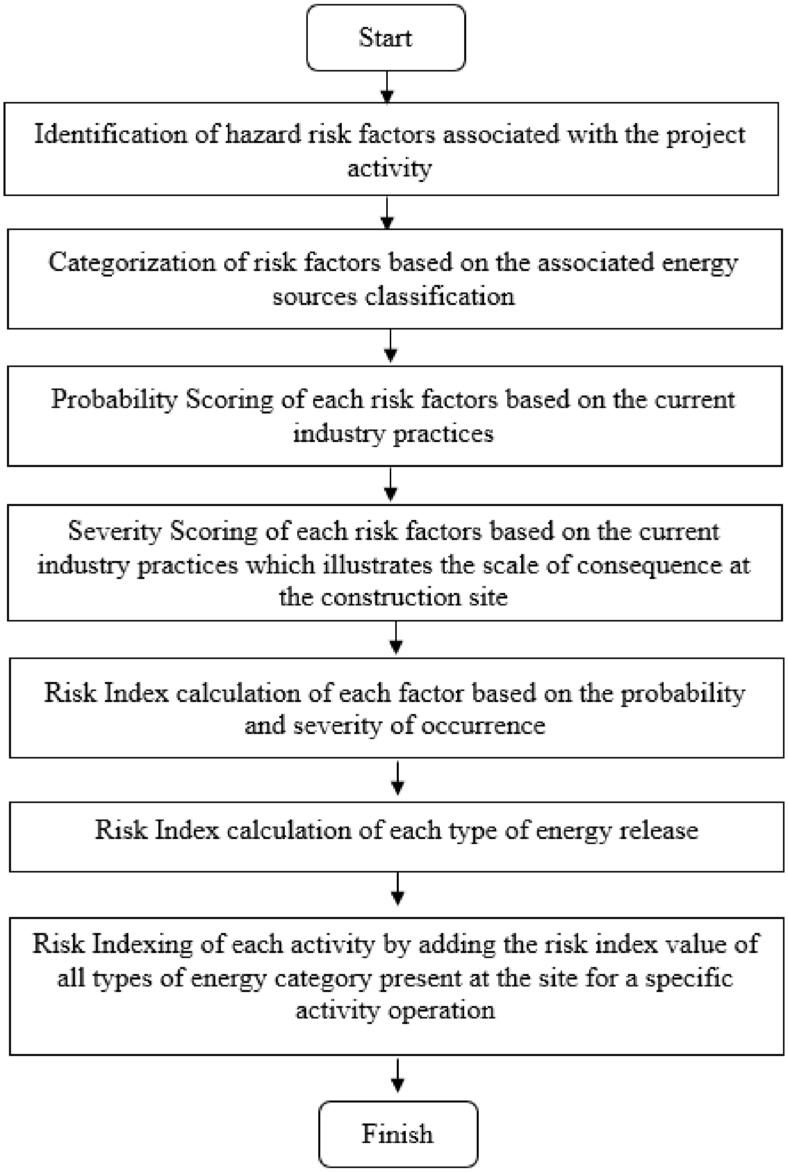


Figure 1: Flowchart of Risk index calculation methodology

The following procedure is proposed to guide the calculation of the risk index values of the project activities.

3.3.1 Calculation of Risk Index for Each Individual Factor

This step will consider both the severity of the potential loss, as well as the likelihood of it occurring. To calculate the average risk index for each individual factor, the probability and severity for the occurrence of each factor mentioned in Table 2 need to be fixed first based on the particular project situation. The following rating systems (Table 3 and Table 4) to assign risk points for each specific factor can be utilized for assessing the probability and severity value. After fixing the likelihood and severity value for each risk factor, the risk index value for each category of risk factors is calculated by the following equation (Equation 3).

Risk Index for each factor, $RI_i = \sum_{i=1}^{n} Pi * Si$ (3)

Here,
RI_i = Risk Index for risk factor i
P_i = Probability of risk factor i
S_i = Severity of each individual factor

The following tables (Table 3 and Table 4) illustrate a detailed description of the exemplary set of tailorable assessment scales for assessing the risk factors. Those are the potentially valuable inputs related to the probability and severity of occurrence of the threat source identification factors.

Table 3: Severity Index Scale to assign risk points for each factor (source: ACS, 2020)

Value	Qualitative value	Remarks
10	Catastrophic	• Multiple permanent injuries or irreversible health effects to the workers • An event that impacts the construction operation and delays • The incident led to the death
8	Major	• Significant injury leading to long-term incapacity or disability • Requiring time off work for >14 days
6	Moderate	• Moderate injury requiring professional intervention • Requiring time off work for 4–14 days • Agency reportable incident • An event that impacts a small number of workers
4	Minor	• Minor injury or illness requiring minor intervention • Expected delay <3 days
2	Negligible	• Minimal injury requiring no/minimal intervention or treatment • No delays • Minor property damage
0	No Risk	• No injuries, damage, or delays

Table 4: Probability Scale to assess the risk of each factor (source: MITRE, 2020)

Probability Score	Description	Remarks
1.00	Issue	Certain to occur
0.95-0.99	High	Extremely sure to occur
0.85-0.95	High	Almost sure to occur
0.75-0.85	High	Very likely to occur
0.65-0.75	High	Likely to occur
0.55-0.65	Medium	Somewhat more significant than an even chance
0.45-0.55	Medium	An even chance to occur
0.35-0.45	Medium	Somewhat less than an even chance
0.25-0.35	Low	Not very likely to occur
0.15-0.25	Low	Not likely to occur
0.00-0.15	Low	Almost sure not to occur

3.3.2 Calculation of Risk Index for Each Type of Energy Release

The risk index calculation for each energy source is done using the following mathematical expression (Equation 4). Here, the risk index value for each type should be 0 to 10.

Risk Index for each type of energy release, $RI_e = \frac{\sum_{i=1}^{n} RIi}{n}$ (4)

Here,

RI_i = Risk Index for the risk factor i

n = Total number of factors in each type of energy release sources

3.3.3 Calculation of Risk Index for Each Activity

The risk index is calculated by adding up all the values for each risk factor associated with the activity. The final risk index value ranges from 0 to 100.

The following equation (Equation 5) has been developed to calculate the final risk index for any specific activity type.

$$\text{Risk Index for Individual Activity} = \sum \text{Risk Index of Each Type of Energy release} \quad (5)$$

The impact of all the energy categories must not necessarily be the same for all the energy types. The level of the effects of different energy categories is achieved by assessing the impact of the severity value of the risk factors. The severity value illustrates the consequence of any incident at the construction site.

The nest step of the risk assessment process is to evaluate the risk index value. This step aims to ensure that decision-makers across the construction company have the appropriate risk-related information needed to inform and guide the construction decisions based on the risk index value of the project activities.

The following table (Table 5) templates for summarizing and documenting the risk index quantification of the construction project activities results.

Table 5: Interpretation of risk index value (source: NIST, 2012)

Qualitative Values	**Quantitative Values**	**Description**
Very High	96-100	Very high risk means that a threat event could be expected to have multiple severe adverse effects on construction operations, assets, individuals, and other resources
High	80-95	A threat event could be expected to have a severe adverse effect on the operation of that specific activity
Moderate	21-79	A threat event could be expected to have a severe adverse effect on the operation of that specific activity
Low	5-20	A threat event could be expected to have a limited adverse effect on the operation of that specific activity
Very Low	0-4	A threat event could be expected to have a negligible adverse effect on the operation of that specific activity

It is noteworthy that in the interpretation table (Table 5), the 80-point limit of the risk index value is defined between moderate level and high level of risk; hence, it is taken as the acceptable threshold of risk. Table 5 indicates that the risk index value of more than 80 may evolve with a severe or catastrophic adverse effect on the operation of that specific activity. So, when the risk index value is 80 or above, it is recommended not to continue that activity without taking essential measures to reduce its associated OHS-related risks.

3.3.4 Risk Slope Calculation

The first step of risk slope calculation is defining the risks for "accelerated case" vs. "normal case" on an activity in the project AON. The normal case is the activity's execution plan under normal circumstances regarding construction method, resource use, crew configuration and productivity, and the accelerated case is the activity's execution plan under accelerated circumstances.

Activity acceleration is the shortening of the duration of a project activity by reducing the time of that specific task. Construction project acceleration is accomplished by increasing project resources, which allows tasks to be completed in less time than was initially planned. On the other hand, the related risk indices of the project activities are also increased due to overstaffing, increased equipment use, etc.

As a result of project activity acceleration, the project's critical path may shift and a new, distinct critical path may emerge. It could also refer to spending more money to complete the activities faster.

The activity acceleration accounts for generating risk slopes for different scenarios. Risk slope of an activity can be defined as the additional risk index value generated due to the decrease of one unit of activity duration.

In the proposed methodology, the risk slope will be calculated as follows:

$$Risk\ Slope = \frac{Crash\ Risk\ index - Normal\ Risk\ index}{Available\ Crash\ Days} \qquad (6)$$

The proposed energy source-based risk indexing methodology seamlessly materializes the integration of risk assessment in the safety management of project activities. The following section includes a detailed example illustrating the applicability of the project.

3.4 Example Case

An example case study is developed to check the applicability of the energy source-based risk indexing methodology in the construction field. For the purposes of evaluation and analysis, the case pertains to the painting operation of a highway bridge construction project located at Miette Hot Springs, Jasper, Alberta.

3.4.1 Project Description

Miette Hot Springs are a significant attraction at Jasper National Park in Alberta. The springs have been in use since the 1930s. Before 2016, access to the springs required crossing over a small ravine called sulfur creek that was conveyed by two steel corrugated culverts under a gravel road passage. The bridge structure facilitates and maintains pedestrian and maintenance crew access to the hot spring. The bridge is also used as a crossing to access the Fiddle River Trail. The bridge is comprised of a 22 m superstructure, 6 m wide and supported on strip footings. The two 1800 mm diameter culverts were in poor condition and were eventually replaced by a single-span bridge.

The bridge was constructed in five major stages. The stages are as follows:

- Site preparation and survey work
- Pile foundation and footing installation
- Installation of the abutment walls
- Girder beam and concrete deck install; and
- Finishing operations, including painting and site clearance.

3.4.2 Work Breakdown Structure

A work breakdown structure of the bridge construction process is shown in Figure 1. The general progression of work included site prep, foundations installation, abutment wall construction, girder beam and a precast deck slab installation, and finally, the finishing operations. In total, the project has 44 activities which are further broken down in a detailed schedule. The following figure (Figure 2) illustrates the bridge construction project's work breakdown structure, which shows the major activities under each stage.

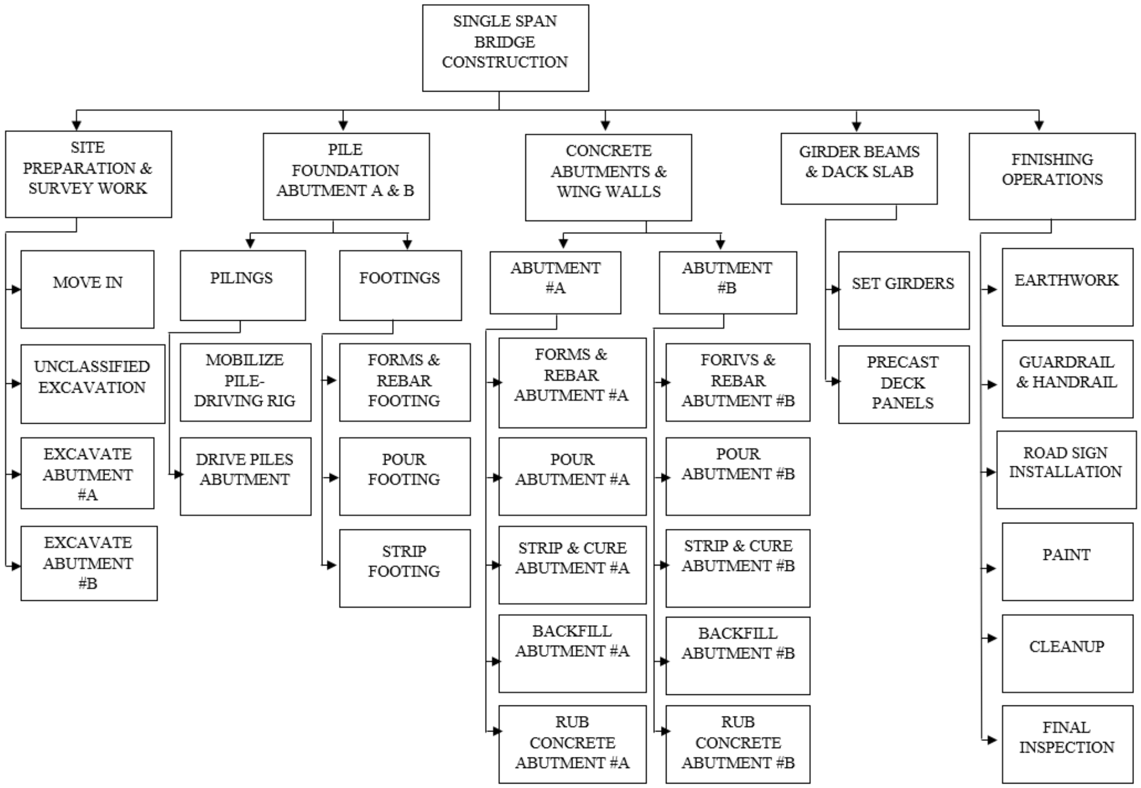


Figure 2: Project work breakdown structure

The activity level detail description of the Miette Hot Springs - Culvert and Bridge Replacement project with activity duration is illustrated in the following table (Table 6).

Table 6: Activity details for the bridge construction project example

Activity ID	**Activity Name**	**Duration (days)**	**Description**
1	Move-in (start activity)	3	Before starting construction, it is essential to set up the site perimeter. Upon completing of which, set up of safety measures follows.
2	Fabricate and deliver girders	25	After drawing approval, girder fabrication is started in the shop and prepared for delivery.
3	Fabricate and deliver precast deck panels	32	After drawing approval, deck fabrication is started in the shop and is ready for delivery.
4	Set up environmental and safety measures	7	Safety measures installation needs to be finished before starting utility structure demolition.
5	Demolition of Existing Structures	15	Includes removal of utility lines, which abutment excavation can be started.
6	Deliver piles and all Rebar	3	As per the drawing, piles and rebar are ordered for delivery to the site.
7	Prefabricate and deliver abutment forms	2	This activity can be started immediately after moving in.

8	Mobilize pile driving rig	3	After utility lines demolition, a piling rig can be mobilized to the site
9	Excavate abutment #1	2	Without finishing excavation, this activity can’t be started.
10	Drive piles, abutment #1	2	After excavation and having a piling rig on site, this activity can be started.
11	Excavate abutment #2	3	This can be started after finishing 1st abutment.
12	Forms and rebar, footing #1	1	After finishing pile driving, footing forms and rebar placement can be started.
13	Drive piles, abutment #2	1	After finishing the 2nd abutment excavation and pile installation in the 1st abutment, pile driving can begin.
14	Pour footing #1	6	Concrete can be poured after installing footing forms and rebar.
15	Demobilize pile driving rig	1	The pile rig needs to be demobilized before bringing the girder & deck crane.
16	Mobilize girder and deck cranes	4	It is needed to lift structural steel and concrete deck panels.
17	Strip footing #1	2	It combines curing after the concrete has ben poured.
18	Forms and rebar, abutment #1	2	After finishing footing, prefabricated forms and rebar placement can be done.

19	Forms and rebar, footing #2	1	After finishing pile driving, footing forms and rebar placement can be started.
20	Pour footing #2	3	Concrete can be poured after installing footing forms and rebar.
21	Strip footing #2	1	It combines curing after the concrete has ben poured.
22	Temporary shoring for abutment #1	4	Temporary shoring is required before pouring abutment 1 in order to provide additional support for the free-standing wall and potentially reduce the design thickness requirements for the wall.
23	Pour abutment #1	2	Concrete can be poured after installing abutment forms and rebar.
24	Strip and cure, abutment #1	3	It combines curing after the concrete has ben poured.
25	Forms and rebar, abutment #2	3	After finishing footing 2, abutment forms and rebar placement can be done.
26	Temporary shoring for abutment #2	3	Temporary shoring is required before pouring abutment 1 in order to provide additional support for the free-standing wall and potentially reduce the design thickness requirements for the wall.
27	Pour abutment #2	3	Concrete can be poured after installing abutment forms and rebar.

28	Rub concrete, abutment #1	3	This can be done after abutment 1 stripping
29	Backfill abutment #1	2	Backfilling can be started after finishing stripping and curing
30	Strip and cure, abutment #2	3	It combines curing after the concrete has ben poured.
31	Rub concrete, abutment #2	3	This can be done after abutment 2 stripping
32	Backfill abutment #2	5	Backfilling can be started after finishing stripping and curing
33	Temporary fall protection system 1	1	A fall protection system ensures workers can install girders and decks safely while installation of girders and decks proceed.
34	Set girders	3	After finishing both abutments and having cranes in place, girder lifting can be started.
35	Temporary fall protection system 2	1	A fall protection system ensures workers can install girders and decks safely while installation of girders and decks proceed.
36	Remove shoring for abutment #1 & #2	1	Removal of equipment
37	Precast concrete deck	7	After finishing both abutments and having girders in place, concrete deck placement can be started.

38	Apply joint expansion fillers	3	Joint fillers need to be applied for connecting decks
39	Guardrails	3	After finishing concrete rubbing and joint fillers application. This activity can be done.
40	Add road signage	3	Signage installation can be started after guardrail erection.
41	Remove temporary fall protection systems 1 & 2	3	Removal of the equipment.
42	Paint	2	This can be done after finishing deck placement, backfill and rubbing
43	Cleanup	3	Cleaning can be started after finishing signage and paint application
44	Final inspection	2	After cleanup, this can be done to inspect the presence of errors

For the detailing of the risk index calculation methodology, the risk factor identification and the calculation procedure are shown for the painting operation (activity ID #42) of the bridge construction project. Painting a bridge structure is an expensive operation with glowing emphasis on environmental, health and safety-related issues. Consequently, it is more important now than ever to obtain the longest possible life from bridge coatings which require adequate specifications, high-quality materials, proper usage, maintenance of equipment, and practical inspection. Coating failures are caused mainly by either inadequate surface preparation or coating application. Painting operations generate dust, solvent fumes, and noise. So, the environmental constraints governing the project must be taken care of, along with proper and safe disposal of abrasive material used to accomplish the paint removal according to the applicable laws and regulations (Alberta Bridge Construction Inspection Manual, 2015).

With numerous complex activities associated with a single-span bridge construction project, the painting operation was chosen to illustrate the risk indexing calculation. To calculate the risk index value for this specific activity, the associated risk factors were identified first and then the described methodology of risk indexing was applied to estimate the final index value. The following table (Table 7) shows the risk factors associated with the painting operation of the bridge construction project.

Table 7: Risk factors associated with painting operation

Type	**Risk Factor Associated**	**Description**
Mechanical	Presence of rotating equipment	• Equipment brakes not set, equipment left in gear, wheels not chocked, and controls not locked out can lead to equipment movement that could strike nearby workers. • Mechanical system failures such as hydraulic, steering, tailgate latching, lifting mechanism, tire pressure, etc. result in injury or property damage. • It's been checked and found that there are no guards and devices to prevent access to danger areas.
Motion	Vessel or equipment movement	• Wind, rain, and other weather conditions can create hazards while working at heights, such as falls, struck-by, or other injuries.
	Flowing water	
	Wind action	

		• It's been found that there is an abrupt movement of trucks and cranes. • The wind action is very high as the bridge site is located near a large spring. • Besides, there is flowing water while trenching. • Unpredictable pedestrian movements and unanticipated animal crossings can lead to struck-by incidents.
Gravity	Falling object	• Falls to a lower level without fall protection can result in severe injury or death. • Suspension trauma injury can occur when someone is suspended in a fall protection harness if a rescue plan is not executed immediately. • Inadequate anchor points can negate fall protection equipment and result in a fatal fall. • Falling objects (tools, materials, equipment, etc.) can result in injury. • Elevated work platforms or scaffolding can collapse, resulting in severe injury or death. • There are no guardrail systems with toe boards and warning lines or installed control line systems to protect

		workers near the edges of floors and roofs.
Electrical	Power lines	• Overhead power lines present an electrocution hazard for employees working from ladders, scaffolds, or elevated work platforms. • Striking overhead power or communication lines, or underground utilities can lead to electrocution. • There are new energized (hot) electrical circuits without all power shut off and attached grounds.
Temperature	Steam	• Vehicles operating near explosive atmospheres or dried-out vegetation can create an additional ignition source, leading to fire or explosion. • Cold weather conditions such as ice, snow, and freezing rain can reduce driver vision and vehicle traction, which may result in a collision. • As it is a hot spring bridge, there is hot steam from the spring. Besides, the weather condition is unpredictable here on the site.
	Extreme or changing weather conditions	
Chemical	Welding fumes and spills of chemicals	• Toxic gases that are heavier than air can collect in low areas and result in high concentrations.

		• Flammable gases may be present and can lead to an explosion. • Risk of drowning from leaks or rain runoff that might fill the excavation or trench. • Contaminated land, either naturally occurring or from previous land use (e.g., hydrocarbons, heavy metals, asbestos, or anthrax), can result in illness. • Exposure to vehicle exhaust can result in respiratory illness and other health conditions. • The work plan fails to recognize the hazards associated with chemicals that can cause chemical burns, respiratory problems, fires and explosions.

3.4.3 Risk Indexing

After identifying all associated risk factors, the probability and severity of each factor were assigned based on the comments and suggestions of the experts like the project manager or the safety coordinator of the project, project managers, the authors themselves and the colleagues within the research group and the construction company to ensure that it reflects the real ground scenario.

According to the proposed methodology for risk indexing of activities described previously, the risk index values of the painting activity of the bridge construction project are calculated and shown in detail in the table below:

Table 8: Risk index calculation of painting operation

Energy Category	Risk factor	Severity		Probability Value		Risk index
Mechanical	Presence of rotating equipment	Major	8	Very likely to occur	0.85	6.8
Motion	Flowing water	Moderate	6	Somewhat greater than an even chance	0.65	3.45
	Wind action	Minor	4	Likely to occur	0.75	
Gravity	Falling object	Moderate	6	Not very likely to occur	0.35	2.1
Electrical	Power lines	Minor	4	An even chance to occur	0.55	2.2
Temperature	Steam	Catastrophic	10	Almost sure to occur	0.95	9.75
	Extreme or changing weather conditions	Catastrophic	10	Certain to occur	1	

Chemical	Welding fumes and spills of chemicals	Negligible	2	Not likely to occur	0.25	0.5

3.4.4 Results and Discussion

The calculated total risk index value for the painting operation on the bridge construction project is 24.8, which indicates the moderately low value of risks. As described in Table 5 of the risk indexing methodology section, it is interpreted as a threat event that could have an adverse effect on the operation of that specific activity.

The energy source-based risk quantification method involves scoring hazard and exposure parameters to quantify the risk index value in a rapid, simple and structured manner. Assessment of risk index value in quantitative terms will help to anticipate potential accidents. It will help the construction manager to prevent the possibility of occurrence of accidents at the worksite. As a means of setting priorities and managing resources, the principles of risk indexing can be applied to various risk assessment projects.

Chapter 4: Generalized MPSLSR Operation for Acceleration Planning

4.1 Introduction

In this study, an efficient mathematical model is developed to achieve a minimum project schedule at the lowest safety risks as the best possible solution. This method can be called MPSLSR, which is the short form of "minimizing project schedule at lowest safety risks." The mathematical model is formulated as zero-one linear programming that minimizes the project risk index value. The discrete activity time-risk relationship is considered and adopted in the analysis. In this method, the overlap between project activities is allowed as overlapping activities allow for more realistic modeling of the construction projects (Harris, 1978). The model constraints include zero-one variables constraints and network logic constraints. The model results from various scenarios indicate that the risk index can change the project schedule's decision in connection with the duration of accelerated activities.

This research has investigated the impact of the safety risk on the project time-risk trade-off problem in connection with the critical path method. CPM is used to fix the critical paths and project duration, then MPSLSR operation is performed to expedite project completion while mitigating project OHS risks. To add OHS to the model analysis, a risk index consisting of the likelihood and severity of accident occurrence on each activity is defined.

To initiate the method, a brief explanation of the "minimizing project schedule at lowest safety risks" analysis is necessitated. In theory, "minimizing project schedule at lowest safety risks" (MPSLSR) is a new classic planning problem appealing to construction management followed by time-cost trade-off (TCT) analysis. For the modeling, the project duration can be shortened in each expediting cycle based on path-float analysis by shortening activities on the critical path(s) with the least risk slope. For TCT optimization, the goal is to limit the overall length of the project based on critical path analysis, in order to meet project deadlines while minimizing the total cost of the project (Elbeltagi, 2009). TCT analysis is intended to obtain results from all the cycles that point to "optimum" solutions for the lowest project cost or the shortest project duration (Nasiri and Lu, 2019).

In this research, project risk substitutes for the project cost in the methodology. The simplified version of the Critical Path Method (CPM), called the path-float-based critical path method (PFCPM; Lu et al., 2017), is used to determine project duration. PFCPM circumvents the backward pass analysis of traditional CPM and hence is more straightforward to apply, which is essential as critical path analysis is entailed in MPSLSR operation. Once all the paths are identified, recalculating the project duration of the updated project network (with new times for accelerated activities) requires only updating the lengths of those paths containing accelerated activities of the project (Lu et al., 2017).

In this chapter, the mathematical model of the MPSLSR problem solution for acceleration planning is developed and discussed in further detail. The model and method of analysis developed in this research integrate two critical elements, which are the project schedule and project risk index. By solving the model, the optimal solution could be obtained so that the most desirable risk response strategies to cope with the risk events can be determined. The process is based on an iterative process that involves making trade-offs between the project activity's time and risk index according to the project condition. The iterative process ends if the best-case scenario has been achieved. Two demonstration case study projects are also provided to illustrate the practicality and usefulness of the proposed method.

The following figure (Figure 3) illustrates the step-by-step procedure of the proposed analysis, including the input data preparation to interpret the output results for the acceleration planning of a construction project.

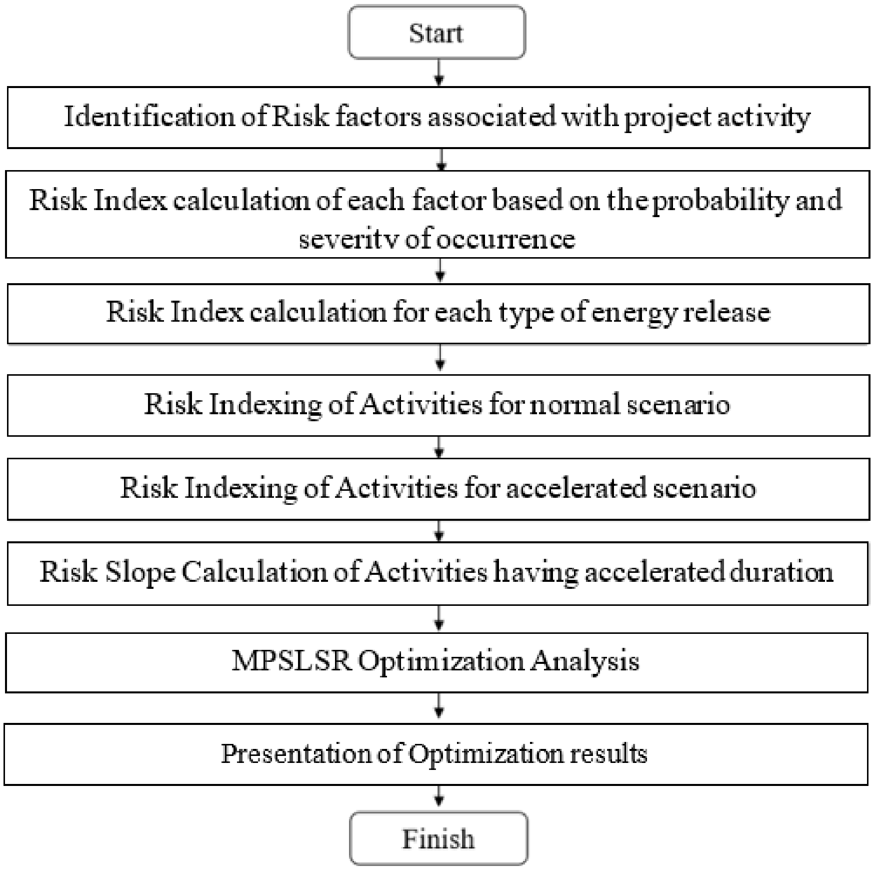


Figure 3: Flowchart of stepwise methodology of risk evaluation

In this research, a new approach involving the assessment of the release of energy sources is instrumental in systematically determining the risk index on a 100-point scale for each activity to structure the risk evaluation and reduce the bias of experts' judgments (ASSP, 2018). This approach is recommended for complementing the proposed new methodology and is reviewed herein. To show the ten primary energy sources as risk assessment categories in a better structured, more systematic way. Instead of evaluating risks for an activity on a construction project at the aggregate level, the energy source-based approach essentially breaks down risk into more granular sub-levels based on a standardized structure.

Minimizing project schedule at the lowest safety risks' (MPSLSR) operation requires either using CPM in heuristics or formulating CPM as part of the problem in mathematical programming. Path-based methods for critical path scheduling provide a streamlined alternative to substitute for the traditional CPM, thus presenting opportunities to streamline the Time-Risk trade-off. The traditional CPM-based problem formulation has a few limitations over the Path based Mathematical Programming method as per the findings of Nasiri and Lu (2022). According to their results, the traditional CPM-based Heuristic Method lacks mathematical rigor and there is no guarantee of the best possible solution. The Heuristic Method assumes a linear relationship between time and risk index, necessitating repeated use of the traditional CPM. Hence the following methodology applies the path-float concept for critical path identification in each cycle of time-risk trade-off. As a result, there is no need to perform the backward pass of CPM for total float calculation on each project activity.

4.2 Concept of CPM-Based Model Formulation

Heuristic methods can be described as simple rules of thumb (Hegazy, 2002) that require less computational effort than mathematical programming (Liu et al., 1995). Ahuja et al. (1994) provided an example of an iterative heuristic method. The compression procedure outlined in Ahuja et al. (1994) used a relatively similar method but without the IP formulization.

In the classic CPM analysis, the earliest begin time, the latest begin time LS, the earliest end time EF, the latest end time radio frequency, and total float TF should be documented for each activity (Lu and AbouRizk, 2000). The criticality of the activity will be determined by supported TF. The classic CPM analysis is easy and effective for straightforward, small-scale CPM networks. However, once facing complicated, large-scale CPM networks with a good variety of nodes and activities, the classic CPM formula becomes cumbersome and inefficient for two reasons:

First, the period for all the activities should be caterpillar-tracked and held on throughout the pass calculation to conduct the following backward pass calculations. Second, 5-time attributes (ES, EF, LS, LF, and TF) should be calculated before determinant the criticality of an activity. An actual project might compass many distinct activities. The simulation may have to be run many times to reveal the implicit schedule risk of every activity and of the total project.

The AON is used to demonstrate the CPM-based problem formulation for the following project activities. Figure 4 is a simple Activity-On-Node (AON) network with eight activities, including the start and finish activity, with only four critical paths.

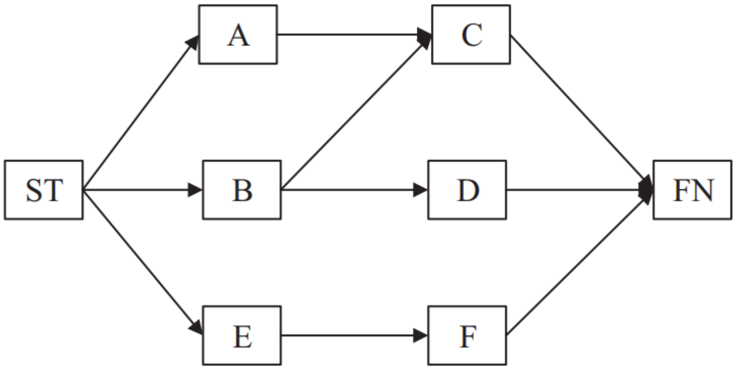


Figure 4: Sample AON

According to the critical path concept, the longest path is the critical path. For each non-critical path, path-float is defined as the difference in length between that particular path and the critical path.

In this case, it is assumed that the AON is based on the Classic Time-Risk trade-off problem solution, where the activity time-risk relationship is considered to be linear. To complete the project, a target project duration selection of activities is necessary to shorten by how much to result in the lowest total risk index at the project level. It is against unnecessarily crashing all activities to their shortest limits at the expense of a significant project risk index increase. As a result, the solution includes the best options to execute individual activities without compromising safety requirements while controlling the project duration to the minimum. The total duration would be expected to fall within the acceptable limit; otherwise, a solid case can be made to increase the project duration based on safety requirements and modeling analysis.

Heuristic methods are easy to understand and can provide acceptable solutions (Hegazy, 2002). However, these methods lack mathematical rigor, assume a linear time-cost relationship (Hegazy, 2002), and do not guarantee the best possible solutions (Hegazy, 2002; Ammar, 2018).

Mathematical programming methods convert the problem into standard mathematical optimization models and use linear, integer, or dynamic programming to obtain the optimal solution (Ammar, 2018). Most formulations minimize total cost as the objective function and apply certain time and other resource constraints (Jiang and Zhu, 2010).

Regarding mathematical programming methods, formulating constraints and objective function is time-consuming and prone to errors. For large networks, the effort that is required to check and verify the program's formulation could be substantial. Mathematical programming knowledge is necessary to formulate these models correctly. Few construction planners are trained to perform this type of formulation, especially for large networks (Liu et al., 1995). Exact solution algorithms for TCT are known to be exponential in the worst case and the solution time would increase exponentially as the problem size increases (Moussourakis and Haksever, 2004). Mathematical programming can be ineffective when dealing with a large number of variables or nonlinear objective functions (Jiang and Zhu, 2010).

4.3 Time-Risk Trade-off Methodology

For the MPSLSR operation, the first step is to define activity Time and Risk Index data given each activity in the project network model. The general MPSLSR problem can be formulated as an integer programming problem in which a zero-one integer variable $x_{jtm} = 1$ if Activity j operating in mode m ($1 < m < M_j$) is assigned a completion time in period t; otherwise, $x_{jtm} = 0$. Mj is an integer number denoting the discrete modes for executing activity in given time duration and at a certain level of risk

Considering a project having N activities where discrete points represent time and risk index data of project activities. Each activity i has m_i discrete points where $m_i \geq 1$. Each discrete point corresponds to a specific plan for carrying out the activity. Let d_i and r_i be variables representing duration and risk index of activity i, respectively. Let d_{i1} and r_{i1} represent the normal point, while d_{imi} and r_{imi} correspond to the accelerated point. For activities having only one discrete point, normal and accelerated points coincide and hence $m_i = 1$. These characteristics of discrete activity's time-risk relationship are depicted in Figure 5, noting the general trend of risk index increasing as activity time is shortened from the normal point to the accelerated point

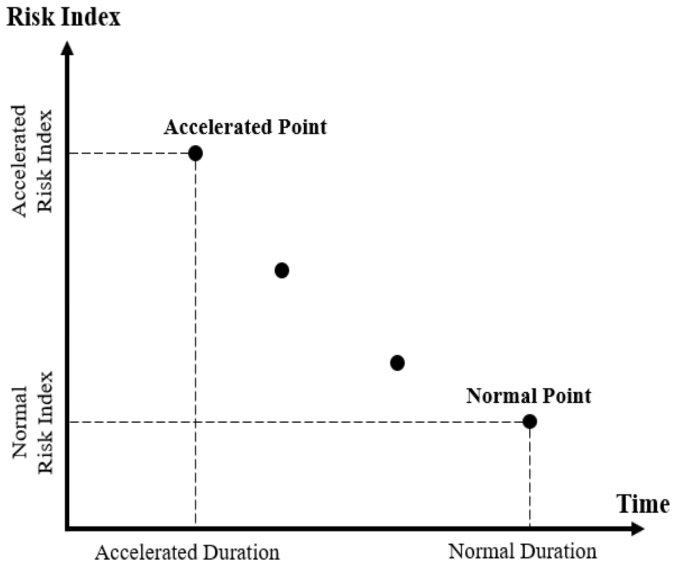


Figure 5: Activity's time-risk relationship

For each activity, a zero-one variable (x) is needed for each discrete point. These zero-one variables are introduced to ensure that only one discrete point is selected per activity (Ammar, 2020).

4.3.1 Calculation of Project Duration

Duration and risk index of activity *i*, in terms of zero-one variables, can be expressed by Equation (7) and Equation (9), respectively, where x_{ij} is a zero-one variable belonging to discrete point *j* of activity *i*. For Equation (8), critical path analysis on the project network is required to fix project duration, subject to precedence relationship constraints. Here, the activity set consists of critical activities along one critical path in the project network model.

Activity duration, $d_i = [d_{i1}x_{i1} + d_{i2}x_{i2} + \ldots\ldots + d_{imi}x_{imi}]$

$$d_i = \sum_{j=1}^{m_i} d_{ij} \times x_{ij} \qquad (7)$$

A critical path in project management is the longest sequence of activities that must be finished on time in order for the entire project to be completed. Here, the total project duration is calculated by Equation (8) along the critical path for the mathematical analysis.

$$Project\ Duration\ (critical\ activities), PD = \sum_{i=1}^{N}\sum_{j=1}^{m_i} d_{ij} \times x_{ij} \qquad (8)$$

4.3.2 Calculation of Project Risk Index

The risk index of each individual activity has been calculated by using equation (9). The project risk index is the summation of all individual activities' risks and is expressed mathematically by Equation (10). For each activity, the model has been forced to select a single discrete point (duration and corresponding risk) at a time by satisfying the zero-one variables constraint expressed by Equation (11).

Activity risk, $r_i = [\, r_{i1}x_{i1} + r_{i2}x_{i2} + \ldots\ldots + r_{imi}x_{imi}]$

$$r_i = \sum_{j=1}^{m_i} r_{ij} \times x_{ij} \qquad (9)$$

$$Project\ Risk\ Index, PRI = \sum_{i=1}^{N}\sum_{j=1}^{m_i} r_{ij} \times x_{ij} \qquad (10)$$

$$\sum_{j=1}^{m_i} x_{ij} = 1, \quad i = 1, 2, \ldots, N \qquad (11)$$

Activities are labeled from 1 to N, with Activity N being the unique terminal activity without successors. If such an Activity N does not naturally exist, then a Dummy Activity N having one mode with zero duration and zero resource requirements is appended to the project network model. Because each discrete point requires a zero-one variable, the needed number of zero-one variables is the sum of discrete points for project activities, whereas the number of zero-one variables constraints is equal to the number of project activities (N).

4.3.3 Logical Precedence Constraints

The project network is usually comprised of a set of paths, each of which includes a number of project activities. Each path k (P_k) can be expressed mathematically by the following equation:

$$P_k = a_{1k}y_{1k}, a_{2k}y_{2k}, \ldots\ldots, a_{ik}y_{ik}, \ldots\ldots, a_{Nk}y_{Nk} \qquad (12)$$

Where y_i is a zero-one parameter that takes a value of 1 if activity a_i exists on path P_k, otherwise, it takes a value of zero.

The set of paths includes P1, P2, …, Pk, …, PK, where K is the number of network paths. The set of paths could be determined either by visual inspection (for small project networks) or automatically using techniques such as Excel Based Path Finding Programming (Hegazy and Ayed, 1999). A linear integer programming mathematical model is proposed by extending the classic resource scheduling model formulated in operation research and computer science by Pritsker et al. (1969) and Talbot (1982). By specifying activities comprising each path, values of zero-one parameter (y) can be identified (Ammar, 2020).

Having the set of project paths determined, network logic constraints can be specified. The duration length of a path must be less than or equal to desired project duration; λ. That is to say, for any path k:

$$d_{1k}y_{1k} + d_{2k}y_{2k} + \ldots\ldots + d_{ik}y_{ik}, \ldots\ldots + d_{Nk}y_{Nk} \leq \lambda \qquad (13)$$

Where d_i is the duration of activity i belongs to path k, as given by Equation (7). If overlap exists between any two consecutive activities along path k, overlap values need to be deduced and non-Finish to Start precedence relationships need to be avoided or transformed. It must be noted that logical dependency constraints expressed by Equation (13) assume only traditional Finish-to-Start relationship. In the present research, it is also assumed activity duration is defined as integers (number of workdays) and any intermediate value between the normal and accelerated options would be deemed feasible; hence its corresponding time and risk index can be fixed through interpolation. The MPSLSR model can be summarized as the general steps described in the following steps.

4.3.4 Objective Function

Conceptually it is a multi-objective problem subject to complex activity time-risk constraints and project precedence constraints. The following equation is the objective function intended to minimize project completion time and risk index value:

$$\textit{Minimize Project duration}, PD = \sum_{j=1}^{m_i} d_{ij} \times x_{ij} \quad (14)$$

$$\textit{And minimize Project Risk Index}, PRI = \sum_{j=1}^{m_i} r_{ij} \times x_{ij} \qquad (15)$$

Subject to Zero-one Variables:

$$\sum_{j=1}^{m_i} x_{ij} = 1, \;\; i = 1, 2, \ldots, N \qquad (16)$$

4.3.5 Normalization of Objective Functions

Many multi-objective methods involve comparing and making decisions about different objective functions. However, values of various functions may have different units and significantly different orders of magnitude, making comparisons difficult. Thus, it is usually necessary to transform the objective functions into similar orders of magnitude. Although there are different approaches proposed for such a purpose, one of the simplest and the most robust is to normalize the objective functions as follows (Arora, 2017):

$$f_i^{norm} = \frac{f_i\,(x) - f_i{}^{\circ}}{f_i^{max} - f_i{}^{\circ}} \quad (17)$$

So, for the project duration, the normalization equation will be as follows:

$$PD_i^{norm} = \frac{PD_i\,(x) - PD_i{}^{\circ}}{PD_i^{max} - PD_i{}^{\circ}} \quad (18)$$

And the Project Risk Index value will be normalized by using the following equation:

$$PRI_i^{norm} = \frac{PRI_i\,(x) - PRI_i{}^{\circ}}{PRI_i^{max} - PRI_i{}^{\circ}} \qquad (19)$$

4.4 MPSLSR Model Validation

To validate and compare the developed mathematical model, a real-life project is considered as a case study. Initially, the project is solved with a detailed CPM-based mathematical calculation to identify the minimum project completion time and risk index following the developed mathematical algorithm. To avoid human calculation errors and accelerate the calculation process, a piece of software designed by Nasiri and Lu (2022) is used as an engine to develop a new program for modeling. It is an Excel-based automated computerized program that Nasiri and Lu used to find the best possible solution for TCT optimization.

During the operation process, the optimizer tries different combinations of adjustable values of Risk Index and Project Duration. Each such set is often called a trial. For each trial, the model is recalculated, and a new value for the targeted schedule and Risk Index is generated. Any trial that fails one or more constraints is not among the possible solutions to the problem (i.e., it is not a "valid" solution). Based on what it finds, the optimizer uses an algorithm to make modifications to come up with the next set of adjustable values. It will try to meet the constraint and further improve the target value. This process repeats until the operation ends.

This prototype TCT program has been prototyped to implement the newly proposed MPSLSR modeling methodology by taking advantage of Excel to handle a large number of activities (i.e., 100 activities project or more than that). The Excel-based algorithm has two programs. One is the Path Finding Program and another one is the Optimization Program. The path-finding algorithm is coded in Microsoft Visual Basics, while the Solver embedded in Excel is used to execute integer programming regarding selecting "To Accelerate" activities, resulting in the minimum project risk index value. The stepwise user guideline of the MPSLSR modeling prototype program has been added in the appendix section to ease the application method for future program users.

The program is instrumental in performing case studies, verifying the proposed methodology, and demonstrating its potential practical application. The next chapter illustrates two demo case studies to prove the applicability of the developed MPSLSR operation methodology in a real-life construction project.

Chapter 5: Case Studies on MPSLSR Operation for Activity Acceleration Planning

In the following chapter, the model framework outlined in the previous chapters will be applied to two case studies in order to illustrate its functionality for acceleration planning. In the first case study, the construction of a TBM tunnel project is planned to use the model framework. For the second case study, a 100-activity demo project is constructed to conduct the analysis. For each case study, the energy source-based risk indexing method was used at the first stage and afterward, the mathematical model was used for the trade-off between time and risk index value of the project. In this research, MPSLSR modeling application program has been utilized based on the TCT optimization engine program developed by Nasiri (2019). Validation of the model was carried out using the MPSLSR operation tool.

5.1 Case 1: TBM Tunnel Construction

To adequately illustrate and validate the steps and features of the developed methodology, a case study based on the activities and the associated risk index value of a TBM tunnel construction project is provided in this research. Here the case study is based on the demo data of the partner company's TBM tunnel construction operation.

Tunnel construction is an infrastructure project that includes many interfered and sophisticated tasks. The construction process is broken down into several activities and a network diagram is developed to represent the project logic.

The project is depicted by the AON network shown in the following figure (Figure 6).

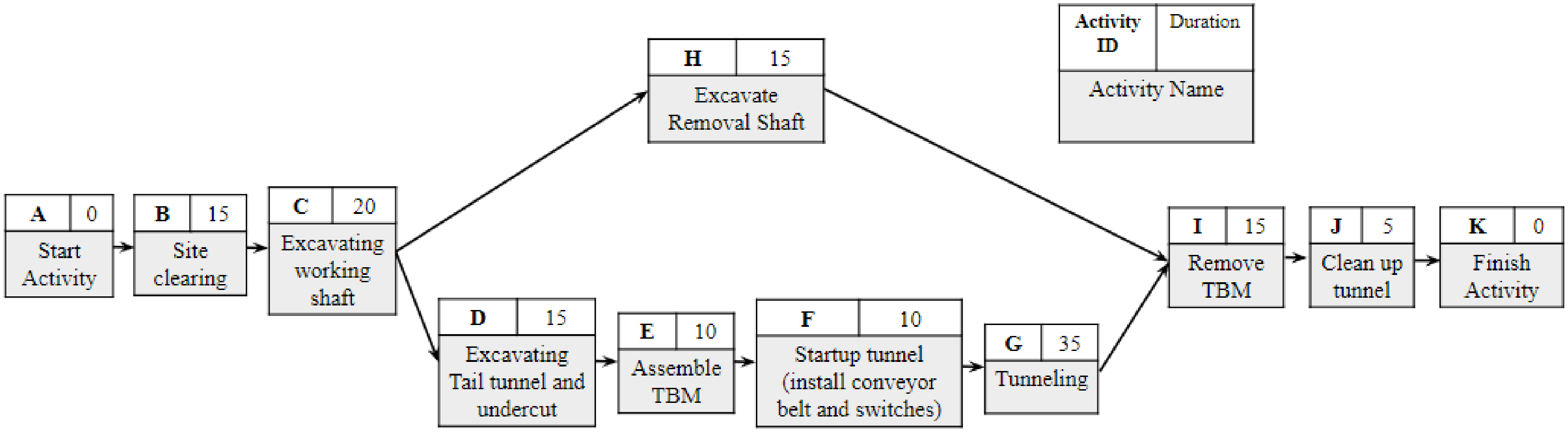


Figure 6: AON network model for the TBM tunneling case study

The tunneling project network consists of eleven (11) significant activities, including the start and the finish activities. The start and end activities are considered zero-risk activities in the AON (Fig. 1), which means there are no risk considerations associated with these two procedures. A brief description of the activities related to TBM tunneling is illustrated in the following section:

Site Clearing: Fixing and preparing the site location is the first step in any tunneling project. In this stage, the project team should look into several factors, including the availability of water supplies, electricity, easy access points, and space to store material on site. Site clearing includes clearing and grubbing (if any) of topsoil consisting mainly of loose soil, vegetable and organic matter, drift sand, unsuitable soil and rubbish by scarifying the areas to be excavated and sidewalks to a minimum depth from the natural ground level. All materials resulting from the above operations shall be removed from the site, loaded and transported and off loaded, spread and leveled to approved dumps as directed by the engineers.

Excavating Working Shaft: The working shaft needs to be excavated as part of the excavation process.

Excavating Tail Tunnel and Undercut: Upon completion of the shaft, the workers will begin excavating the tail tunnel, which will be used for material handling during excavation, and then the undercut, which will be used for the assembly of the TBM.

Assemble TBM: Earth Pressure Balance Machine (EPBM) has been assembled for this tunneling project. The project is located in an urban environment where ground surface subsidence cannot be tolerated.

Startup Tunnel: The workers can begin tunneling after installing the TBM. Due to the use of a single dirt car, TBM tunneling will be slow at the beginning and will be subject to frequent stoppages. Upon completion of a section, the crew must install the gantry and conveyor belt sections. As part of the installation process, they must also install a liner, and every time they complete a specific number of sections, they must stop to install tracks for the train.

Tunneling: Following the installation of the gantries and conveyor belts, the crew can use a full train once installed. To accelerate the tunneling operation, tunneling may be stopped to install switches, allowing workers to operate two trains simultaneously. After that, full-scale tunneling can begin. When the train arrives at the TBM, the material car is unloaded, which may contain concrete liners or ribs and leggings. A TBM excavates a section measured by the materials used and local specifications. Once filled with soil, the train begins traveling toward the working shaft as the TBM installs the tunnel's support material. Once the full train reaches the operating shaft, the other train (if empty) begins to move towards the TBM.

Upon reaching the TBM, that train begins excavating the next section if the TBM has finished installing the material. Otherwise, the train will wait. As soon as the train reaches the working shaft, the crew checks to see if the previous train has finished unloading. Depending on whether the trains are loaded or unloaded, the second train can begin unloading the dirt and loading the materials; otherwise, the second train should wait for the earlier train to complete loading or unloading. As long as the TBM reaches the end of the tunnel, this operation will continue.

Excavate Removal Shaft: When the TBM reaches the end of the tunnel, the removal shaft will be excavated in the same way as the working shaft.

Remove TBM: After the excavation of the removal shaft, the TBM will be removed from the tunnel.

Clean up Tunnel: The final step is cleaning up the tunnel by removing all the machinery and equipment.

There are several risk factors associated with tunnel construction activities. The partner company’s tunnel construction projects have numerous risk considerations like soil conditions risk, stiffness, issues related to the presence of boulders and cobblers etc. The construction process is also affected by atmospheric conditions like extreme cold weather, heat wave or snowing. According to the company’s database, cold temperatures usually shuts down the site for around 2 weeks on average a year as the risk of freezing the pipes is too high below -250C. Also, cold conditions require heaters and heat tracing, which increases costs and risks due to potential equipment failures or fire hazards.

In tunnel construction, if tunneling stops for any reason or the production rate is very low, there is a risk that the TBM may become stuck. This is because the drilling slurry is a clay mix, so if it sits too long outside the pipe/machine, it will settle and stiffen, requiring higher jacking forces to drive the TBM forward, which may not be feasible if the jacking forces exceed the capacity of the system. This would require a new work shift of 1 to 3 months.

The occupational health and safety risks associated with the tunneling activities are higher than the other construction projects. The associated hazard identification and data collection were done in collaboration with experienced construction planners and safety officers in the company. The details of the hazard database for the tunneling operation activity of the partner company have been shown in the following table:

Table 9: Hazard and risk data for the TBM tunnel construction project

Activity Details	**Hazard**	**Consequence**	**Likelihood**
EPB (Earth Pressure Balance)/TBM (Tunnel Boring Machine) break through	Falling debris	3	4
Removal of supporting tunneling equipment (rails, timber, pumps, hoses, piping)	Live loads	6	4
Removal of supporting tunneling equipment (rails, timber, pumps, hoses, piping)	Manual lifting	3	5
Removal of supporting tunneling equipment (rails, timber, pumps, hoses, piping)	Overhead hazards	6	4
Removal of supporting tunneling equipment (rails, timber, pumps, hoses, piping)	Pinch Points	3	5
Conveyor systems operations	Limited communication	5	5
Conveyor systems operations	Manual lifting	3	5
Conveyor systems operations	Pinch Points	3	5
Conveyor systems operations	Stored energy during mechanical	6	4

	adjustments and maintenance		
EPB/TBM maintenance (Hydraulic, electrical, transformer, mechanical, grease and oil)	Pinch points	3	5
EPB/TBM maintenance (Hydraulic, electrical, transformer, mechanical, grease and oil)	Pressurized lines	5	5
EPB/TBM maintenance (Hydraulic, electrical, transformer, mechanical, grease and oil)	Stored energy (high voltage)	6	4
Operating EPB/TBM	Crossing railways	5	5
Operating EPB/TBM	Entering cutting head	6	4
Operating EPB/TBM	Engulfment (dirt)	3	4
Operating EPB/TBM	Limited communication	5	5
Operating EPB/TBM	Noise	5	5
Operating EPB/TBM	Pinch points	5	4
Propulsion Jacks and Push Ring	Line of fire	3	5
Transporting/erecting segments	Line of fire	3	3
Transporting/erecting segments	Mechanical lifting, live loads	3	3

Transporting/erecting segments	Pinch points	5	4
Tunneling operations	Electrical power cut off due to hazardous gas detection from EPBM (Earth Pressure Balance Machine) monitors during excavation	2	5
TBM Eye Seal installation	Cutting and grinding	2	5
TBM Eye Seal installation	Falling debris	2	5
TBM Eye Seal installation	Live loads	6	4
TBM Eye Seal installation	Manual lifting	3	4
TBM Eye Seal installation	Overhead hazards	6	4
TBM Eye Seal Installation	Pinch points	3	4
TBM Eye Seal installation	Atmospheric hazards - Silica dust	2	5
Excavation of removal undercut (5m)	Engulfment (dirt)	5	5
Excavation of removal undercut (5m)	Hydraulic/Pneumatic hand tools (jackhammer)	2	5
Excavation of removal undercut (5m)	Manual lifting	3	5
Excavation of removal undercut (5m)	Pinch points	3	5

Track installation and leveling	Manual lifting	3	5
Track installation and leveling	Pinch points	3	5
Tugger and dirt car operations	High voltage batteries	2	5
Tugger and dirt car operations	Transporting heavy loads	5	5
Tunneling operations	High-pressure gas and oil pipeline crossing	5	5
General	Animal bites - insects	2	3
General	Animals - wildlife	2	1
Removal and loading of equipment and materials	Cutting and grinding	5	5
Shaft assembly (rib and lagging/shaft plates)	Hot work in a confined space	4	5
Lowering and installation of supporting rehab equipment (shaft plates/rib and lagging, dirt cars, rebar, forms, concrete buckets)	Overhead hazards	6	4
Removal and loading of equipment and materials	Overhead hazards	6	4

The raw data was further transformed in line with the energy source classification before determining the risk index value. Followed by Table 3 and Table 4 illustrated in the energy source-based risk indexing methodology section (Chapter 3), the data were converted to the required severity and probability scales. Afterward, the developed equations were applied to calculate the risk index value. The following table (Table 10) illustrates the modified raw dataset through the proposed input data processing method.

Table 10: Activity details with normal duration and different acceleration duration

ID	**Activity Name**	**Energy Type**	**Available crash days**	**Risk Index**				
				Normal Duration	**Acceleration duration**			
					1-day	**2-day**	**3-day**	**4-day**
A	Start Activity	-	-	-	-	-	-	-
B	Site clearing	Biological	2	0.4	0.9	1.6		
C	Excavating working shaft	Biological	3	5	5.9	7	8.3	
		Electrical						
		Motion						
D	Excavating Tail tunnel and undercut	Biological	2	5	5.9	7		
		Electrical						
		Motion						
E		Gravity	1	10.4	12.3			

	Assemble TBM	Pressure Electrical Chemical Mechanical Mechanical						
F	Startup tunnel (install conveyor belt and switches)	Biological Chemical Mechanical Gravity Motion Temperature	1	9.73	13.5			
G	Tunneling	Biological Electrical Sound Motion Chemical Pressure	4	11.82	13.8	16.12	18.87	22
H		Gravity Mechanical	2	5.18	8.03	11.48		

	Excavate Removal Shaft	Motion						
I	Remove TBM	Mechanical	2	2.5	3.6	4.9		
J	Clean up tunnel	Gravity	0	7.07				
		Biological						
		Mechanical						
		Motion						
K	Finish Activity	-	-	-	-	-	-	-

When construction delays occur due to the anticipated pace and progress of a project, it can become necessary to accelerate the schedule and recover the time lost. Likewise, a schedule may need to be shortened to achieve completion earlier. Accelerating the activities inevitably increases the occupational health and safety risks due to the presence of extra resources, overcrowding, overstaffing and any other factors associated with schedule compression. Utilizing the developed risk indexing framework, the risk index values for normal and accelerated scenarios have been calculated in this step. The project network consists of eleven (11) activities with activity risk index vs. time relationship being continuous curvilinear (given in Table 11). The following table illustrates the summary of results for the risk index values of activities for normal and accelerated situations. As can be seen from the table, the risk indices for different activities are relatively small. The highest score is 22/100 for the tunneling operation of the project. In accordance with the company's culture, tunnel contractors tend to take a conservative approach, avoiding risk rather than being aggressive or risk-taking in planning the construction.

Table 11: Risk index value of each activity for normal and accelerated scenarios

Activity ID	Activity Name	Normal Scenario		Accelerated Scenario	
		Duration (Day)	Risk Index	Duration (Day)	Risk Index
A	Start activity	0	0	0	0
B	Site clearing	15	0.4	13	1.6
C	Excavating working shaft	20	5	17	8.3
D	Excavating Tail tunnel and undercut	15	5	13	7
E	Assemble TBM	10	10.4	9	12.25
F	Startup tunnel (install conveyor belt and switches)	10	9.73	9	13.45
G	Tunneling	35	11.82	31	22.02
H	Excavate Removal Shaft	15	5.18	13	11.48
I	Remove TBM	15	2.5	13	4.9
J	Clean up tunnel	5	7.47	5	7.47
K	Finish activity	0	0	0	0

Afterward, the project utility data is calculated to use those results as input for the developed mathematical model. The utility data for project activities are given in Table 12, in which Risk Index slope values represent additional risk associated with accelerating an activity by one day beyond its normal condition.

Table 12: Example project input data

Activity ID	Predecessor	Duration (days)		Risk Index Slope ($/day)
		Normal	Accelerated	
A	-	0	0	-
B	A	15	13	0.6
C	B	20	17	1.1
D	C	15	13	1
E	D	10	9	1.85
F	E	10	9	3.72
G	F	35	31	2.55
H	C	15	13	3.15
I	G, H	15	13	1.2
J	I	5	5	-
K	J	0	0	-

If all activities are performed at their normal durations, the normal project duration is 125 days. Table 13 illustrates the possible acceleration duration and risk index value for each accelerated scenario of all the activities.

Table 13: Activities' acceleration data

Act. Opt.	B		C		D		E		F		G		H		I	
	D	RI	D	RI	D	RI	D	RI	D	RI	D	RI	D	RI	D	RI
1	15	0	20	0	15	0	10	0	10	0	35	0	15	0	15	0
2	14	0.9	19	5.9	14	5.9	9	12.3	9	13.5	34	13.8	14	8	14	3.6
3	13	1.6	18	7	13	7					33	16.1	13	11.5	13	4.9
4			17	8.3							32	18.9				
5											31	22.0				

Here, D = activity duration, RI = activity risk index. Act. Opt. = Activity Operation

The project network comprises two paths which are listed in Table 14. A value of one is inserted in the column that belongs to an activity if this activity exists on a path; otherwise, it takes a value of zero. Assuming normal duration for all activities (considering the overlap between consecutive activities), the normal path length (NPL) is calculated and the results are also given in the last column of the following table.

Table 14: Network paths of example project

Path No	A	B	C	D	E	F	G	H	I	J	K	Overlap	NPL
1	1	1	1	1	1	1	1	0	1	1	1	-	125
2	1	1	1	0	0	0	0	1	1	1	1	-	70

Comparing normal path length with accelerated project duration (110 days), it is obvious that only one path (Path 1) is dominant and the other one is redundant (Path 2). The activities comprising dominant paths are A, B, C, D, E, F, G, I, J and K. Zero-one variables constraints are required for activities B, C, D, E, F, G and I, since other activities (A, J, and K) have single point utility data and H is not in the critical Path. The following section illustrates the detail elaboration of the following steps defining the objective functions and constraints based on the data of the example project.

5.1.1 Elaboration of Objective Function and Constraints for Tunneling Case Study

Activity duration: For the critical path, the activities' duration in terms of zero-one variables would be:

$$D_B = 15x_{B1} + 14x_{B2} + 13x_{B3} \tag{20}$$

$$D_C = 20x_{C1} + 19x_{C2} + 18x_{C3} + 17x_{C4} \tag{21}$$

$$D_D = 15x_{D1} + 14x_{D2} + 13x_{D3} \tag{22}$$

$$D_E = 10x_{E1} + 9x_{E2} \tag{23}$$

$$D_F = 10x_{F1} + 9x_{F2} \tag{24}$$

$$D_G = 35x_{G1} + 34x_{G2} + 33x_{G3} + 32x_{G4} + 31x_{G5} \tag{25}$$

$$D_I = 15x_{I1} + 14x_{I2} + 13x_{I3} \tag{26}$$

Activity Risk Index: The total project risk index value adds up all the activities risk index value in consideration of zero one variable for all the possible acceleration scenarios. All activities' risk index in terms of zero-one variables would be as below:

$$RI_B = 0.4x_{B1} + 0.9x_{B2} + 1.6x_{B3} \tag{27}$$

$$RI_C = 5x_{C1} + 5.9x_{C2} + 7x_{C3} + 8.3x_{C4} \tag{28}$$

$$RI_D = 5x_{D1} + 5.9x_{D2} + 7x_{D3} \tag{29}$$

$$RI_E = 10.4x_{E1} + 12.25x_{E2} \tag{30}$$

$$RI_F = 9.73x_{F1} + 13.45x_{F2} \quad (31)$$

$$RI_G = 11.82x_{G1} + 13.8x_{G2} + 16.1x_{G3} + 18.9x_{G4} + 22x_{G5} \quad (32)$$

$$RI_H = 5.18\,x_{H1} + 8x_{H2} + 11.5x_{H3}$$

$$RI_I = 2.5\,x_{I1} + 3.6x_{I2} + 4.9x_{I3} \quad (33)$$

$$RI_j = 7.47x_{J1} \quad (34)$$

Objective Function:

Minimum Project Duration $= [15x_{B1} + 14x_{B2} + 13x_{B3}] + [20x_{C1} + 19x_{C2} + 18x_{C3} + 17x_{C4}] + [15x_{D1} + 14x_{D2} + 13x_{D3}] + [10x_{E1} + 9x_{E2}] + [10x_{F1} + 9x_{F2}] + [35x_{G1} + 34x_{G2} + 33x_{G3} + 32x_{G4} + 31x_{G5}] + [15x_{I1} + 14x_{I2} + 13x_{I3}] + 5x_{J1}$ (35)

According to the critical path-based concept, here the duration of all the activities on the critical path is considered. Here, activities A, B, C, D, E, F, G, I, J and K are on the critical path, where activity A is the start activity and activity K is the finish activity. The remaining activities which are not in the critical path are not included in the minimum project duration calculation.

Minimum Risk Index $= [0.4x_{B1} + 0.9x_{B2} + 1.6x_{B3}] + [5x_{C1} + 5.9x_{C2} + 7x_{C3} + 8.3x_{C4}] + [5x_{D1} + 5.9x_{D2} + 7x_{D3}] + [10.4x_{E1} + 12.25x_{E2}] + [9.73x_{F1} + 13.45x_{F2}] + [11.82x_{G1} + 13.8x_{G2} + 16.1x_{G3} + 18.9x_{G4} + 22x_{G5}] + [5.18x_{H1} + 8x_{H2} + 11.5x_{H3}] + [2.5\,x_{I1} + 3.6x_{I2} + 4.9x_{I3}] + 7.47x_{J1}$ (36)

Here, the minimum risk index value includes the risk indices of all activities (according to the mathematical modeling concept).

Subject to: Zero-one constraints

$$x_{B1} + x_{B2} + x_{B3} = 1 \quad (37)$$

$$x_{C1} + x_{C2} + x_{C3} + x_{C4} = 1 \quad (38)$$

$$x_{D1} + x_{D2} + x_{D3} = 1 \quad (39)$$

$$x_{E1} + x_{E2} = 1 \tag{40}$$

$$x_{F1} + x_{F2} = 1 \tag{41}$$

$$x_{G1} + x_{G2} + x_{G3} + x_{G4} + x_{G5} = 1 \tag{42}$$

$$x_{H1} + x_{H2} + x_{H3} = 1 \tag{43}$$

$$x_{I1} + x_{I2} + x_{I3} = 1 \tag{44}$$

5.1.2 Computerized Program Results for Tunneling

If all activities are performed at their normal durations, the normal project duration is 125 days. However, an all-augmented solution produces a project completion time of 110 days. Therefore, the two extreme project durations are 125 and 110 days. If the example project is formulated as a traditional MPSLSR problem, it requires 28 zero-one variables (number of activities' discrete points- Table 13), and 11 zero-one variable constraints.

Afterward, the minimum duration and minimum risk index values are normalized by following the equation (18) and (19). The total risk index of all the activities in normal settings is 57.5 with a project duration of 125 days. The total risk index of all the activities at accelerated settings is 88.5, with a project duration of 110 days. Despite the shortened project duration, the substantial increase in total risk index is noteworthy (from 57.5 in the normal scenario to 88.5 in the accelerated scenario, i.e., 54% increase in total risk index). The problem was solved by using mathematical modeling, which produced the near optimum solution in terms of the lowest total risk index value to realize the shortest total project duration (i.e., 80 in 110 days). The total risk index had been reduced from 88.5 in the accelerated scenario to 80 in the best case scenario in the realization of 110 days' project duration.

The following table (Table 15) compares the results from the normal, accelerated, and near optimum scenarios.

Table 15: Risk index value at normal, accelerated and optimized scenario for tunneling construction

	Normal Scenario	**Accelerated Scenario**	**Optimized Scenario**
Duration (days)	125	110	110
Risk Index	57.5	88.47	80.27

This one is a simple case study with only 11 significant activities, including the “Start” and “Finish” activities. For large-scale projects with a large number of activities, there will be too many constraints to calculate the near optimum duration and risk index value by interpolating the value of zero-one variables. The manual calculation process followed in the earlier stage is too much complicated and time-consuming for running this kind of trial and error. To overcome this challenge, the manual hand calculation part of this research has been switched to a computerized prototype program called MPSLSR automated program.

It is a computer-based program developed here to generate the best possible activity duration and risk index to cross-check the result found from the manual calculation. The automated prototype program has been run by using the inputs used in the manual calculation. The result from the computerized program gives almost the same values of risk index and duration. Along with the near optimum risk index and time, the automated prototype program provides the risk with the risk index value for all accelerated duration.

Table 16 shows the activity time and risk index as part of the best possible solution derived in the near optimum scenario, which is contrasted against the normal scenario and the accelerated scenario; it is noteworthy five activities (C,D,E,F, and I, as bolded) are accelerated to the shortest time limit; while the others still have potential room for shortening activity duration but are deemed unnecessary for achieving the shortest project duration in this case (i.e. 110 days).

Table 16: Activity time and risk index in the near optimum scenario against the normal scenario and the accelerated scenario for tunneling case study

Activity ID	**Normal Scenario**		**Accelerated Scenario**		**Near Optimum Scenario**	
	Duration	**RI**	**Duration**	**RI**	**Duration**	**RI**
A	0	0	0	0	0	0
B	15	0.4	13	1.6	14	0.84
C	20	5	17	8.3	17	8.3
D	15	5	13	7	13	7
E	10	10.4	9	12.25	9	12.25
F	10	9.73	9	13.45	9	13.45
G	35	5.18	31	11.48	30	10.54
H	15	11.82	13	22.02	14	15.52
I	15	2.5	13	4.9	13	4.9
J	5	7.47	5	7.47	5	7.47
K	0	0	0	0	0	0

The generated result from the automated program denotes the sweet spots between different sets of possible acceleration scenarios resulting in the best trade-off between the normal and accelerated duration and RI at each activity (no need to accelerate at all or to the limit). The third column shows the cumulative impact on the risk index value for the different number of activities accelerated. It considers all the possible acceleration scenarios and is reflected as a cumulative sum of individual activity's acceleration for each cycle.

The following table represents the results of all the activities of the tunneling case study obtained from different acceleration scenarios.

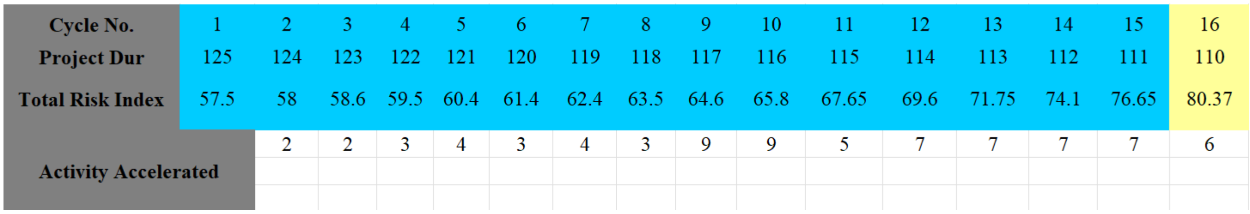
Table 17: Normal vs. accelerated scenarios of the automated prototype program

Cycle No.	**Total Project Duration (Days)**	**Risk Index**	**No of Activity Accelerated**
1	125	57.5	-
2	124	58	2
3	123	58.6	2
4	122	59.5	3
5	121	60.4	4
6	120	61.4	3
7	119	62.4	4
8	118	63.5	3
9	117	64.6	9
10	116	65.8	9
11	115	67.65	5
12	114	69.6	7
13	113	71.75	7
14	112	74.1	7
15	111	76.65	7

16	110	80.37	6

Figure 7 illustrates the results obtained from the automated prototype program. The blue shaded portion shows all possible combinations of different duration and risk index values for different possible scenarios and the yellow shaded one is the near optimum scenario generated from the program which can be denoted as the best-case scenario for the near optimum solution of the MPSLSR operation.

Because of the streamlined modeling formulation, the computing time in running the prototype program on this small case is negligible (only 3 seconds).



Cycle No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Project Dur	125	124	123	122	121	120	119	118	117	116	115	114	113	112	111	110
Total Risk Index	57.5	58	58.6	59.5	60.4	61.4	62.4	63.5	64.6	65.8	67.65	69.6	71.75	74.1	76.65	80.37
Activity Accelerated		2	2	3	4	3	4	3	9	9	5	7	7	7	7	6

Figure 7: Screenshot of results generated from the automated prototype program

The simplicity in operation along with the resultant computing efficiency potentially makes the proposed methodology capable of tackling problems of practical size (projects having more than 100 activities) and complexity, while the classic MPSLSR modeling solution would fail, as demonstrated in a second case study based on a 100-activity project network in the following section.

5.2 Case 2: 100 Activity AON Network

This global case study is a 100-activity project with the time and cost of each activity outlined, and the relationship between them. This new case is developed to demonstrate the implementation of the proposed methodology on a larger project network with curvilinear time-risk relationships on activities. The case consists of one hundred and two activities (activity 1 is the "Project Start" milestone and activity 102 is the "Project Finish" milestone), with fifty of them having acceleration options. Activity time-risk relationships are continuous curvilinear, which is either convex, concave, or a combination of convex and concave. Complete case data, including activities, risk index valuation, precedence relationships, durations, acceleration options and risk slopes for activities are provided in this section.

In this example, it is assumed that the duration of 200 days is in excess and requires accelerating the project schedule. If the lower possible time for each activity is assigned, the P6 schedule results in a project risk index of 1600 and a project duration of 191 days.

The following table (Table 18) depicts activities 1 to 102, with their respective normal duration, crash capacity, risk slopes and succeeding activities. The data used here for the detail calculation is assumed based on the current industry best practices. Historical data has also been used for the risk indexing of different activities. For validation purposes, most information is taken from various reference projects with similar risk factors associated with each activity.

Table 18: Activity ID, normal duration and risk slope

Activity ID	Normal Duration	Available Acceleration Duration	Normal Risk Index	Max. Risk Index	Succeeding Activities	Risk Slope			
						1	2	3	4
1	Start	-	0	0	2, 52				
2	18	0	8.55	12.25	3, 4, 5	3.7			
3	13	2	13.49	20.49	6, 7	3.5	6.7		
4	16	4	19.3	28.5	8	2.3	2.8	4.4	6.4
5	20	0	11.48	11.48	9, 10, 56				
6	16	2	15.1	18.5	11, 12	1.7	3.3		
7	16	1	22.8	25	13	2.2	2.5	3.1	5.8
8	19	2	13.65	20.25	14	3.3	3.4		
9	17	0	31.5	31.5	14, 15				
10	17	0	19.5	19.5	16, 17				
11	14	3	7.55	25.25	18	5.9	7.1	7.2	
12	14	4	6.8	16	19	2.3	2.4	4.3	6.5
13	17	2	28.5	33.5	19, 20	2.5	2.6	3.2	6.6
14	10	4	20.9	28.5	21	1.9	3.2	5.4	6.1
15	17	0	17	17	22				
16	10	4	26.85	33.25	22, 23	1.6	1.8	4.5	5.1

17	17	0	17.25	17.25	24, 25				
18	12	4	27.8	37	26	2.3	2.4	4.3	6.5
19	14	4	8.2	15	27	1.7	2.9	3	
20	14	1	10.05	17.25	28	7.2			
21	11	2	9	23	29	7	7.2		
22	13	0	20.5	20.5	30				
23	19	3	6.7	17.5	31	3.6	3.8	5	
24	19	3	17.7	31.5	32	4.6	4.9	5.4	
25	14	1	19.2	21	33, 68	1.8	2	7.3	
26	12	1	15.6	19	34	3.4			
27	20	4	13.1	29.5	34	4.1	4.2	6	6.1
28	18	1	9.25	16.25	34, 35, 36	7			
29	15	2	16.9	21.5	36	2.3	5.9		
30	14	0	19	19	36, 37				
31	13	1	14.1	17.5	38	3.4			
32	15	4	21.45	34.25	39	3.2	6	6.2	6.3
33	11	1	18.8	23	39	4.2			
34	19	3	13.4	21.5	40	2.7	5.1	6.7	
35	10	2	15.65	25.25	40	4.8	7.3		

36	20	0	13.5	13.5	41				
37	17	3	14	27.8	42	4.6	5	6.2	
38	12	3	19.3	25	43, 44	1.9	4.9	6.4	
39	15	2	19.85	23.25	44	1.7	4.6		
40	10	4	12.8	28	45	3.8	5.5	6.1	6.5
41	19	0	16	16	45	1.9	3.2	3.7	
42	16	3	14.3	21.5	45, 46	2.4	4.1	5.9	
43	14	1	9.8	11.5	47	1.7			
44	12	2	11.4	25	48	6.8	7.2		
45	15	0	12	12	49				
46	13	2	17.1	22.5	49	2.7	4.2		
47	19	4	9.6	26	50	4.1	5.8	6.8	6.8
48	11	3	16.2	21	50	1.6	3.6	4.7	
49	19	0	31.5	31.5	51				
50	15	1	9.7	16	51	6.3			
51	20	0	35.25	35.25	102				
52	19	0	19.5	19.5	53, 54, 55				
53	18	3	17.3	26	56, 57	2.9	5.2	5.4	
54	18	4	14.05	27.25	58	3.3	6.6	7	7.4

55	20	0	25	25	59, 60	2.3	2.5	3.4	
56	11	4	17.45	28.25	61, 62	2.7	3.8	6.4	6.6
57	18	1	7.3	12	63	4.7			
58	19	2	14.8	18.6	64	1.9	4.6		
59	18	1	8.8	14	65	5.2			
60	14	3	14.3	20	66, 67	1.9	4.5	4.7	7.2
61	19	3	19.75	24.25	68	1.5	1.9	2.5	
62	16	1	14	20	69	6			
63	10	4	16	24	70	2	2.4	5.1	6.6
64	20	3	13.9	23.5	71	3.2	4	4.2	
65	20	1	4.8	11	72, 73	6.2			
66	19	1	5.4	12.5	73	7.1			
67	16	1	10.2	14	74, 75	3.8			
68	16	1	23.9	25.5	76	1.6	3.2	5.3	6.4
69	16	1	15.9	20.5	77	4.6			
70	20	3	11.6	17	77, 78	1.8	2.9	3.3	
71	17	4	19.5	25.5	78, 79	1.5	2.9	5	6.8
72	17	1	8.9	11.5	79, 80	2.6			
73	12	4	13.2	24	81	2.7	4.2	7.2	7.4

74	20	2	10.6	15	82	2.2	3.8	3.9	
75	15	3	1.4	20	83	6.2	6.8	7.4	
76	18	0	11.25	11.25	84				
77	15	1	10.5	14	84	3.5			
78	19	4	23.4	31.8	85	2.1	3.1	3.6	7.3
79	12	1	14.4	21	86	6.6			
80	10	1	14.8	20	87, 88	5.2			
81	17	3	11.6	23	88	3.8	6.2	7.4	
82	19	2	2.45	6.25	89	1.9	3	7	
83	10	3	11.7	21	89	3.1	3.2	5.6	
84	14	2	23.4	27	90	1.8	6.9	7.1	
85	10	3	18.3	25.5	90	2.4	3.4	7.3	
86	15	3	12.6	24	91	3.8	6.2	6.9	
87	19	3	12.3	22.5	92	3.4	4	4.5	
88	11	1	8.5	15	93	6.5			
89	10	0	12	12	94				
90	20	1	9.1	14.5	95	5.4	5.7	6	
91	11	4	14.8	22	95	1.8	2.5	3.3	5.4
92	16	4	12.65	22.25	95, 96	2.4	3.5	4.4	5.2

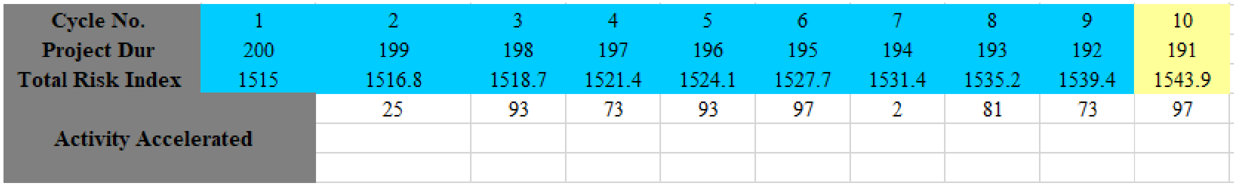
93	13	3	11.3	17	97	1.9	2.7	5.6	
94	20	3	1.5	9	98	2.5	3.6	6.2	7.2
95	13	0	19.5	19.5	99				
96	17	0	25	25	99				
97	12	3	13.7	24.5	100	3.6	4.5	6	
98	16	1	18	21	100	3	3	6.4	
99	13	0	22	22	101				
100	19	0	19.25	19.25	101				
101	11	0	14.5	14.5	102				
102	Finish		-	0					

As discussed in the introduction, the curvilinear relationship in typical construction activities is predominantly convex. The total risk index of all the activities in normal settings is 1515 with a duration of 200 days. A total of forty-one paths are found in the project network. The feasible solution which reflects the near optimum condition is the duration of 191 days with a total risk index value of 1544 (Figure 7).

The minimizing project schedule at lowest safety risks" (MPSLSR) modeling shows that there lies a best possible solution of schedule compression by keeping the risk index value lower. It is a clear outcome that this computer-based automated program is able to find the sweet spot between the normal and the maximum acceleration scenarios, which makes the task of the project manager easier than the earlier time when they had to proceed with manual calculation, which further leads to human error for the more extensive mathematical calculation.

The MPSLSR modeling result illustrates the activities and how much of the project duration has been accelerated. To clarify, applying an optimally accelerated project schedule at the global level, it is not necessary to fast-track each activity to its extreme. It is noteworthy to mention that the final total risk index value is the cumulative sum of accelerating all individual activities for different possible scenarios.

Figure 8 represents the final results of the “minimizing project schedule at lowest safety risks" (MPSLSR) automated program.



Cycle No.	1	2	3	4	5	6	7	8	9	10
Project Dur	200	199	198	197	196	195	194	193	192	191
Total Risk Index	1515	1516.8	1518.7	1521.4	1524.1	1527.7	1531.4	1535.2	1539.4	1543.9
Activity Accelerated		25	93	73	93	97	2	81	73	97

Figure 8: Results for 100 activity case

The result shows how much of the project duration has been accelerated for different activities. To clarify, applying an optimally accelerated project schedule at the global level, it is not necessary to fast-track each individual activity to its extreme. The total risk index of all the activities in normal settings is 1515 with a normal duration of 200 days.

If the prototype automated program outlined in this research is applied to this dataset, the duration of 191 days is generated, but with a risk index value of 1543.9. The computer-based integer programming produced the near optimum solution in terms of the lowest total risk index value which is 1543.9 whereas the risk index value for the maximum accelerated scenario is approximately 1600 (P6 solution). This resulting risk index value is 56.1, or 8% 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 accelerated scheduling at the lowest possible activity time. Overall, a realistic acceleration plan can be developed using the MPSLSR analysis for project duration and risk index while controlling for risk index increase.

The following table (Table 19) shows the comparison of the results from the P6-manual calculation done in this research for the normal scenario and the optimized scenario:

Table 19: Risk index value at normal, accelerated and near optimum scenario for 100 activity case

	Normal Scenario	**Accelerated Scenario**	**Near Optimum Scenario**
Duration (days)	200	191	191
Risk Index	1515	1600.25	1543.9

Table 19 illustrates the risk index values of three different scenarios and how much of the project duration has been accelerated. To clarify, applying an optimally accelerated project schedule at the project activity level, it is not necessary to fast-track each activity to its extreme. Only selected activities need to be accelerated to meet the objectives in terms of project risk or project duration.

The details of the results from running the automated program by using the data for 100 activity case are shown in the appendix section (appendix 2). The result from the computerized prototype program can be used as a guideline to the project managers or schedulers to design their project by minimizing the risk index value for an accelerated project duration of different critical activities of the project.

The following table (Table 20) shows the different sets of duration and risk index values for all the possible trials of the MPSLSR automated program.

Table 20: Detailed results of MPSLSR operation

Cycle No	**Project Duration (days)**	**Total Risk**	**Activity Accelerated**	**Remarks**
1	200	1515	-	Normal scenario
2	199	1516.8	25	Set of discrete point solutions
3	198	1518.7	93	
4	197	1521.4	73	
5	196	1524.1	93	
6	195	1527.7	97	
7	194	1531.4	2	
8	193	1535.2	81	
9	192	1539.4	73	
10	191	1543.9	97	Optimized scenario

In summary, it can be concluded that only selected activities need to be accelerated to meet the objectives in terms of project risk or project duration. As a result, the risk index of multiple activities would not necessarily change from the 'Normal' scenario, and only a few activities would entail implementing the 'Accelerated' scenario. In this way, the desired project scheduling and safety objectives can be achieved by realizing the shortest project time attainable.

5.3 Automated Computerized Engine Performance

The computer program for MPSLSR operation created in this study had been custom developed based on the TCT optimization engine designed by Nasiri (2022). The computing performance benchmarked on the engine program is also applicable to the application program. The TBM tunneling case illustrated in this thesis took only 3 seconds, and the 100-activity case took around 15 seconds to generate the results on a desktop computer with a 1.50 GHz CPU (Intel Core i5-1035G7).

For the purpose of benchmarking the computing performance of the computerized engine, this study retrieved data on the CPU time vs. project size testing data from Nasiri and Lu (2022). According to their findings, it takes the prototype program 12s to produce the solution for a 100-activity case study, running on a commonplace desktop computer with a 2.60 GHz CPU (Intel Core i7- 6700HQ). Given the scale and complexity of the case problem, formulating an optimization solution by the other established methods for optimization (like GA- scheduler, PSO framework, modified adaptive weight approach (MAWA), Next Search approach, Particle Swarm optimization method etc.) would be overcomplicated and practically infeasible, if not impossible. Therefore, the solution algorithm developed previously by other researchers may require a very long time to complete its computations before reaching the best answer or may fail to find any local minimum solutions at all. To further elaborate, the TCT algorithm developed by Nasiri (2019) breaks down the problem into smaller parts, reducing the number of variables.

Impact of Project Size on Computing Performance Evaluation:

Nasiri and Lu (2022) developed nine case scenarios to assess the efficiency of the TCT optimization technique for various network sizes ranging from 50-activity networks to 250 activity networks. The 50-activity network has 16 paths, each with around 11 activities, which was further enlarged by adding 25 new activities for each ensuing new case until reaching 250 activities. All activity durations were generated randomly on a range of 10 to 20 days. In order to increase the complexity, numerous precedence relationships were added between these paths to evaluate the computing performance. Each path has a similar number of activities, which increases the likelihood of similar path lengths, resulting in a more significant number of concurrent critical paths. Activities were added in each step to form parallel paths with the existing paths, resulting in multiple paths in the project network with mostly similar numbers of activities. Instead of extending the existing paths, new parallel paths were created in each step which increases the number of paths, resulting in a higher number of concurring critical paths. The computing time depends on the complexity of the integer programming problem (i.e., number of critical accelerable activities) in each cycle and the number of times integer programming is performed (i.e., number of cycles).

A summary of case characteristics and computing time performances is provided in Table 21.

Table 21: Case characteristics and computing times (source: Nasiri and Lu, 2022)

Case Number	**Number of Activities**	**Number of Paths**	**Number of Accelerable Activities**	**Number of Cycles**	**Computing Time (secs) on 2.6 GHz**	**Computing Time (secs) on 3.6 GHz**
1	50	16	35	23	12	10
2	75	28	54	23	14	12
3	100	32	70	24	24	21
4	125	44	89	24	25	23
5	150	51	105	20	25	23
6	175	61	124	20	26	24
7	200	65	140	20	30	27
8	225	77	165	20	34	30
9	250	81	190	28	51	44

The automated prototype program algorithm was coded and tested on two computer platforms independently, namely: one with a 2.60 GHz CPU (Intel Core i7-6700HQ) and the other with a 3.60 GHz CPU (AMD Ryzen 53,600) by Nasiri and Lu (2022).

The study has found that the developed computerized MPSLSR automated program's solution time is significantly low for the relatively larger complex project networks (e.g., less than one minute operation time on the 250 activities) compared to existing methods.

There are a few evidences related to the computing time performance benchmarking of different solvers developed by earlier researchers. One of the earlier solvers used an approximate model on a PC with i7-4700MQ CPU and 8GB RAM memory which failed to solve the 100-activity case in 1 hr. Furthermore, not a single instance of the 80, 90, or 100-activity cases could be solved in 3 hours using the exact method.

Another example case shows that a 33-activity case took 30 mins to get the solver results using an Intel 2.0 GHz CPU with 1G RAM PC. To compare against the present research, the proposed algorithm solved a 50-activity case in 12 s with a 2.4 GHz CPU. Nasiri (2019)'s TCT algorithm, on the other hand, solved a complex 100-activity case in 24 seconds using a 2.4 GHz CPU.

Chapter 6: Conclusion

6.1 General Findings

In addressing the substantial risks of occupational health and safety (OHS) in the construction industry, construction planners play a critical part in preventing occupational injuries or illnesses by following a systematic evaluation of OHS risks and adequately planning methods, resources and sequences for construction activities. The current practice of project acceleration planning would consequently result in increased vulnerability of the project in regard to OHS risks, especially on projects susceptible to high-level hazards in construction (such as tunneling and underground construction).

According to Lingard (2013), construction safety risk analysis involves decomposing the construction project activities and hazards to quantify the associated risks. This view is further reinforced by the concept of energy in this research, which breaks down the OHS risks to the most fundamental component, making the energy source-based risk indexing method applicable to all construction projects. This research defines the new project planning problem as "minimizing project schedule at lowest safety risks" (MPSLSR) for tunneling projects. Risks associated with planning activity methods are adequately assessed using a consistent, systematic approach. In addition, the MPSLSR problem is designed to mitigate the significant increase in OHS-related risks resulting from accelerating construction progress on projects by preventing the incurrence of unnecessary activity time crashing and associated OHS-related risks.

The main contribution of this research is to formalize MPSLSR as a new planning problem in the domain of construction management. The MPSLSR operation identifies the shortest project duration within an acceptable threshold of risks by adjusting individual activity time and corresponding risk index. In the end, the shortest project duration would be realized at the lowest value of the total risk index at the project level. The MPSLSR mathematical model is formulated in the form of zero-one linear programming that minimizes the project risk index value. The discrete activity time-risk relationship is considered and adopted in the analysis. Besides, the energy source-based risk indexing provides a new structured framework model to represent the complex OHS risk evaluation problem. It provides a potential new standard to classify, identify, and assess OHS on construction projects. Two case studies were performed and the results showed that the risk index could impact the project schedule's best possible decision regarding time and risk index settings on accelerated activities.

6.2 Limitations

This research has investigated the impact of the safety risk index on the high OHS risk-prone project’s duration problem in connection with applying the critical path method. Inspired by energy source-based hazard recognition, this research attempts to reduce subjectivity and enhance transparency by creating this energy source-based breakdown structure. However, in the proposed indexing method, each particular energy source's risk assessment on a project still utilizes the established techniques that can be subjective and dependent on individual experts. Formal brainstorming sessions would be effective in reconciling discrepancies in the subjective assessment. The ensuing research will address such limitations by providing more specific, quantitative guidelines for risk indexing assessment in particular application domains (e.g., tunneling) where certain energy sources might be quantitatively analyzed based on physical configurations and equipment used on site. Respective energy sources will also be elaborated in the context-specific of site and project and further analyzed with data and logic to evaluate safety risks instead of only counting on domain experts' experiences.

Nonetheless, it can be challenging to objectively evaluate safety risks in reality in the lack of proper and practical information about accidents or safety risks. Therefore, in the future, it would be essential to conduct energy source-based analysis to provide a database holding all the data related to construction accidents, including direct and indirect risks of accidents, likelihood, severity, and types of accidents associated with specific construction methods or activities. It is noteworthy that the MPSLSR analysis does not include the cost. It deals with risks and project duration only and the trade-off between them. Despite the limitations, this research will open new opportunities for the researcher to follow the proposed framework and enhance risk index quantification methods.

6.3 Future Study

At the project planning and scheduling stage, there is a practical need to identify the hazards and assess the associated risks to mitigate the hazards and bring the risks to a tolerable level. Hazard identification and risk assessment are carried out by identifying undesirable events that could lead to a hazard, analyzing the hazard of this unpleasant event that could occur, and estimating its extent, magnitude, and the likelihood of harmful effects. Numerous risk assessment techniques contribute significantly toward improvements in the safety of complex operations and equipment. Still, there is room for enhancement in quantifying the risk index value by using a scientific method, such as the practical need for a well-established methodology for risk indexing, which can be used to identify the severity of any associated risks activity of the construction project.

The energy source-based safety risk analysis concept is likely to natural disaster modeling, which forecasts the potential effects of a natural disaster by considering the scale of the occurrence and the resiliency of the impacted area (Johnson, 2004). This method utilizes the same underlying analytical strategy by considering the severity and probability of an accident event. Energy source-based safety risk analysis could produce a standard method to assess and forecast the seriousness of prospective injuries in any environment by quantifying the energy present in these potential hazards. Besides, project resource allocation is an important factor that was not considered here. The higher the schedule compression is required; the associated risk of any project activity increases accordingly, and so does the cost; hence, the cost dimension (activity or project levels including direct and indirect costs) is taken out of the MPSLSR problem definition to confine the complexity; project time-cost-risk further integration in optimized project planning will be worthy of pursuit in the future. In addition, there is still significant room for improvement in this method which can further reduce the subjectivity in risk assessment. For example, in particular construction actions, various forms of energy like potential energy or motion energy causing safety hazards can be quantitatively modeled and calculated, resulting in a more scientific assessment of OHS risks. By investigating the potential energy sources causing an accident in more realistic and scientific ways, future researchers may uncover deeper degrees of information.

References

Alhajeri, M. (2011). “Health and safety in the construction industry: challenges and solutions in the UAE.” Ph.D. thesis, Dept. of Civil Engineering, Univ. of Coventry, UAE.

Ahuja, H. N., Dozzi, S. P. & AbouRizk, S. M. (1994). *Project Management: Techniques in Planning and Controlling Construction Projects*. John Wiley & Sons, New York.

Agarwal, P. & Everett, J. G. (1997). “Strategies for Construction Contractors to Reduce Workers’ Compensation Costs.” *Journal of Management in Engineering*, 13(October), 70–75.

Albert, A., Hallowell, M. R. & Kleiner, B., M. (2014). “Enhancing Construction Hazard Recognition and Communication with Energy source-based Cognitive Mnemonics and Safety Meeting Maturity Model: Multiple Baseline Study.” *Journal of Construction Engineering & Management*, 140. doi:10.1061/(ASCE)CO.1943-7862.0000790.

Akintoye, A. S. & MacLeod, M. J. (1997). “Risk analysis and management in construction.” *International Journal of Project Management*, 15 (1996), 31-38.

American Society of Safety Professionals (2018). *American Society of Safety Professionals in conjunction with American Industrial Hygiene Association and Orr Safety Present: The Energy Wheel—an innovative approach to Hazard identification & Risk Assessment.* Retrieved from https://greatplains.assp.org/events/energy-wheel-risk-assessment/. Accessed on 12 Jan 2021, 1:30 pm.

American Chemical Society (2020). “Risk rating and assessment.” Retrieved from https://www.acs.org/content/acs/en/chemical-safety/hazard-assessment/fundamentals/risk-assessment.html. Accessed on 16 Jan 2021, 11:05 am

Alexander, D., Hallowell, M. & Gambatese, J. (2015). “Energy source-based safety risk management: using hazard energy to predict injury severity.” In *International Construction Specialty Conference*, 5 (2015), 214-224.

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.

Ayag, Z. & Ozdemir, R. G. (2006). "A fuzzy AHP approach to evaluating machine tool alternatives." *Journal of Intelligent Manufacturing*, 17 (2), 179–190.

Bonyuet, D. (2001). "Planning for safety." *PM Network.* 15(10), 49–51.

Bahamid, R., A. & Doh, S. I. (2017). "A review of risk management process in construction projects of developing countries." In *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 12-42.

Baradan, S., & Usmen, M. A. (2006). "Comparative Injury and Fatality Risk Analysis of Building Trades." *Journal of Construction Engineering and Management*, 132(May), 533–539. doi:10.1061/(ASCE)0733-9364(2006)132:5(533).

Bridge Construction Inspection Manual, Government of Alberta (2015), 2nd ed. Technical Standards Branch, Alberta Transportation, Alberta, Canada.

Carter, G. & Smith, S. D. (2006). "Safety Hazard Identification on Construction Projects." *Journal of Construction Engineering and Management*, 132(2), 197–205. doi:10.1061/(ASCE)0733-9364(2006)132:2(197).

Chatterjee, K., Zavadskas, E. K., Tamošaitienė, J., Adhikary, K. & Kar, S. (2018). "A hybrid MCDM technique for risk management in construction projects Symmetry." *Journal of MDPI*, 10(2), 46.

Computers: Construction Health and Safety Resources, Occupational Hazards, M. Blotzer (2005), Penton Media, Cleveland, Ohio, USA.

Cooke, R. & Pinter, J. (1989). "Optimization in risk management." *Civil engineering systems*, 6(3), 122-128.

Desvignes, M. (2014). “Requisite Empirical Risk Data for Integration of Safety with Advanced Technologies and Intelligent Systems.” M.Sc. thesis, Dept. of Civil, Environmental and Architectural Engineering, Univ. of Colorado, USA.

Everett, J. (1999). “Overexertion Injuries in Construction.” *Journal Construction and Engineering Management,* 125, 109–114.

Eskesen, S. D., Tengborg, P., Kampmann, J. & Veicherts, T. H. (2004). “Guidelines for tunnelling risk management: International Tunnelling Association, Working Group No. 2.” *Tunnelling and Underground Space Technology*, 19(3), 217–237. http://dx.doi.org/10.1016/j.tust.2004.01.001.

Ebrat, M. & Ghodsi, R. (2014). “Construction project risk assessment by using adaptive-network based fuzzy inference system: An empirical study KSCE.” *Journal of Civil Engineering*, 18, 1213-27.

Elbeltagi, E., Hegazy T. & Grierson, D. (2005). “Comparison among five evolutionary-based optimization algorithms.” *Advanced Engineering Information*, 19(1), 43–53.

Fleming, M. (2009). “Hazard Recognition.” *ASSE*, 11–15.

Fung, I. W. H., Tam, V. W. Y., Lo, T. Y. & Lu, L. L. H. (2010). “Developing a Risk Assessment Model for construction safety.” *International Journal of Project Management*, 28(2010), 593–600.

Grant, A. & Hinze, J. (2014). “Construction worker fatalities related to trusses: An analysis of the OSHA fatality and catastrophic incident database.” *Safety Science*, 65, 54-62.

Haddon, W. (1973). “Energy damage and the ten countermeasure strategies.” *Journal of Human Factors*, 15(4), 355–366.

Hallowell, M. R. (2020). “The Energy Wheel: Review of the Art and Science of Energy source-based Hazard Recognition.” *Safety Function*, 93, 1-8.

Huang, X. & Hinze, J. (2003). “Analysis of Construction Worker Fall Accidents.” *Journal of Construction Engineering and Management*, 129(June), 262–271. doi:10.1061/(ASCE)0733-9364(2003)129:3(262).

Hinze, J., Huang, X. & Terry, L. (2005). “The Nature of Struck-by Accidents.” *Journal Construction and Engineering Management*, 131(2), 262–268.

Hola, B. & Szóstak, M. (2014). “Analysis of the Development of Accident Situations in the Construction Industry.” *Procedia Engineering*, 91 (2014), 429 – 434.

HSE (1998). “Five steps to risk assessment.” *INDG163 (rev1)*, London.

HSE, (2002). “Revitalizing Health and Safety in Construction.” *Discussion Document on Casual factors in construction accidents London*, Health and Safety Executive.

Jannadi, O. & Assaf, S. (1998). “Safety Assessment in the Built Environment of Saudi Arabia.” *Safety Science*. 29 (1), 15-24.

Jannadi, O. A. & Almishari, S. (2003). “Risk Assessment in Construction.” *Journal of Construction Engineering and Management*, *129*(October), 492–500. doi:10.1061/(ASCE)0733-9364(2003)129:5(492).

Johnson, J. D. (2004). “Natural Disasters and Adaptive Capacity.” *OECD Development Centre*, 237 (2004), 45.

Keng, L. K. (2004). “A study of the factors influencing the implementation of occupational safety and health program for the construction firms in Penang.” B.Eng. thesis, Univ. Teknologi, Malaysia.

Krokhmal, P., Zabarankin, M. & Uryasev, S. (2011). “Modeling and optimization of risk.” *Surveys in Operations Research and Management Science*. 16(2011), 49-66.

Kendrick, T. (2003). “Identifying and managing project risk: essential tools for failure-proofing your project.” *Journal of American Management Association*, 368.

Kim, J. Y., Kang, C. W. & 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*, 30 (2012), 264–272.

Laryea, S. & Mensah, S. (2010). "Health and safety on construction sites in Ghana." *The Construction, Building and Real Estate Research Conference of the Royal Institution of Chartered Surveyors* (pp. 8-19).

Liu, L., Burns, S. & Feng, C. (1995). "Construction time-cost trade-off analysis using LP/IP hybrid method." *Construct Eng Manage ASCE*, 121(4), 446–454.

Lim, N. (2003). "Consumers' perceived risk: sources versus consequences." *Electronic Commerce Research and Applications*. 2 (2013), 216–228.

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

López, M. A. C., Fontaneda, I., Alcantara, O., J., G. and Ritzel, D., O. (2011). "The special severity of occupational accidents in the afternoon: The lunch effect." *Accident Analysis & Prevention*, 43 (3), 1104-1116.

Lingard, H. (2013). "Occupational health and safety in the construction industry." *Construction Management and Economics*, *31*(2015), 505–514. doi:10.1080/01446193.2013.816435

Lu, M., & AbouRizk, S., M. (2000). "Simplified CPM/PERT Simulation Model." *Journal of Construction Engineering and Management*, 126(3).

Lu, M., Liu, J., & 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.

Lu, M., Hasan, M., Patel, N. & Wang, B. (2020). "Tunneling Safe: Occupational Health & Safety in Tunneling." Retrieved from https://sites.google.com/a/ualberta.ca/ohst/home, accessed on 27th February, 2020.

Mahdavian, S., Bellale Manjunatha, K. S., Pereira, E. & Lu, M. (2020). "Safety-Centric Construction Acceleration Planning Guidance for Enabling Time Cost Tradeoff Analysis in Project Scheduling." *In Construction Research Congress 2020: Project Management and*

Controls, Materials, and Contracts (pp. 1186-1193). Reston, VA: American Society of Civil Engineers.

Merriam-Webster's collegiate dictionary (2015). 11th ed. Springfield, MA, Merriam-Webster Incorporated.

MITRE (2020). "Risk impact assessment and prioritization." Retrieved from https://www.mitre.org/publications/systems-engineering-guide/acquisition-systems-engineering/risk-management/risk-impact-assessment-and-prioritization. Accessed on 21 Jan 2021, 1:30 pm.

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

Nasiri, S. (2019). "Integer-Programming-Assisted Path-Float-Based Method for Time-Cost Tradeoff Optimization in Project Planning." M.Sc. thesis, Dept. of Civil and Environmental Engineering, Univ. of Alberta, Canada.

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.

Nasiri, S. & Lu, M. (2022). "Streamlined project time-cost tradeoff optimization methodology: Algorithm, automation, and application." *Journal of Automation in Construction*, 133(104002). doi: 10.1016/j.autcon.2021.104002.

National Institutes of Standards and Technology (2012). "Guide for conducting risk assessments." Retrieved from https://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-30r1.pdf. Accessed on 12 Jan 2021, 4:30 pm.

Nyirenda, V., Chinniah, Y. & Agard, B. (2015). "Identifying Key Factors for an Occupational

Health and Safety Risk estimation Tool in Small and Medium-size Enterprises.” *IFAC- Papers Online*, 48, 541 – 546.

Occupational Safety and Health in the Age of High Technology, D. L. Goetsch (1996), Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Okoye, P. U. (2018). “Occupational health and safety risk levels of building construction trades in Nigeria.” *Construction Economics and Building*, 18(2), 92-109.

OHS (2009). “Occupational Health and Safety Code.” *Occupational Health and Safety Act*, Province of Alberta, Canada.

Perry, J. G. & Hayes, R. W. (1985). “Risk and its management in construction projects.” *Journal of Institution of Civil Engineers*, 78 (1), 499-521.

PMP: Project management professional exam study guide. K. Heldman, C. Baca & P. Jansen, (2007). 2nd ed. John Wiley & Sons, New York.

Precedence and arrow networking techniques for construction, R. Harris (1978), John Wiley & Sons, New York.

Principles of Construction Safety, A. S. J. Holt (2001), Blackwell Science, London.

Renaulta, B. Y., & Agumba, J. N. (2016). “Risk management in the construction industry: a new literature review.” In *4th International Building Control Conference* (Vol. 66, pp. 1-6).

Risk analysts and its applications, D. B. Hertz & H. Thomas (1983). John Wiley & Sons, New York.

Rozenfeld, O., Sacks, R., Rosenfeld, Y. & Baum, H. (2010). "Construction Job Safety Analysis." *Safety Science*, 48 (2010), 491–498.

Sadeghi, M. & Lu, M. (2020). “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.

Salah, A., & Moselhi, O. (2016). “Risk identification and assessment for engineering procurement construction management projects using fuzzy set theory.” *Canadian Journal of Civil Engineering*, 43 (2016), 429-442.

Siddika, A. & Lu, M. (2021). “Evaluating Risk Indices for Execution Plans of Construction Activities: Energy Sources Approach.” In *Canadian Society of Civil Engineering Annual Conference 2021* (pp. 185-196), Springer.

Shapira, A. & Lyachin, B. (2009). “AHP-Based Weighting of Factors Affecting Safety on Construction Sites with Tower Cranes.” *Journal of Construction Engineering and Management*, 135(January), 307–318.

Siang, L.Y., Ghazali, F. E. M., Zainun, N. Y. and Ali, R. (2017). “General risks for tunnelling projects: An overview.” In *International Conference of Global Network for Innovative Technology and AWAM International Conference in Civil Engineering* (pp. 8–9).

Sriprasert, E. & Dawood, N. (2003). “Genetic algorithms for multi-constraint scheduling: An application for the construction industry.” In *Conference on Information Technology in Construction* (pp. 341–352).

Sousa V., Almeida, N. & Dias, L. (2014). “Risk-based management of occupational safety and health.” *Safety Science,* 66 (2014), 75-86.

Su, Z. X., Qi, J. X. & Wei, H. Y. (2015). “A float-path theory and its application to the time-cost tradeoff problem.” *Journal of Applied Math*, 17 (2015), 19-32.

System Analysis & Design for Safety, D. B. Brown (1976), Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA.

Tian, Z., Zhu, N., Zheng, G., Chen, Y. & Sun, B. (2012). “Application of a trapezoidal fuzzy AHP method for work safety evaluation and early warning rating of hot and humid environments.” *Safety Science*, 50 (2012), 228–239.

Tran, D. H. & Long, L. D. (2017). “Project scheduling with time, cost and risk trade-off using adaptive multiple objective differential evolution." *Journal of Engineering, Construction and Architectural Management*, 25(5), 623-638.

Villanova, M. P. (2014). "Attribute-based Risk Model for Assessing Risk to Industrial Consturction Tasks." M.Sc. thesis, Dept. of Civil, Environmental and Architectural Engineering, Univ. of Colorado, USA.

Wang, S. Q., Dulaimi, M. F. & Aguria, M. Y. (2004). "Risk management framework for construction projects in developing countries." *Construction Management and Economics*, 22, 237-52.

Watts, A. (2014). *Project Management. Victoria, B.C.: BCcampus*. Retrieved from https://opentextbc.ca/projectmanagement/.

Wilson, H. A. (1989). "Organizational behaviour and safety management in the construction industry." *Construction Management and Economics*, *7*(4), 303–319.

Yang, I. (2005). "Chance-Constrained Time–Cost Tradeoff Analysis Considering Funding Variability." *Journal of Construction Engineering and Management,* 131(9), 1002-1012.

Yazdani-Chamzini, A., Yakhchali, S. H., Volungevičienė, D. & Zavadskas, E. K. (2012). "Forecasting gold price changes by using adaptive network fuzzy inference system." *Journal of Business Economics and Management*, 13(5), 994–1010. http://dx.doi.org/10.3846/16111699.2012.683808.

Zafirovski, Z., Gacevski, V., Lazarevska, M., & Ognjenovic, S. (2019). "Procedures for risk analysis and management in tunnelling projects." In *ITESE-2019 Conferences* (pp. 1001).

Zhou, Z., Goh, Y. M. & Li, Q. (2015). "Overview and analysis of safety management studies in the construction." *Safety Science*, 72 (2015), 337-350.

Zhou, J., Love, P., Wang, X., Teo, K. L. & Irani, Z. (2013). "A Review of Methods and Algorithms for Optimizing Construction Scheduling." *Journal of Operation research Society*, 64 (2013), 1091-1105.

Appendix

Input Data Preparation

To implement the proposed new methodology by taking advantage of computerized program, the input data needs to be prepared. It is a specialized automated, complicated prototype program. The prototype program requires the following dataset to run the computerized model:

1. Precedence relationship between activities (including start and finish activity)
2. The total risk index value for the normal scenario
3. Number of available paths on the AON network
4. Risk Index Value for the normal scenario
5. The risk index value for the accelerated scenario
6. Risk slope for a unit acceleration of each activity

Computerized MPSLSR Program User Guideline

The Excel-based TCT program concept developed by Nasiri and Lu (2022) has been tailored as an engine here in this research, where the project risk index has been considered instead of the project cost. The proposed MPSLSR methodology has been fully automated, consisting of two programs.

- The first program is used to automate path finding, where the user enters precedence relationships and the paths are generated.
- The second program automates the methodology, where the user enters activity data (normal duration, available acceleration time, and risk slopes) and paths generated from the first program in order to obtain the MPSLSR operation results.

The proposed method consists of several steps divided into the following two parts:

1. Path Finding Program
2. Optimization program

In this section, the tunneling project case explained earlier has been used as an example to show how to use the prototype program with step-by-step screenshots. This section also contains the process of input preparation along with how to check the outputs.

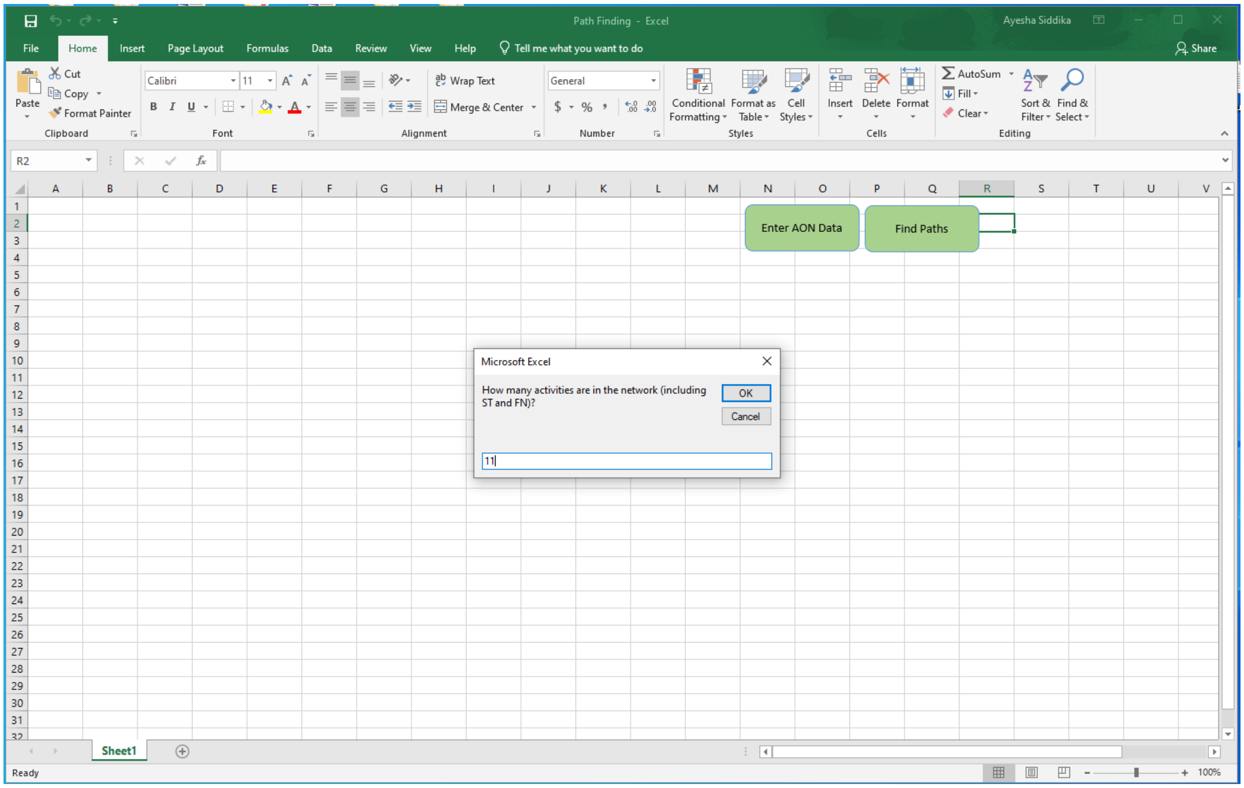
Part 1: Path Finding Program (Initialization)

The first step in the proposed method is to find all possible paths from start to finish in the AON network. For small project networks, this task can be easily done manually by visual inspection. However, for large-sized complex networks, identification of each existing path can become challenging, if not practically impossible.

This program determines the total number of paths and the set of activities on each path. The path-finding program has multiple different steps to find all the possible paths from start to finish for the AON network. The steps are explained in the following section:

Step 1: Finding all the possible paths in the project AON network model

In step 1, the user has to 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.



Microsoft Excel

How many activities are in the network (including ST and FN)?

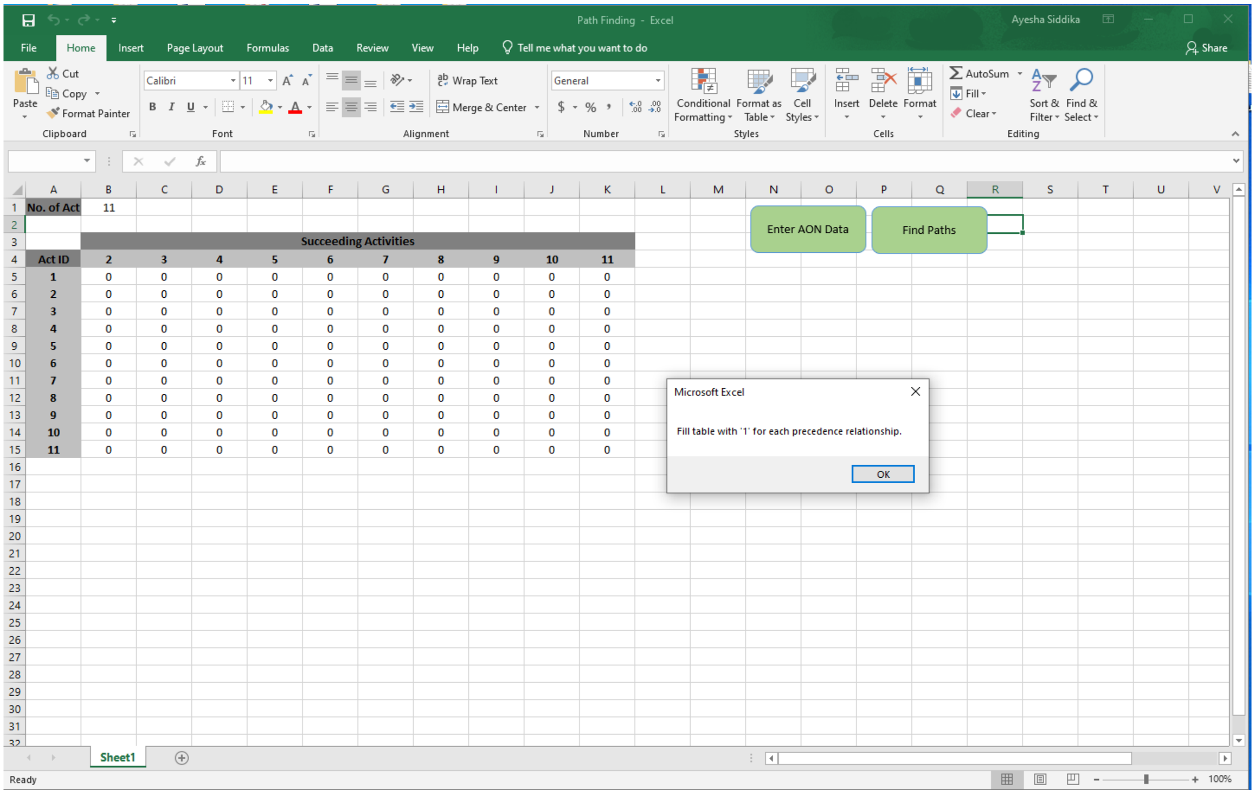
11

Figure 9: Entering number of activities in a project

For the tunneling case study, the total number of activities, including start (ST) and finish (FN) activity is 11.

Step 2: Fill the table with “1” for each precedence relationship

The second step is to fill the table based on the precedence relationship of the example AON network.



No. of Act 11

	Succeeding Activities									
Act ID	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0

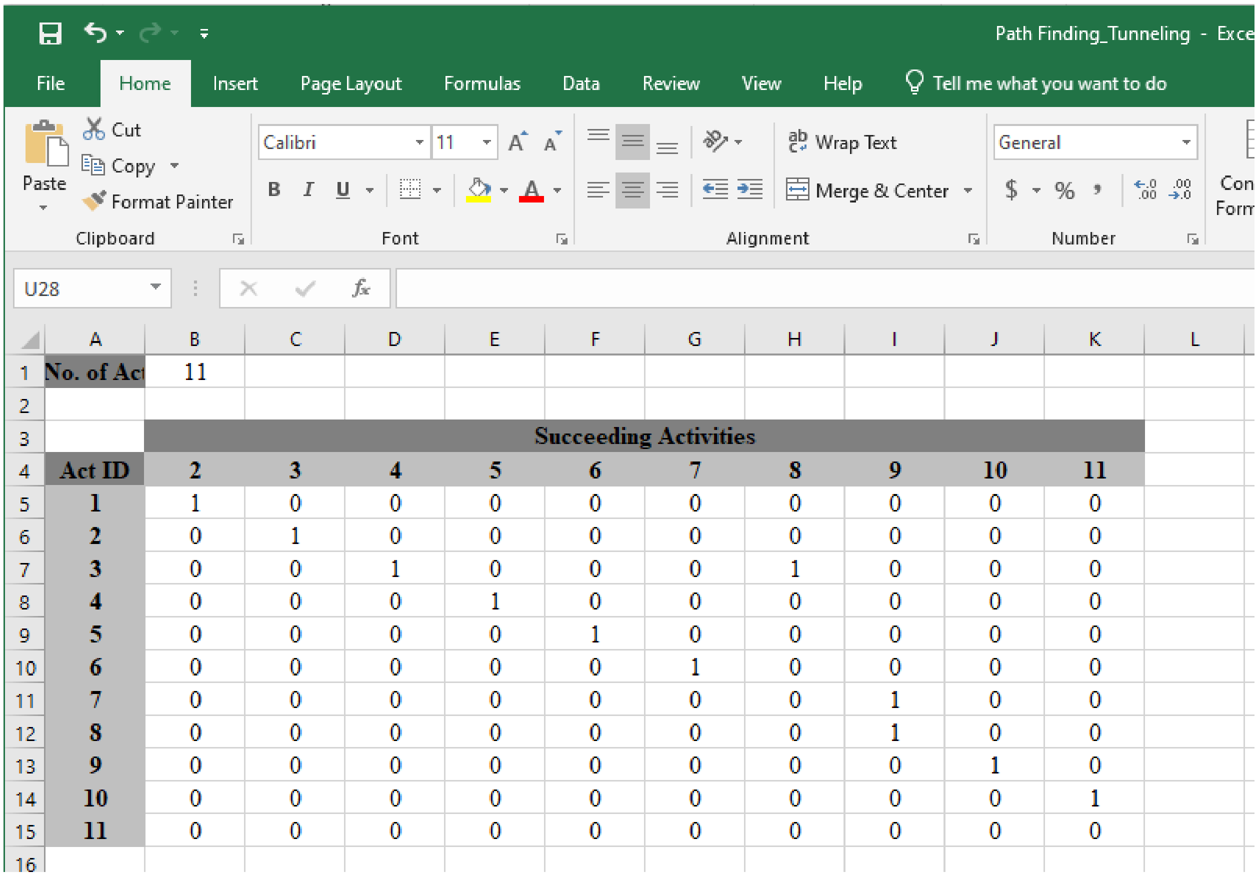
Microsoft Excel

Fill table with '1' for each precedence relationship.

OK

Figure 10: Defining successor activities

Here, the 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, the user has to put 0. The Completed succeeding activities table is presented below in Figure 11.



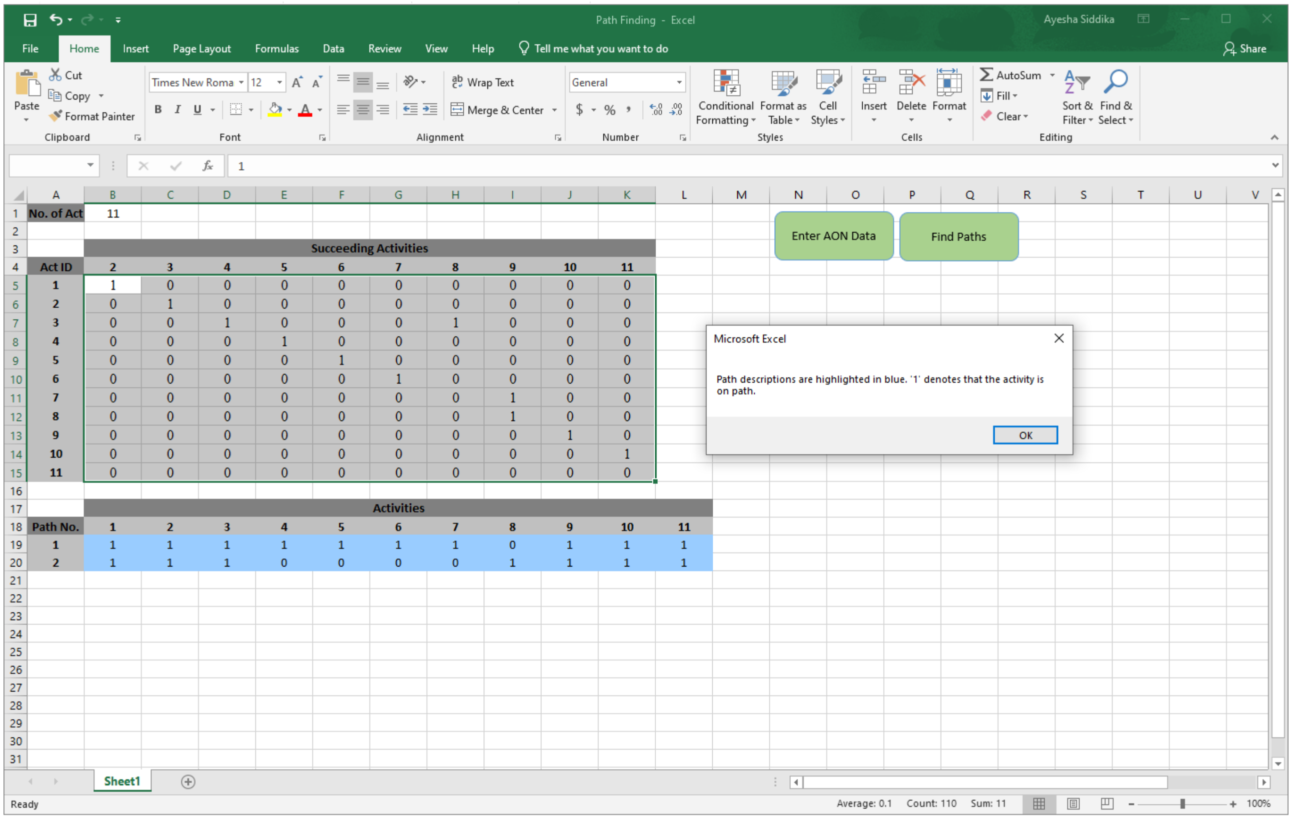
No. of Act	11									
	Succeeding Activities									
Act ID	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	1	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	1	0	0	0
4	0	0	0	1	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	0	1	0	0
8	0	0	0	0	0	0	0	1	0	0
9	0	0	0	0	0	0	0	0	1	0
10	0	0	0	0	0	0	0	0	0	1
11	0	0	0	0	0	0	0	0	0	0

Figure 11: Successor activities for tunneling case study

Step 3: Generating Paths

Step three generates all the associated paths related to all the activities (including the start to finish activities) of the AON network for the tunneling case study.

The following figure (Figure 12) illustrates all the possible paths generated from the example project case.



No. of Act	11

	Succeeding Activities									
Act ID	2	3	4	5	6	7	8	9	10	11
1	1	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	1	0	0	0
4	0	0	0	1	0	0	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0
6	0	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	0	0	1	0	0
8	0	0	0	0	0	0	0	1	0	0
9	0	0	0	0	0	0	0	0	1	0
10	0	0	0	0	0	0	0	0	0	1
11	0	0	0	0	0	0	0	0	0	0

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

Microsoft Excel

Path descriptions are highlighted in blue. '1' denotes that the activity is on path.

OK

Figure 12: Generating path definitions

Table 22 shows all existing paths from start to finish in the tunneling case study.

Table 22: Generated paths for case study

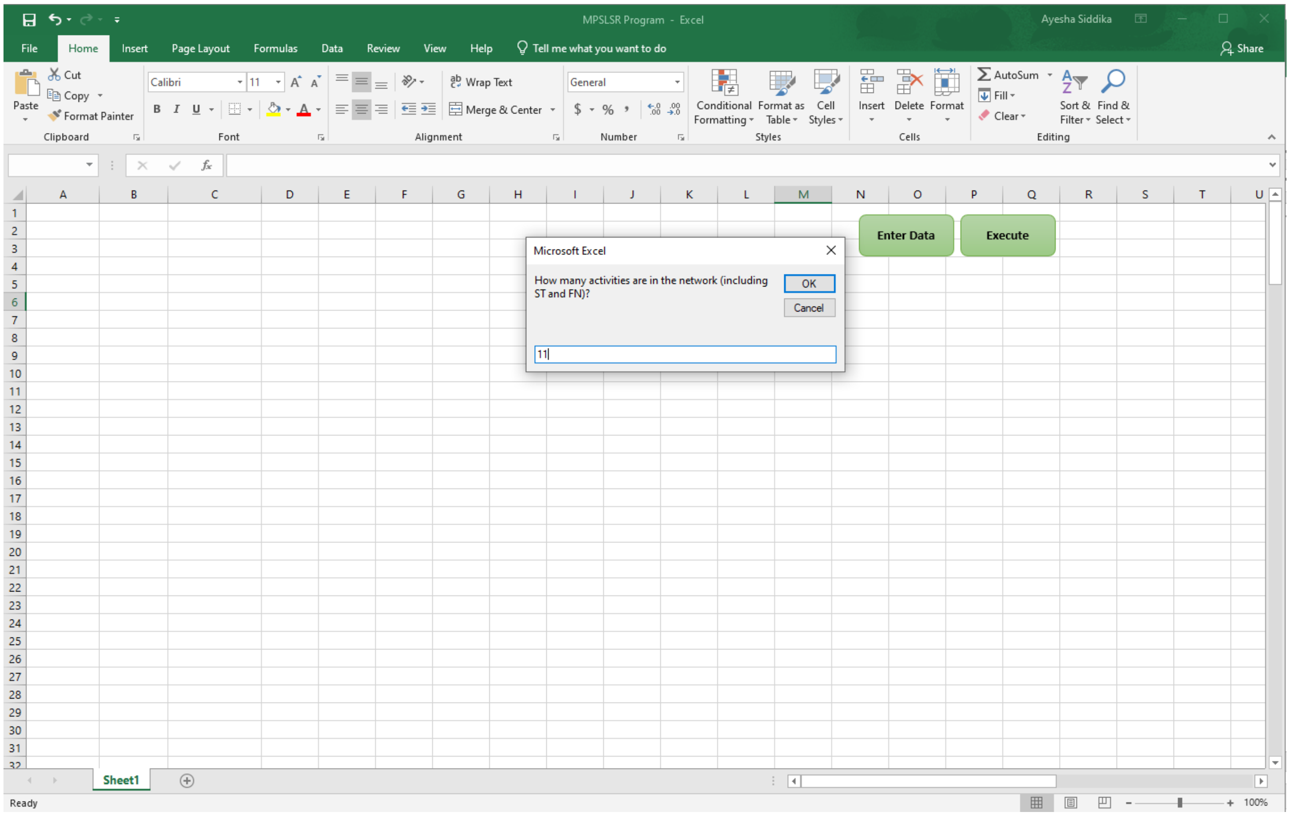
	Activities										
Path No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	1	1	1	1	1	1	1	0	1	1	1
2	1	1	1	0	0	0	0	1	1	1	1

Part 2: MPSLSR Operation Sheet (Iterative Cycles)

Step 1: Input the number of activities in the network

Firstly, the user has to press the “Enter Data” button. The program will ask the “number of activities including start and finish”. The user has to give input according to the total number of activities for the project AON network. For the tunneling project, the number of total activities is 11 as mentioned in Part 1, Step 1.

The following figure (Figure 13) shows the details of step 1.



Microsoft Excel

How many activities are in the network (including ST and FN)?

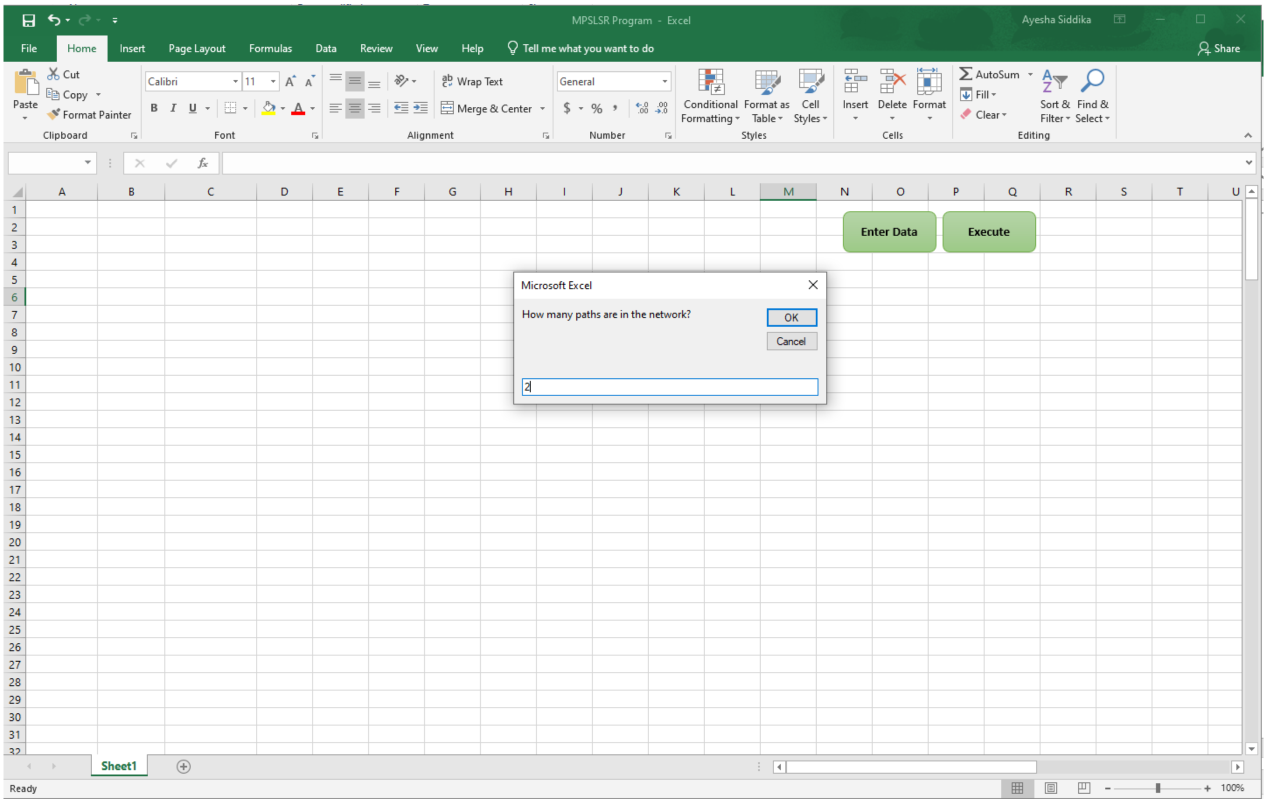
11

Figure 13: Entering number of activities

Step 2: Input the total number of paths in the network

This step will ask the user to input the total number of existing paths in the project AON model, which is obtained in part 1.

For the tunneling case study, the obtained number is 2.



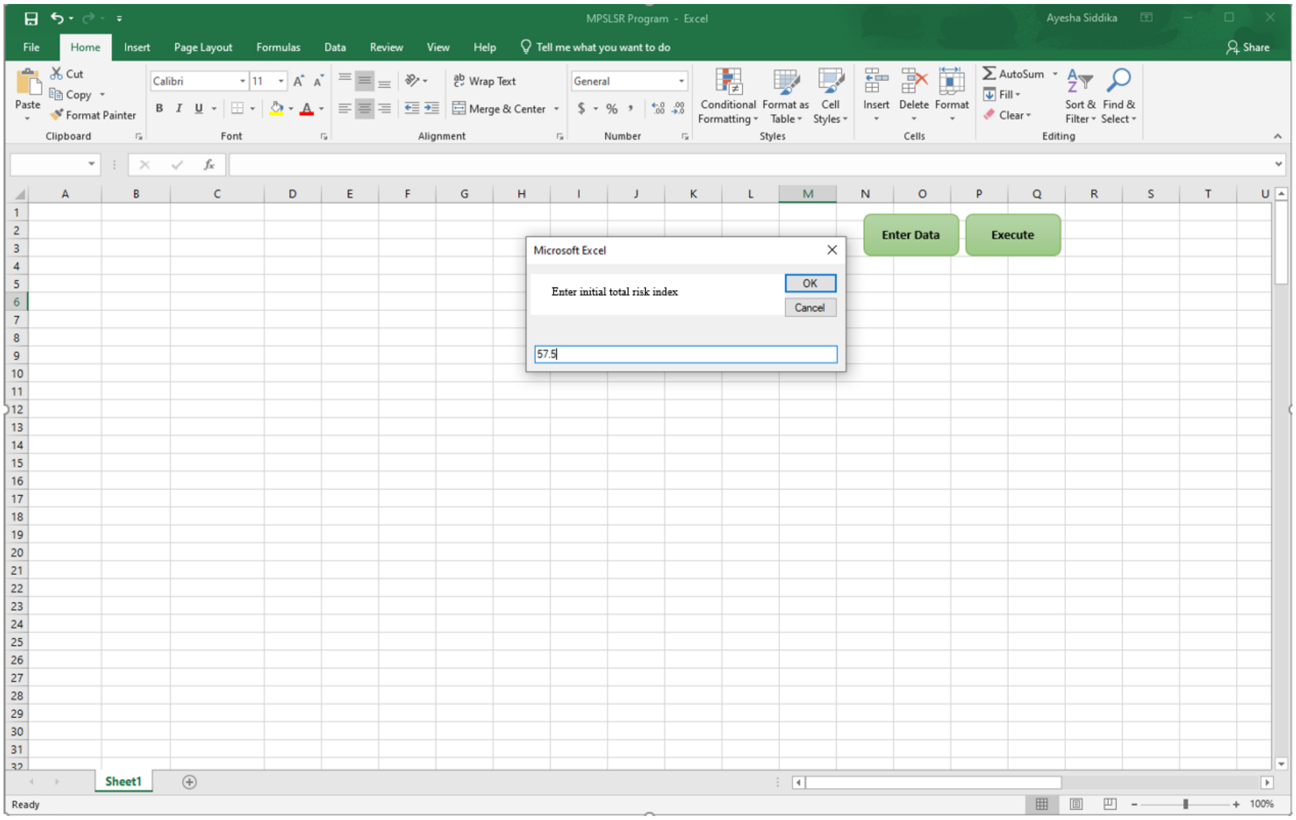
How many paths are in the network?

2

Figure 14: Entering number of existing paths

Step 3: Enter the initial total risk index

This step will ask the user to input the initial total risk index value. The initial total risk index basically denotes the sum of all the individual activities' risk index related to the project under normal settings. A detailed stepwise description of the input data preparation is given in the next section.



Microsoft Excel

Enter initial total risk index

57.5

Figure 15: Entering total initial risk index for normal scenario

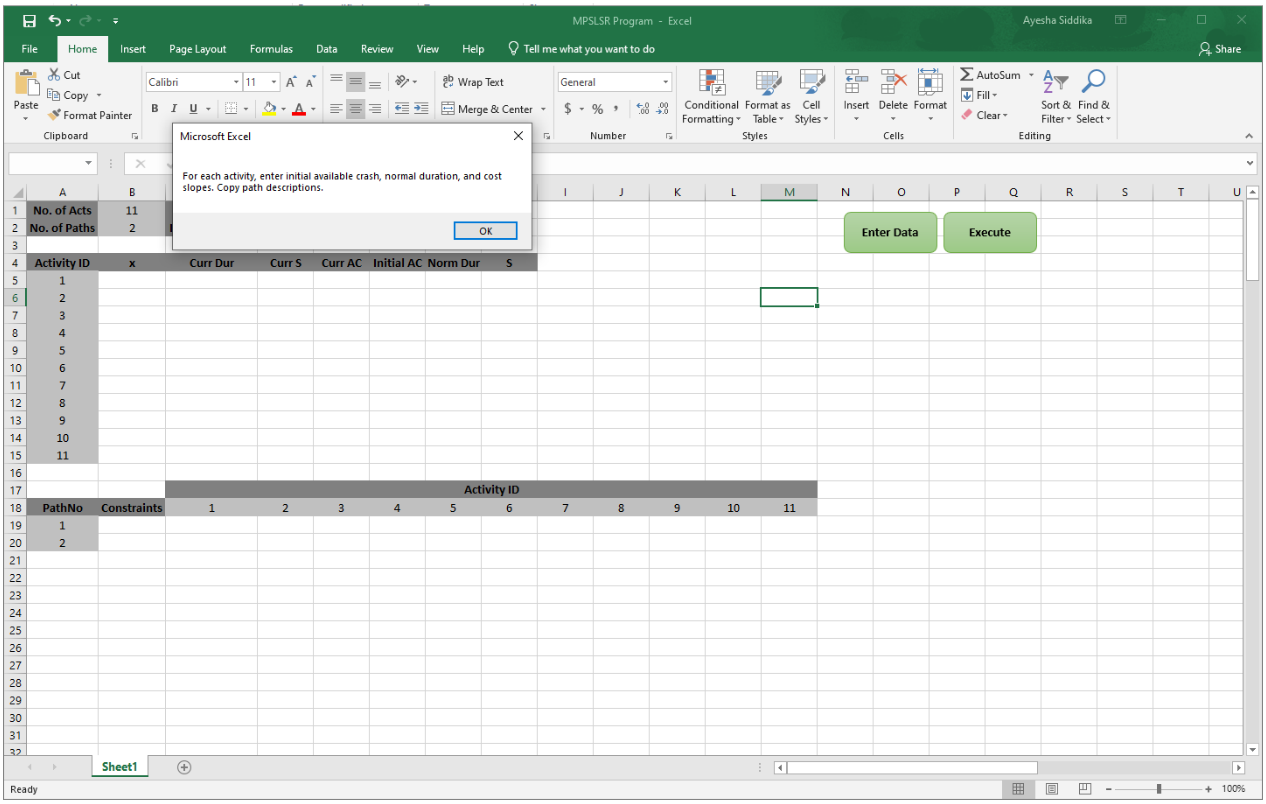
Step 4: Entering risk slope, available acceleration duration and Path description

In this step, the solver will ask the user to enter initially available acceleration, normal duration and risk slope data. Afterward, the path description needs to be copied from the path-finding program (solver 1). The highlighted three columns of the table in Figure 16 should be entered by the user to define activity acceleration data including:

Initial AC: Initial available acceleration days for each activity

Norm Dur: Normal duration of each activity

S: Risk slope of each activity having an acceleration time



Microsoft Excel

For each activity, enter initial available crash, normal duration, and cost slopes. Copy path descriptions.

OK

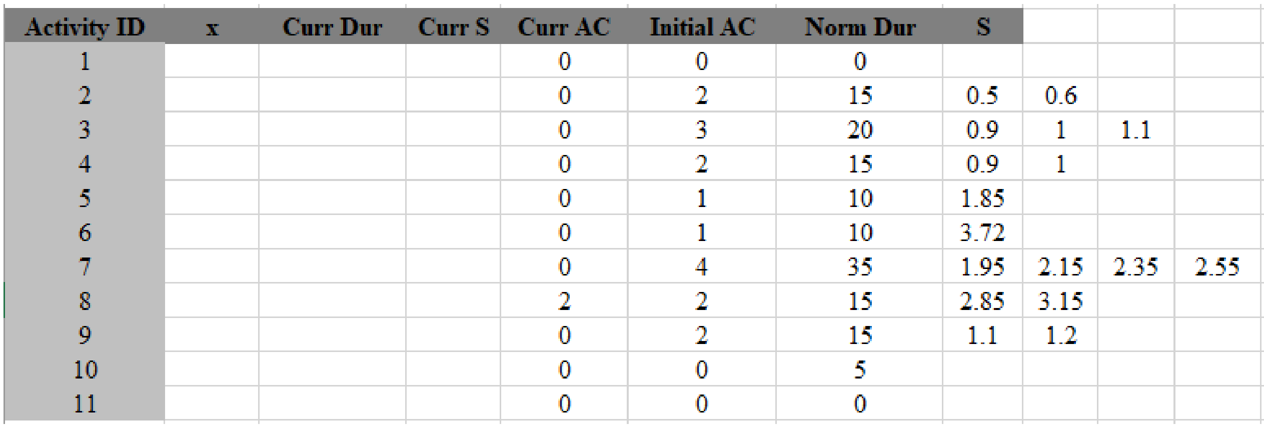
No. of Acts	11
No. of Paths	2

Activity ID	x	Curr Dur	Curr S	Curr AC	Initial AC	Norm Dur	S
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							

		Activity ID										
PathNo	Constraints	1	2	3	4	5	6	7	8	9	10	11
1												
2												

Figure 16: Entering activity risk index and duration data

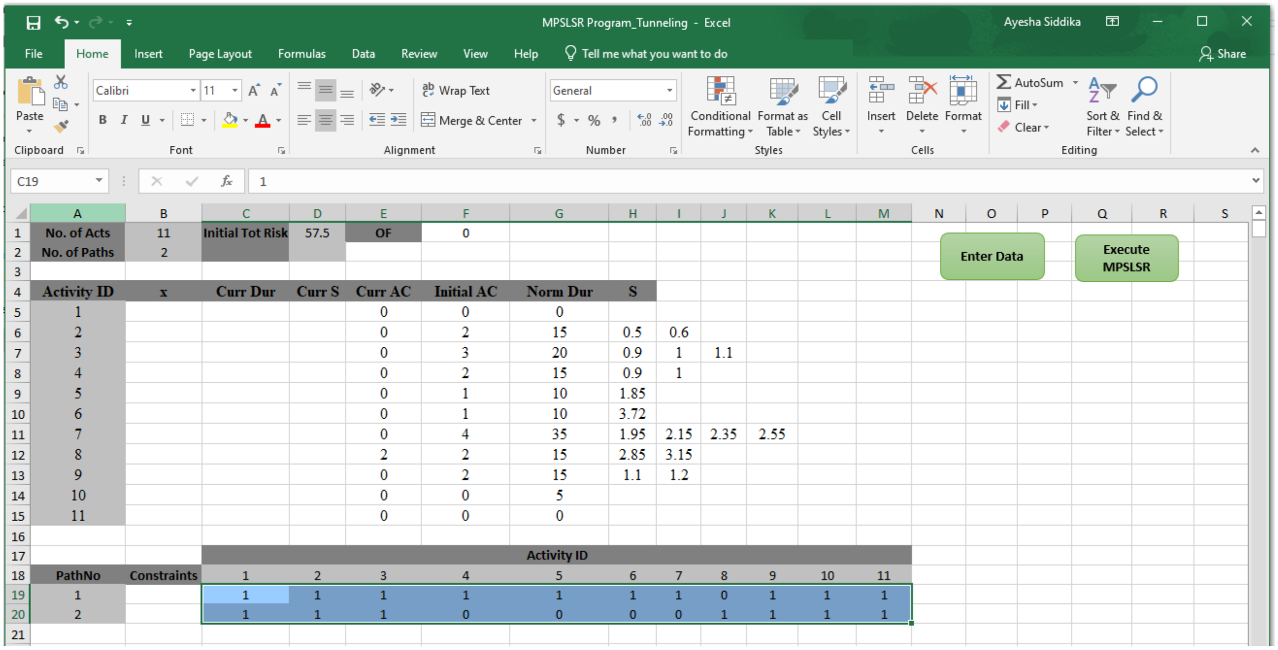
Note that, for each available acceleration time unit, a risk index slope must be defined. For instance, if an activity has three available acceleration duration units, one needs to enter the risk index slope for each of the accelerating steps, from left to right, for as many as needed.



Activity ID	x	Curr Dur	Curr S	Curr AC	Initial AC	Norm Dur	S			
1				0	0	0				
2				0	2	15	0.5	0.6		
3				0	3	20	0.9	1	1.1	
4				0	2	15	0.9	1		
5				0	1	10	1.85			
6				0	1	10	3.72			
7				0	4	35	1.95	2.15	2.35	2.55
8				2	2	15	2.85	3.15		
9				0	2	15	1.1	1.2		
10				0	0	5				
11				0	0	0				

Figure 17: Entering available acceleration time and risk slope data for the activity presented in the tunneling case study

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



C19 | 1

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	No. of Acts	11	Initial Tot Risk	57.5	OF	0							
2	No. of Paths	2											
3													
4	Activity ID	x	Curr Dur	Curr S	Curr AC	Initial AC	Norm Dur	S					
5	1				0	0	0						
6	2				0	2	15	0.5	0.6				
7	3				0	3	20	0.9	1	1.1			
8	4				0	2	15	0.9	1				
9	5				0	1	10	1.85					
10	6				0	1	10	3.72					
11	7				0	4	35	1.95	2.15	2.35	2.55		
12	8				2	2	15	2.85	3.15				
13	9				0	2	15	1.1	1.2				
14	10				0	0	5						
15	11				0	0	0						
16													
17			Activity ID										
18	PathNo	Constraints	1	2	3	4	5	6	7	8	9	10	11
19	1		1	1	1	1	1	1	1	0	1	1	1
20	2		1	1	1	0	0	0	0	1	1	1	1
21													

Figure 18: Copying path descriptions from part 1 for tunneling case study

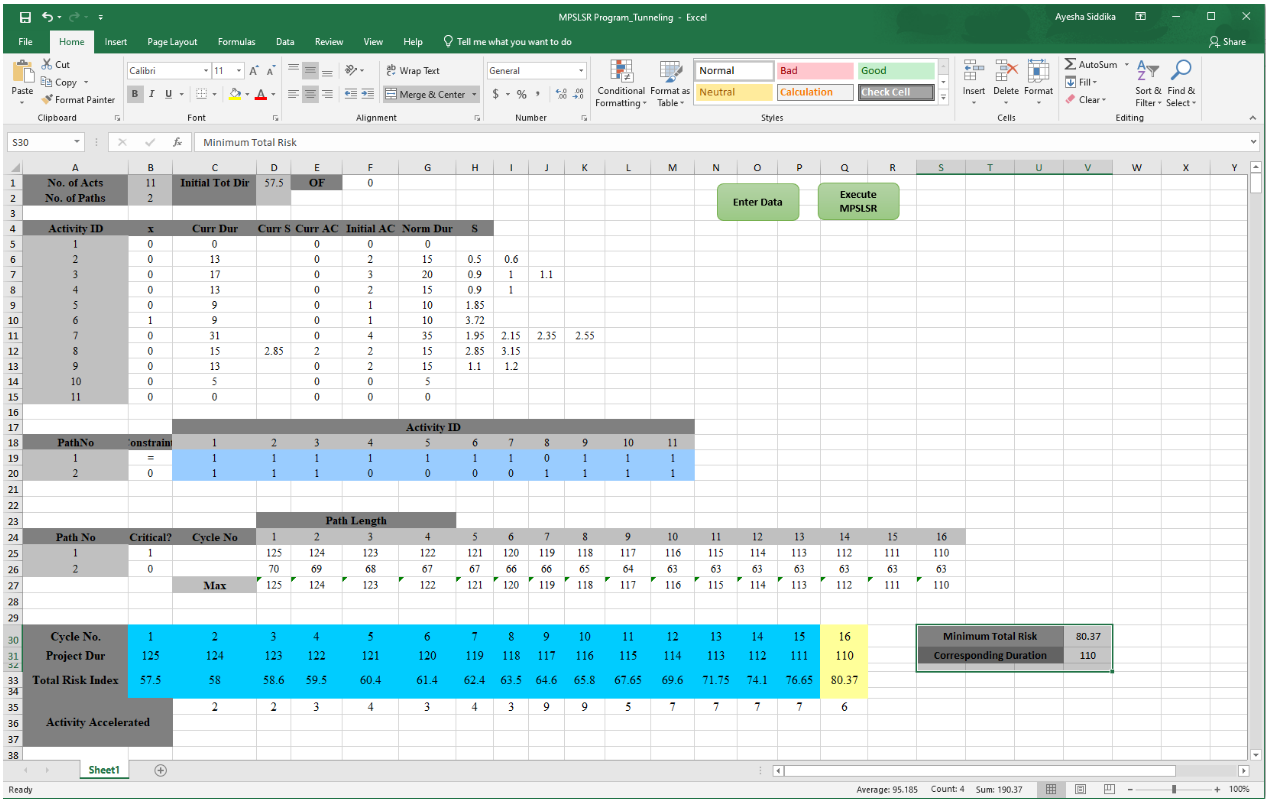
Step 5: Execute MPSLSR Operation

Finally, the last step is to press “Execute MPSLSR” to generate the final results. The final output shows the generated results including the followings:

- Various project durations with their corresponding minimum total risk index.
- Total risk slope slopes in each cycle.
- Crashed activities in each cycle.

It should be noted that all activities are accelerated by 1-time unit in each cycle.

The overall minimum total risk index and its corresponding duration are highlighted in yellow.



No. of Acts	11	Initial Tot Dir	57.5	OF	0
No. of Paths	2				

Activity ID	x	Curr Dur	Curr S	Curr AC	Initial AC	Norm Dur	S			
1	0	0		0	0	0				
2	0	13		0	2	15	0.5	0.6		
3	0	17		0	3	20	0.9	1	1.1	
4	0	13		0	2	15	0.9	1		
5	0	9		0	1	10	1.85			
6	1	9		0	1	10	3.72			
7	0	31		0	4	35	1.95	2.15	2.35	2.55
8	0	15	2.85	2	2	15	2.85	3.15		
9	0	13		0	2	15	1.1	1.2		
10	0	5		0	0	5				
11	0	0		0	0	0				

		Activity ID										
PathNo	onstraint	1	2	3	4	5	6	7	8	9	10	11
1	=	1	1	1	1	1	1	1	0	1	1	1
2	0	1	1	1	0	0	0	0	1	1	1	1

			Path Length																
Path No	Critical?	Cycle No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1		125	124	123	122	121	120	119	118	117	116	115	114	113	112	111	110
2	0		70	69	68	67	67	66	66	65	64	63	63	63	63	63	63	63
		Max	125	124	123	122	121	120	119	118	117	116	115	114	113	112	111	110

Cycle No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Project Dur	125	124	123	122	121	120	119	118	117	116	115	114	113	112	111	110
Total Risk Index	57.5	58	58.6	59.5	60.4	61.4	62.4	63.5	64.6	65.8	67.65	69.6	71.75	74.1	76.65	80.37
Activity Accelerated		2	2	3	4	3	4	3	9	9	5	7	7	7	7	6

Minimum Total Risk	80.37
Corresponding Duration	110

Figure 19: Result of tunneling case study

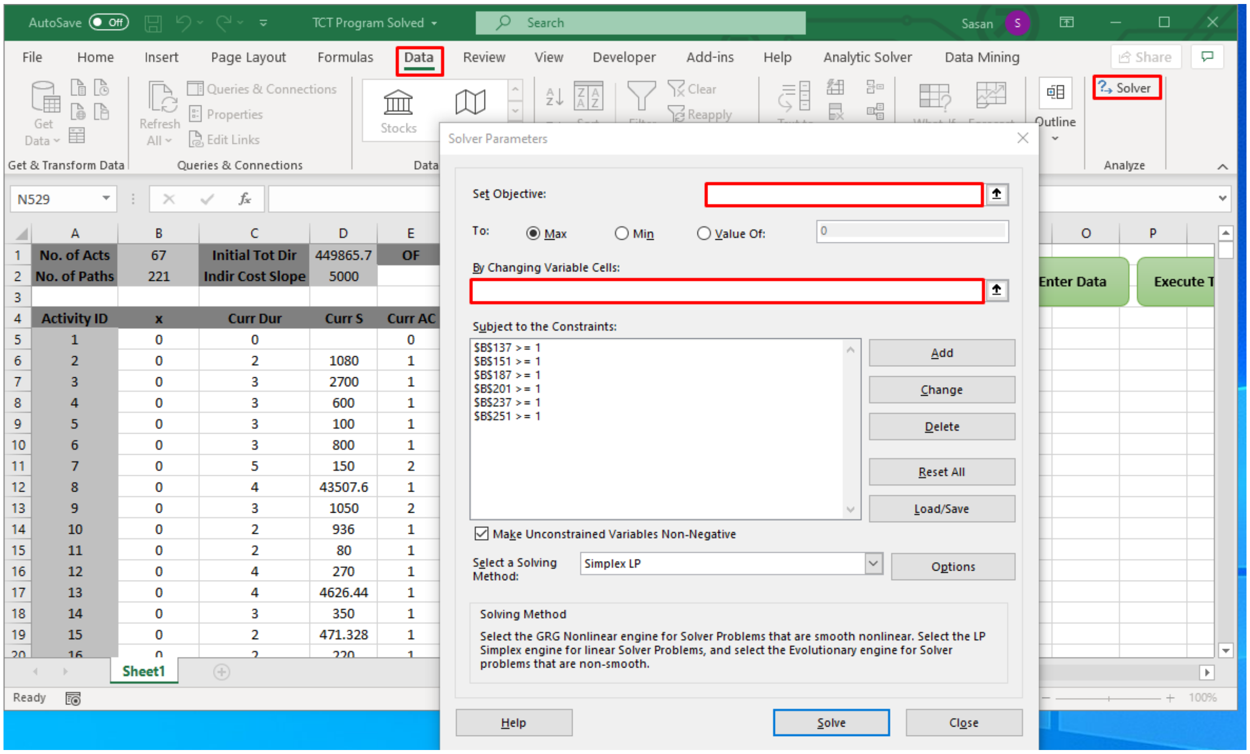
Automated Computerized Engine Program Limitations

It is noteworthy that the Solver's free version (basic solver) is limited to 200 variables and 100 constraints in 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 is larger than 100. If the problem becomes too large for Solver to handle, an error message will be shown at the end (Nasiri, 2019).

The program accelerates each activity by one time unit (i.e., day or hour, depending on the user's definition) and handles non-integer available crash times for activities. However, an available crash time of less than 1 time-unit is considered non-accelerable. 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 non-accelerable.

To ensure that the problem has been properly defined for the Solver, it is recommended to check the followings (Nasiri, 2019):

- Check the objective function (set objective) is not empty.
- Ensure that the variable cells are defined.



	A	B	C	D	E
1	No. of Acts	67	Initial Tot Dir	449865.7	OF
2	No. of Paths	221	Indir Cost Slope	5000	
3					
4	Activity ID	x	Curr Dur	Curr S	Curr AC
5	1	0	0		0
6	2	0	2	1080	1
7	3	0	3	2700	1
8	4	0	3	600	1
9	5	0	3	100	1
10	6	0	3	800	1
11	7	0	5	150	2
12	8	0	4	43507.6	1
13	9	0	3	1050	2
14	10	0	2	936	1
15	11	0	2	80	1
16	12	0	4	270	1
17	13	0	4	4626.44	1
18	14	0	3	350	1
19	15	0	2	471.328	1
20	16	0	2	220	1

Set Objective:

To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells:

Subject to the Constraints:

B137 >= 1
B151 >= 1
B187 >= 1
B201 >= 1
B237 >= 1
B251 >= 1

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: Simplex LP

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

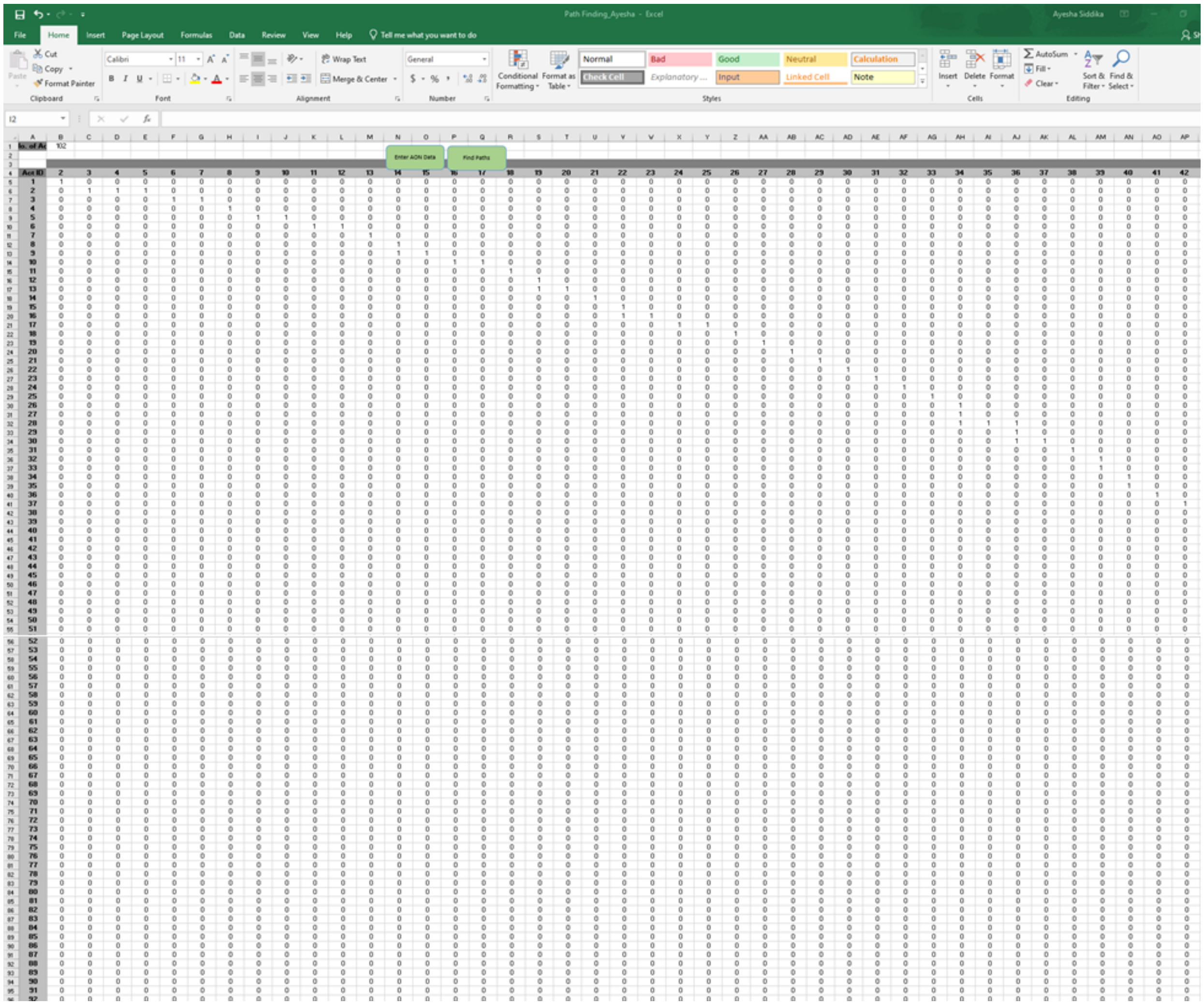
Figure 20: Final check to ensure proper definition of problem in Solver

Results from Computer-based MPSLSR Program for 100-activity Case

The result section consists of two major parts:

1. Results of the Path Finding Program, and
2. Results of the MPSLSR program

Part 1: Results of the Path Finding Program



o. of Ac 102

Act ID	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
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30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
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36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
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40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 21: Preceding relationship for 100 activity case study

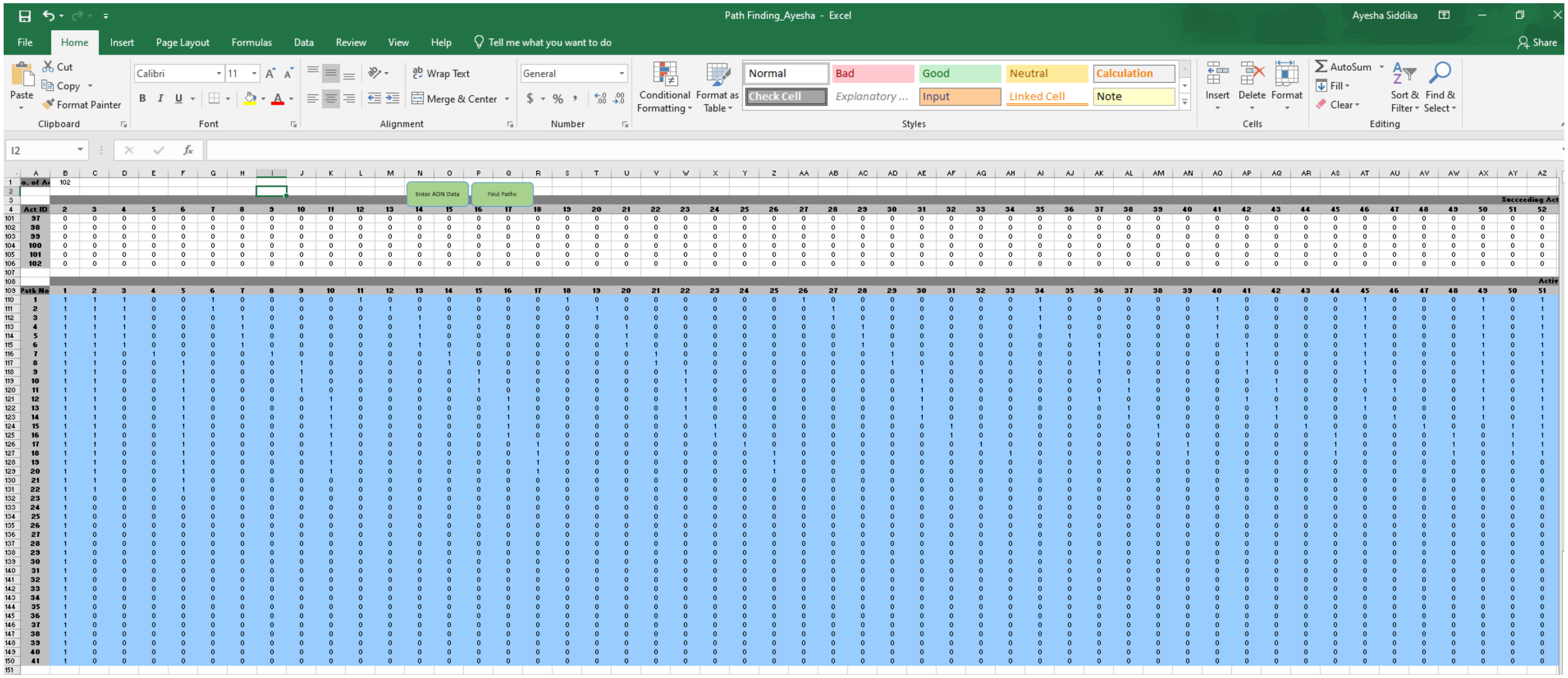
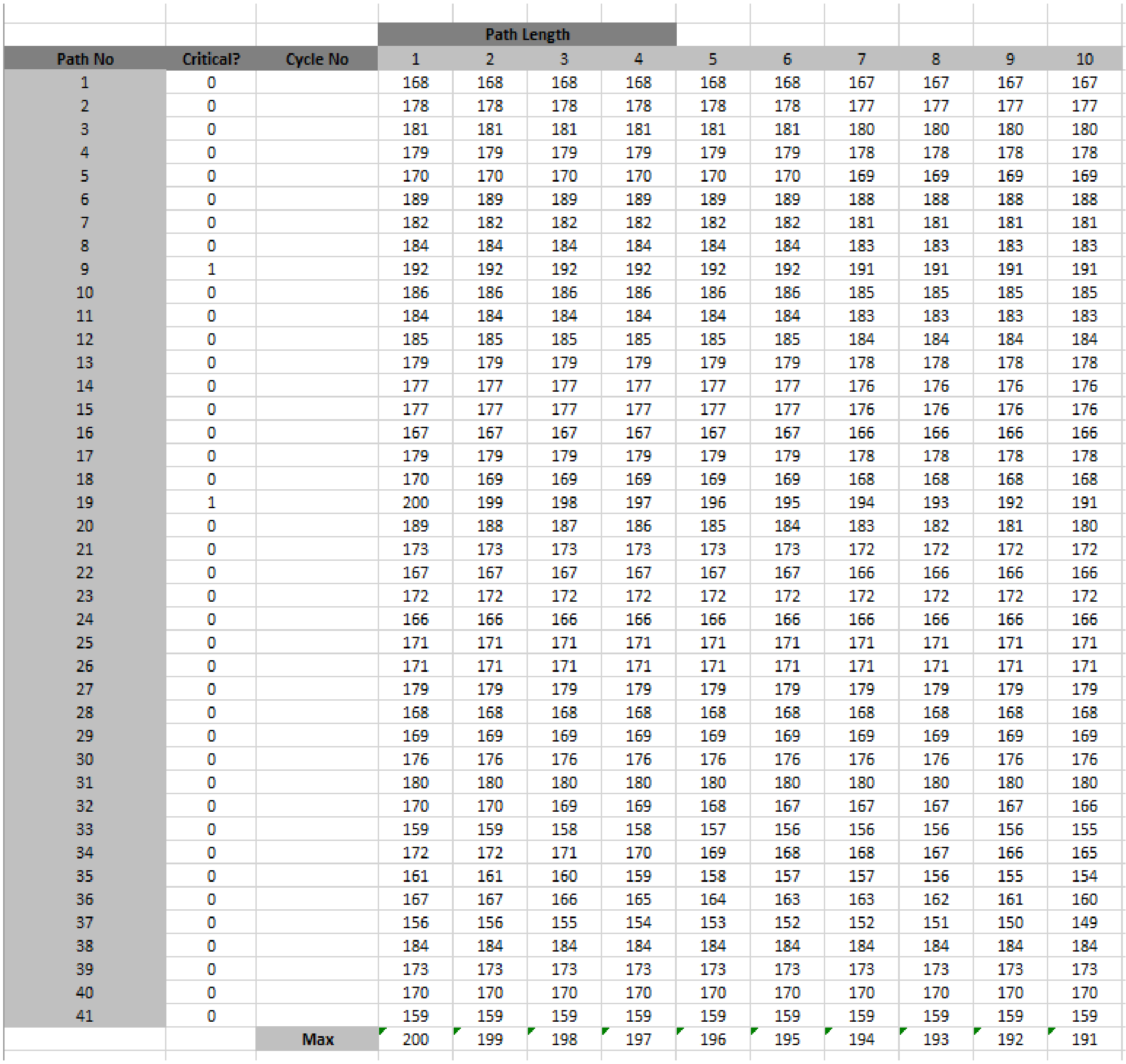


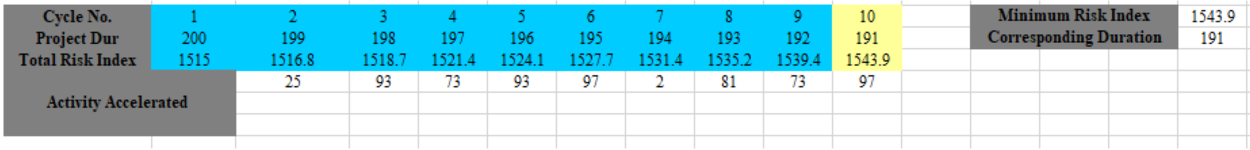
Figure 22: Results from Path Finding Program for 100 activity case study

Part 2: Results of the MPSLSR Program



			Path Length									
Path No	Critical?	Cycle No	1	2	3	4	5	6	7	8	9	10
1	0		168	168	168	168	168	168	167	167	167	167
2	0		178	178	178	178	178	178	177	177	177	177
3	0		181	181	181	181	181	181	180	180	180	180
4	0		179	179	179	179	179	179	178	178	178	178
5	0		170	170	170	170	170	170	169	169	169	169
6	0		189	189	189	189	189	189	188	188	188	188
7	0		182	182	182	182	182	182	181	181	181	181
8	0		184	184	184	184	184	184	183	183	183	183
9	1		192	192	192	192	192	192	191	191	191	191
10	0		186	186	186	186	186	186	185	185	185	185
11	0		184	184	184	184	184	184	183	183	183	183
12	0		185	185	185	185	185	185	184	184	184	184
13	0		179	179	179	179	179	179	178	178	178	178
14	0		177	177	177	177	177	177	176	176	176	176
15	0		177	177	177	177	177	177	176	176	176	176
16	0		167	167	167	167	167	167	166	166	166	166
17	0		179	179	179	179	179	179	178	178	178	178
18	0		170	169	169	169	169	169	168	168	168	168
19	1		200	199	198	197	196	195	194	193	192	191
20	0		189	188	187	186	185	184	183	182	181	180
21	0		173	173	173	173	173	173	172	172	172	172
22	0		167	167	167	167	167	167	166	166	166	166
23	0		172	172	172	172	172	172	172	172	172	172
24	0		166	166	166	166	166	166	166	166	166	166
25	0		171	171	171	171	171	171	171	171	171	171
26	0		171	171	171	171	171	171	171	171	171	171
27	0		179	179	179	179	179	179	179	179	179	179
28	0		168	168	168	168	168	168	168	168	168	168
29	0		169	169	169	169	169	169	169	169	169	169
30	0		176	176	176	176	176	176	176	176	176	176
31	0		180	180	180	180	180	180	180	180	180	180
32	0		170	170	169	169	168	167	167	167	167	166
33	0		159	159	158	158	157	156	156	156	156	155
34	0		172	172	171	170	169	168	168	167	166	165
35	0		161	161	160	159	158	157	157	156	155	154
36	0		167	167	166	165	164	163	163	162	161	160
37	0		156	156	155	154	153	152	152	151	150	149
38	0		184	184	184	184	184	184	184	184	184	184
39	0		173	173	173	173	173	173	173	173	173	173
40	0		170	170	170	170	170	170	170	170	170	170
41	0		159	159	159	159	159	159	159	159	159	159
		Max	200	199	198	197	196	195	194	193	192	191

Figure 23: Possible path lengths for 100 activity case study



Cycle No.	1	2	3	4	5	6	7	8	9	10	Minimum Risk Index	1543.9
Project Dur	200	199	198	197	196	195	194	193	192	191	Corresponding Duration	191
Total Risk Index	1515	1516.8	1518.7	1521.4	1524.1	1527.7	1531.4	1535.2	1539.4	1543.9		
Activity Accelerated		25	93	73	93	97	2	81	73	97		

Figure 24: Results from MPSLSR automated program for 100 activity case study

Table 23: Activity ID with possible acceleration time and risk slopes for 100 activity case

Activity ID	Initial Available Acceleration	Normal Duration	Risk Slope (S)			
1	0	0				
2	1	18	3.7			
3	2	13	3.5	6.7		
4	4	16	2.3	2.8	4.4	6.4
5	0	20				
6	2	16	1.7	3.3		
7	1	16	2.2	2.5	3.1	5.8
8	2	19	3.3	3.4		
9	0	17				
10	0	17				
11	3	14	5.9	7.1	7.2	
12	4	14	2.3	2.4	4.3	6.5
13	2	17	2.5	2.6	3.2	6.6
14	4	10	1.9	3.2	5.4	6.1
15	0	17				
16	4	10	1.6	1.8	4.5	5.1
17	0	17				
18	4	12	2.3	2.4	4.3	6.5
19	4	14	1.7	2.9	3	
20	1	14	7.2			
21	2	11	7	7.2		
22	0	13				
23	3	19	3.6	3.8	5	
24	3	19	4.6	4.9	5.4	
25	1	14	1.8	2	7.3	
26	1	12	3.4			

27	4	20	4.1	4.2	6	6.1
28	1	18	7			
29	2	15	2.3	5.9		
30	0	14				
31	1	13	3.4			
32	4	15	3.2	6	6.2	6.3
33	1	11	4.2			
34	3	19	2.7	5.1	6.7	
35	2	10	4.8	7.3		
36	0	20				
37	3	17	4.6	5	6.2	
38	3	12	1.9	4.9	6.4	
39	2	15	1.7	4.6		
40	4	10	3.8	5.5	6.1	6.5
41	0	19	1.9	3.2	3.7	
42	3	16	2.4	4.1	5.9	
43	1	14	1.7			
44	2	12	6.8	7.2		
45	0	15				
46	2	13	2.7	4.2		
47	4	19	4.1	5.8	6.8	6.8
48	3	11	1.6	3.6	4.7	
49	0	19				
50	1	15	6.3			
51	0	20				
52	0	19				
53	3	18	2.9	5.2	5.4	
54	4	18	3.3	6.6	7	7.4
55	0	20	2.3	2.5	3.4	

56	4	11	2.7	3.8	6.4	6.6
57	1	18	4.7			
58	2	19	1.9	4.6		
59	1	18	5.2			
60	3	14	1.9	4.5	4.7	7.2
61	3	19	1.5	1.9	2.5	
62	1	16	6			
63	4	10	2	2.4	5.1	6.6
64	3	20	3.2	4	4.2	
65	1	20	6.2			
66	1	19	7.1			
67	1	16	3.8			
68	1	16	1.6	3.2	5.3	6.4
69	1	16	4.6			
70	3	20	1.8	2.9	3.3	
71	4	17	1.5	2.9	5	6.8
72	1	17	2.6			
73	4	12	2.7	4.2	7.2	7.4
74	2	20	2.2	3.8	3.9	
75	3	15	6.2	6.8	7.4	
76	0	18				
77	1	15	3.5			
78	4	19	2.1	3.1	3.6	7.3
79	1	12	6.6			
80	1	10	5.2			
81	3	17	3.8	6.2	7.4	
82	2	19	1.9	3	7	
83	3	10	3.1	3.2	5.6	
84	2	14	1.8	6.9	7.1	

85	3	10	2.4	3.4	7.3	
86	3	15	3.8	6.2	6.9	
87	3	19	3.4	4	4.5	
88	1	11	6.5			
89	0	10				
90	1	20	5.4	5.7	6	
91	4	11	1.8	2.5	3.3	5.4
92	4	16	2.4	3.5	4.4	5.2
93	3	13	1.9	2.7	5.6	
94	3	20	2.5	3.6	6.2	7.2
95	0	13				
96	0	17				
97	3	12	3.6	4.5	6	
98	1	16	3	3	6.4	
99	0	13				
100	0	19				
101	0	11				
102	0	0				

Table 24: Comparison of results for normal scenario, accelerated scenario and optimized scenario for 100 activity case

Activity ID	**Normal Scenario**		**Accelerated Scenario**		**Optimized Scenario**	
	Duration	**RI**	**Duration**	**RI**	**Duration**	**RI**
1	Start	-	-	-	-	-
2	18	8.55	17	12.25	**17**	12.25
3	13	13.49	11	20.49	13	13.49
4	16	19.3	12	28.5	16	19.3
5	20	11.48	20	11.48	20	11.48
6	16	15.1	14	18.5	16	15.1
7	16	22.8	15	25	16	22.8
8	19	13.65	17	20.25	19	13.65
9	17	31.5	17	31.5	17	31.5
10	17	19.5	17	19.5	17	19.5
11	14	7.55	11	25.25	14	7.55
12	14	6.8	10	16	14	6.8
13	17	28.5	15	33.5	17	28.5
14	10	20.9	6	28.5	**6**	28.5
15	17	17	17	17	17	17

16	10	26.85	6	33.25	10	26.85
17	17	17.25	17	17.25	17	17.25
18	12	27.8	8	37	12	27.8
19	14	8.2	10	15	14	8.2
20	14	10.05	13	17.25	14	10.05
21	11	9	9	23	**9**	23
22	13	20.5	13	20.5	13	20.5
23	19	6.7	16	17.5	19	6.7
24	19	17.7	16	31.5	19	17.7
25	14	19.2	13	21	14	19.2
26	12	15.6	11	19	12	15.6
27	20	13.1	16	29.5	20	13.1
28	18	9.25	17	16.25	18	16.25
29	15	16.9	13	21.5	**13**	21.5
30	14	19	14	19	14	19
31	13	14.1	12	17.5	13	14.1
32	15	21.45	11	34.25	15	21.45
33	11	18.8	10	23	11	18.8
34	19	13.4	16	21.5	19	13.4

35	10	15.65	8	25.25	10	15.65
36	20	13.5	20	13.5	20	13.5
37	17	14	14	27.8	17	14
38	12	19.3	9	25	12	19.3
39	15	19.85	13	23.25	15	19.85
40	10	12.8	6	28	10	12.8
41	19	16	19	16	19	16
42	16	14.3	13	21.5	16	14.3
43	14	9.8	13	11.5	14	9.8
44	12	11.4	10	25	12	11.4
45	15	12	15	12	15	12
46	13	17.1	11	22.5	13	17.1
47	19	9.6	15	26	19	9.6
48	11	16.2	8	21	11	16.2
49	19	31.5	19	31.5	19	31.5
50	15	9.7	14	16	15	9.7
51	20	35.25	20	35.25	20	35.25
52	19	19.5	19	19.5	19	19.5
53	18	17.3	15	26	18	17.3

54	18	14.05	14	27.25	18	14.05
55	20	25	20	25	20	25
56	11	17.45	7	28.25	11	17.45
57	18	7.3	17	12	18	7.3
58	19	14.8	17	18.6	19	14.8
59	18	8.8	17	14	18	8.8
60	14	14.3	11	20	14	14.3
61	19	19.75	16	24.25	19	19.75
62	16	14	15	20	16	14
63	10	16	6	24	10	16
64	20	13.9	17	23.5	20	13.9
65	20	4.8	19	11	20	4.8
66	19	5.4	18	12.5	19	5.4
67	16	10.2	15	14	16	10.2
68	16	23.9	15	25.5	16	23.9
69	16	15.9	15	20.5	16	15.9
70	20	11.6	17	17	20	11.6
71	17	19.5	13	25.5	17	19.5
72	17	8.9	16	11.5	17	8.9

73	12	13.2	8	24	12	13.2
74	20	10.6	18	15	20	10.6
75	15	1.4	12	20	15	1.4
76	18	11.25	18	11.25	18	11.25
77	15	10.5	14	14	15	10.5
78	19	23.4	15	31.8	19	23.4
79	12	14.4	11	21	12	14.4
80	10	14.8	9	20	10	14.8
81	17	11.6	14	23	17	11.6
82	19	2.45	17	6.25	19	2.45
83	10	11.7	7	21	10	11.7
84	14	23.4	12	27	14	23.4
85	10	18.3	7	25.5	10	18.3
86	15	12.6	12	24	15	12.6
87	19	12.3	16	22.5	19	12.3
88	11	8.5	10	15	11	8.5
89	10	12	10	12	10	12
90	20	9.1	19	14.5	20	9.1
91	11	14.8	7	22	11	14.8

92	16	12.65	12	22.25	16	12.65
93	13	11.3	10	17	13	11.3
94	20	1.5	17	9	20	1.5
95	13	19.5	13	19.5	13	19.5
96	17	25	17	25	17	25
97	12	13.7	9	24.5	12	13.7
98	16	18	15	21	16	18
99	13	22	13	22	13	22
100	19	19.25	19	19.25	19	19.25
101	11	14.5	11	14.5	11	14.5
102	Finish	-	-	-	-	-