Forensic Schedule Information Modeling for Analysis of Time Claims in Construction Projects

by

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Abstract

A review of state-of-the-art research and practice has revealed that while the incidence of claims in the construction industry is increasing, current analysis practices are failing to accurately analyze and evaluate contemporaneous project data. The most common types of construction disputes relate to schedule impacts, or time claims caused by various controllable and uncontrollable events that prevent projects execution from being performed as originally planned either positively or negatively. Yet, they are the least understood and most complex disputes in the construction field. In an attempt to overcome the issues, various analytical methods were developed and used, nevertheless there are shortcomings to these methods that remain unresolved.

A key element in connection with time claims analysis is that project information is often scattered in various contemporaneous records such as daily progress reports, meeting minutes, diaries, emails, etc. This information is required to verify and assess time claims; however, the inadequate organization and overload of information often lead to inaccuracy and discrepancy in progress timelines as well as inefficiency in the process to reach accurate analysis results and claim conclusions.

Driven by the author's practical experience in construction claims analysis, this research identified various administrative and technical shortfalls associated with the practice of time claims analysis from theoretical, technical and professional literature. The identification of these deficiencies led to the formation of a new forensic schedule information modeling framework, abbreviated as ForSIM, for analysis of time claims. ForSIM framework focuses on integrating impact of events with the schedule to reflect the changes on activities durations and the overall schedule. It utilizes the principles of window-based analytical techniques and employs time-step simulation approach to model project data, achieve the automated data processing, analyze time claims, and quantify both acceleration and time extension award along with detailed demonstration of causation.

ForSIM proposes a novel data organization scheme, schedule of events (SoE), for documenting details of project evens that have potential impact on a project schedule. The structure of the event schedule is standardized to facilitate automated retrieval of information and analysis, and it can be implemented in any computer interpreted format, including spreadsheets and database formats. Along with the SoE, ForSIM relies on existence of a mutually agreed upon planned schedule and schedule updates, if available. ForSIM models the dynamic of schedule changes through an entity information model that records all the schedule relevant data, and an entity lifecycle model that imitates the possible routes an entity instance might maneuver through in a schedule network model, simultaneously responding to schedule logic and invoking duration changes. ForSIM can be described as “data-centric” as it places emphasis on events data and how it impacts project schedules. This entity-centric approach facilitates the analysis of time claims in ways that current approaches do not.

A prototype of ForSIM was developed and tested for concept validation, with different case studies used to demonstrate its merits over existing analytical methods. The study reveals that application of ForSIM would significantly improve industry practice and help achieve more efficient and accurate assessment of time claims in construction projects. The benefits of ForSIM framework are also discussed, along with directions for future research.

PREFACE

This thesis is an original work by Muaz Fagiar. Some of the research conducted for this thesis has been published or will be published, and represents collaborative work done with Dr. Yasser Mohamed and Dr. Simaan AbouRizk, at the University of Alberta.

A summarized version of Chapter 3 of this thesis has been published as Fagiar, M., Mohamed, Y., & AbouRizk, S. M. (2019). Simulation-Based Framework for Construction Delay Analysis. 7th International Construction Specialty Conference jointly with the Construction Research Congress. Laval, QC: CSCE/CRC.

I was responsible for the data collection and analysis as well as the manuscript composition. Dr. Yasser Mohamed and Dr. Simaan AbouRizk were the supervisory authors and was involved with concept formation and manuscripts reviewing.

DEDICATION

To my father's soul

To my dear mother, **Salwa A. Sabri**, and sisters, **Mysoon** and **Malaz**

To my lovely wife, **Shahd Ali**

To whom I owe my success in conducting this research

To those who paved my way to reach the end

To those who prayed and asked Allah to guide me

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First and foremost, all praise and thanks to Allah, who gave me health, strength and patience to complete this research.

I would like to express my sincere gratitude and appreciation to my supervisor Dr. Yasser Mohamed for his great support, supervision and continuous suggestions throughout this research. His encouragements inspired me and kept me highly motivated throughout the study. Special thanks also to my co-supervisor Dr. Simaan AbouRizk for his guidance and support in my study.

I would like to express my sincere thanks and gratitude to my mother, sister and extended family for their continuous supports and encouragements to sustain the pursuit of my PhD study. Special thanks to my lovely wife for her unconditional love, endless patience and support since the first day she joined my journey.

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Table of Contents

List of Tables

List of Figures

Chapter 1. General Introduction

1.1. Introduction to the Research Topic

At the initiation of a construction project, numerous resources are invested to ensure development of an accurate and reasonable execution plan to the greatest extent possible. One critical element of this effort includes the development of project schedules to aid in defining the scope of work and setting completion timelines (Ahuja, Dozzi, & AbouRizk, 1994; Newitt, 2008). However, changes to project schedules are inevitable due to various controllable and uncontrollable events, and these changes often lead to disputes among the contracted parties time claims. Along with increasing complexity of projects, demanding requirements, involvement of many disciplines and deteriorating economic conditions, delay claims have become an integral part of the construction industry and are steadily increasing in both number and frequency (Levin, 2016). This situation is unlikely to change within the foreseeable future; therefore, accurate analysis of claims is of significant interest to all practitioners in the construction industry.

Time related claims are the most common type of dispute because they are associated with damages and financial impacts for all contracted parties (Keane & Caletka, 2015). Thus, most standard forms of contracts include provisions which anticipate delays caused by actions taken by and/or inaction of owners or contractors, as well as events outside the control of both parties. Contractors are often excused from consequences and/or provided with financial compensation when delays result from circumstances or events beyond their control. Contractual provisions also allow owners to recover liquidated damages from contractors when they fail to deliver projects within the agreed contract duration (Keane & Caletka, 2015). Disagreement in any of these instances leads to a claim. Delay analysis then plays a vital role in resolving and settling these disputes.

Analysis of time claims is often a study in the relationship of cause and effect, which can be demonstrated in many forms, such as comparisons of cost/value recovery against the contract baseline, labor histograms and cash flow curves (Gibson, 2008). Many delay analysis techniques have been developed; however, most of these techniques are based on manual processes and they do not take into account concurrent delays situations, critical path changes (Yang & Tsai, 2011), quantification of liabilities at the subcontractor level, partial delays (Hegazy & Zhang, 2005), or uncertainty associated with the impact of an event. However, the most critical drawback to existing delay analysis techniques is that they rely on the experience and subjectivity of the analyst. These limitations result in time-consuming processes, errors and inaccuracies in analysis results. Although new analysis techniques have partially addressed some of these limitations, the need for an integrated and comprehensive framework that performs delay analysis in a realistic and timely manner for delay claims is still apparent.

The practice of claim management is ever-increasing. Whereas in the past claims have been managed by parties external to projects, there is an indication that both owners and contractors are investing resources in experts, whether internal or external (consultants), assigned to projects mainly to handle this work. However, the task of forensic schedule analysis is onerous (AACE International, 2011). Contractors perceive most delays as being the owners' responsibility in order to establish entitlement of compensation while owners often view delays as the responsibility of contractors, third parties or events beyond the control of parties involved in projects.

A major development that has occurred in construction generally over the past several decades is the introduction of simulation technologies that are capable of analyzing complex operations (AbouRizk S. , 2010). The construction industry has been using simulation for designing, planning and analyzing construction operations. Over the past three decades, various types of simulation methods have been developed to cope with different system behaviors, including Monte Carlo simulation, discrete event simulation (DES), and system dynamics (SD). These methods are being widely used to study and model construction operations, such as tunneling operations (Rahm, Duhme, Sadri, Thewes, & König, 2013; Ebrahimy, AbouRizk, Fernando, & Mohamed, 2011), scheduling problems (Araúzo, Pavón, Lopez-Paredes, & Pajares, 2009; Tang, Mukherjee, & Onder, 2013), and earthmoving operations (Marzouk & Moselhi, 2004; Zhang H. , 2008; Hsiao, Lin, CT., Wu, & Cheng, 2011; Mohamed & Ali, 2013).

However, despite the proven benefits of simulation applied to the construction industry and the need to develop new delay analysis methods, the application of simulation to delay analysis is limited. Overall, the industry is slow to embrace and benefit from the numerous simulation advantages in claims management flowing from computation, accuracy, scenario analysis, etc. The tendency to use DES in claims analysis focused on modeling different scenarios under different conditions to analyze and evaluate changes in system behaviour (AbouRizk & Dozzi, 1993; Al Malah, Golnaraghi, Biok, Elfaizy, & Zayed, 2013). SD models have also been used in the claims analysis process because the use of concepts and arrows in qualitative models provide clear argument routes and makes things easier to understand than quantitative models (Howick, 2003; Williams, Ackermann, & Eden, 2003).

A thorough review of academic, technical and professional literature revealed the extent of the problem from theoretical and practical perspectives and confirmed the existence of many shortcomings. The deficiencies are predominantly in the area of time claims, where there is a focus on analysis of project schedules and simulation of different delay scenarios. Schedule overrun is worldwide problem and, consequently, responsible party or parties are obligated to meet this liability. Therefore, more accurate and timely approaches for the analysis and quantification of time claims are critical in the construction industry. This research aims at exploring how analysis of time related claims could be improved by taking full advantage of the time-step simulation concept.

1.2. Research Justification

Unsettled claims lead to the development of dispute and restricting resolution to involving a third party through alternative dispute resolution (ADR) mechanisms. All of these factors contribute to lengthy processes and substantial cost expenditures prior to reaching a conclusion. The most common types of construction disputes are related to schedule impacts, or delay claims (ASCE, 2017). They relate to unanticipated events that extend the project and/or prevent its execution from being performed as originally planned. Yet, they are the least understood and most complex disputes in the construction field (SCL, 2017).

Previous studies have focused on the development of technical solutions to facilitate conclusions regarding construction disputes; however, they fail to address some critical administrative issues relative to the management of time related claims. These issues include lack of standardized documentation processes, need for specific delay analysis skills, information overload and lack of data organization and disintegrated claims management processes. Subsequently, various methods for analysis of schedule delays have been developed (Arditi & Pattanalitchamroon, 2006; Gibson, 2008; AACE International, 2011). Among these methods, window-based delay analysis methods have been identified as being the most credible; however, they still have functional limitations and user prerequisites. For instances, window-based analysis methods do not consider partial delay analysis nor allocate delays at a micro-level (subcontractor, suppliers, etc.) (Hegazy & Zhang, 2005). These drawbacks of existing methods form the objectives that are to be addressed in this research. Furthermore, this research highlights additional technical issues that were not previously addressed, including inadequate testing and use of alternate technologies, subjective interaction with schedules, impractical solutions and restricted forms of delay analysis.

Thus, the need for a new approach to perform construction schedule analysis and quantify extension of time (EoT) in a more realistic and efficient manner is apparent and imperative. From this perspective, and to improve overall construction delay analysis practices, new avenues related to recent advances in simulation can be explored and tested. This research aims to explore how quantification of time extensions related to delay claims can be improved by taking advantage of improved simulation techniques. It will introduce the concept of Forensic Schedule Information Modelling (ForSIM) that integrates all the main delay claim management phases in one environment using simulation, and simultaneously models various schedule-related factors, quantifies time extension awards and provides feedback for delay analysts using graphical and statistical tools.

If a simulation-assisted systematic approach is used to model, analyze and evaluate project schedule information and updates, it will provide an improved basis for quantifying the impact of changes or interferences in the construction progress and enable a focused analysis process. Moreover, the integrated approach for managing time can expedite the dispute resolution process and contribute to significant cost savings.

1.3. Research Objectives

In view of the problems identified earlier, the following objectives have been formulated commencing with investigations into current theory and practice. These objectives are:

1) ***To establish a standardized data structure to facilitate automated retrieval of project information and analysis of time claims:*** This objective involves studying the structure and properties of contemporaneous project data, as well as the application of simulation techniques to the organization and retrieval of project data. This objective requires the introduction of a new data schema for documenting contemporaneous project events, which might impact project schedules, through a standardized set of attributes that comprehensively describe these events. Thus, the following research question could be answered:
    - What formal data schema is suitable for modeling project planning, progress and control information to ensure efficient and accurate delay analysis? How can the utilization of the currently deployed tools within the construction industry be maximized to include the analysis of schedule delays and facilitate the smooth adoption of the proposed framework?

2) ***To develop Forensic Schedule Information Modeling (ForSIM) framework for the analysis of time claims.*** This objective is to develop simulation algorithms that forms the basis of a new framework for time delay claims in the construction industry. This new approach should also integrate the main phases of claims management, including delay identification, impact quantification and analysis, as well as liability allocation at micro level, under one environment. The impact quantification will include uncertainty modeling

and mathematical models designed to investigate different causes and impact scenarios. Thus, this research objective strives to answer the following research questions:

- Can simulation aid in facilitating construction schedule analysis to quantify time extensions? If yes, what is the appropriate simulation approach required? what model architecture is capable of supporting decisions and examining scenarios during delay analysis process? How should different schedule change factors be integrated within a simulation environment?

3) ***To develop, test and evaluate ForSIM prototype through a number of case studies and to identify its limitations and advantages.*** This objective involves implementing the proposed framework and modeling delay analysis scenarios at an adequate level of abstraction. The development and implementation of ForSIM prototype should be based on a new standalone modeling environment supported with different sets of services, such as uncertainty modeling and mathematical model functions. These services allow for integration of all different phases of time claims management. ForSIM prototype will then be tested on different case studies and compare its results with the current practices/procedures to identify its implications on extension of time claims. Thus, this objectives could help with answering the following research question:

- What is the degree of confidence that ForSIM brings to claims analysis? what advantages does simulation supported analysis provide over more traditional methods of delay analysis?

1.4. Research Methodology

The principle investigation methods comprised literature review and case studies, as they are able to capture the forms of the research questions. The research methodology is designed in such a way as to progressively meet the research objectives, while building on each completed task and deliverable in an integrated manner that will optimally use available research resources. Figure 1-1 shows the overall approach, which will be detailed with reference to each of the research objectives in the following sections.

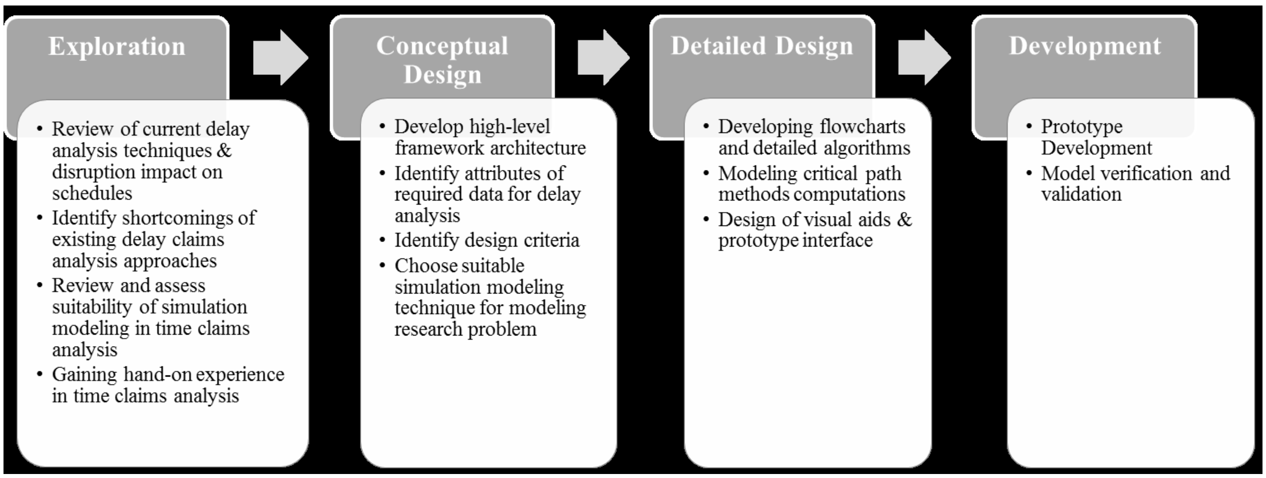


Figure 1-1: Research Methodology

1.4.1. Exploration

This phase aimed to identify the shortcomings in existing claims analysis practice from theoretical and empirical evidences. This aim was accomplished by conducting a thorough literature review in the field of time claims analysis and management, analyzing current practices employed by industry practitioners and identifying problems experienced. The literature review exercise also covered the impact of disrubtion on construction schedules, including identification of factors, quantification of impact on project activities and the methods used to estimate the cumulative impact of these factors on the project. A thorough review of simulation advancements and applications areas in the construction industry was also completed. The phase also included gaingin a hands-on experience on analysing time related claims to incorporate the practicality element to the framework. Furthermore, this phase provided an up-to-date appraisal of the contemporary direction and maturity of previous research in this area.

Also, over the last four years, the author engaged in many time claims analysis cases of which significant hands-on and best practices experience was gained. These claim cases varied in nature and complexity; and some of them were settled while others still ongoing and expected to be settled in court due to their high complexity. This experience also helped in including the practicality element in the design of the proposed framework in order to encourage acceptance by industry practitioners.

1.4.2. Conceptual and Detailed Design

The critical review outcomes and deductions established from the analysis, Chapter 3, coupled with the underlying principles and themes derived from the literature review and industry practices, have led to the formulation and development of a simulation-assisted framework for time claims analysis and the prototype of ForSIM (**Objective 1 and 2**).

The shortcomings identified in this process were used as design criteria for the development of the proposed framework. These design criteria include the following:

- Adhere to current time claims principles,
- Automated analysis process,
- Modeling uncertainty of events duration,
- Integrated analysis process, including identification, quantification, analysis and time award,
- Modeling dynamic changes of critical path of project schedules,
- Project data documentation and organization,

- Tracability of events impact and liability, and
- Future expandability of the framework to include other project management functionalities.

Detialed description and rationale for the selection of these design critera is discussed throughout this thesis.

Because of the significance of docuementation to successful claims submission and analysis, the required attributes for adequate docuemention of project events have been identified through a thorough review of literture and case studies (**Objective 1**). Peer reviewed conference papers, journal papers, best practices and professional reports were reviewed. Although this research focused only on identifying attributes that relate to time claims management, the framework is designed for easy future expansion and incorporation of additional attributes that can be used for other project management functions, such as risk and cost management. In total, 11 attributes were identified namely: ID, description, cause, quantification type, start time, parameters, impact type, responsible party, impacted activities, reference and issue date. Some of these identified attributes facilitate a better understanding of the event circumstances (e.g. description, cause and start time) while others are used for impact quantification (e.g. impact type, duration and impacted activities). Detialed description of these attributes is provided in Section 4.3.2.2 of this thesis.

The conceptual design was undertaken to determine the specifications and behaviour of the main components of the simulation model, together with a high-level of the simulation flow (**Objective 2**). The creation of concepts and designs of the model components to be presented were integral part of the simulation model. Flow charts and sequense diagrams were used for representing the flow logic and communication protocols between the model components for analyzing time claims using simulation paradigms.

The use of simulation modeling is mainly due to the high complexity of time claims. It is very powerful technique for gaining insights into how construction schedules that are characterized by dynamic changes progress over time. Time-step simulation was adopted in this research as approach for analyzing time claims because it is very difficult to comprehend large amount of information generated throughout a construction project and observe changes in the critical path of project schedule. It was also adopted to model the principles and computation of the critical path method (CPM).

The conceptual and detailed design was then presented to experts in the field in the form of flowcharts, activity charts and traditional concept models discussed in Section 4.3 to assess whether the modeling and abstraction level fits the problem. These conceptual and detailed models are further detailed and elaborated in Chapters 4 and 5.

1.4.3. Framework Development

The development of the ForSIM prototype followed a systematic approach to ensure efficient and accurate implementation. To model time claims analysis using simulation, the development required certain knowledge and skills including, but are not limited to, computer simulation modeling, computer programming as well as analysis of time claims. The knowledge of simulation modeling proved to be essential, mainly in two main areas of simulation i.e. continuous simulation and discrete event simulation. Also the knowledge of computer programming proved to be vital for the development of the prototype. Visual Studio version 2017 was used in the development of the simulation model and user interface in the Windows Presentation Foundation (WPF) application which served as means for entering the simulation model inouts and viewing its outputs after simulation. Further details on the prototype development is provided in Chapter 5. Last but not least, a hands-on experience in analyzing time claims using different techniques also came in handy especially when selecting the tools and structure of information that are used in the proposed framework.

At this stage, and to verify and validate the proposed model (**Objective 3**), several case studies were modelled and analyzed to determine if the use of ForSIM results in a significant difference in the analysis process for time claims. A detailed description of verification and validation process is provided in Section 4.4. Simulation features such as the events trace were used to confirm that the logical sequence of events matched the intended sequence. Also, actual project performance records were compared with the results of the ForSIM prototype.

1.5. Structure and Guide to Thesis

The flow of the methodology described in Section 1.4 is used to report the research work that includes this thesis. The thesis is based on a traditional formats, and organised into seven related chapters as briefly described below:

- **Chapter 1** provides an overview of the thesis including a brief introduction to the research topic as well as the statement of problems under investigation. It also presents the research aims, hypothesis and objectives, the research methodology, as well as a summary of contributions and the organization of the thesis.
- **Chapter 2** reports on state-of-the-art practices in project scheduling, changes in schedules and factors impacting construction schedules, delays in construction and simulation modeling paradigms. The review covers relevant analytical techniques and currently known issues with schedule analsyis from theoretical, academic and professional perspectives.
- **Chapter 3** outlines the finding of the literature review, identifies gaps in the body of knowledge and makes deductions establishing the scope and nature of the theoretical and practical limitations in current delay analysis practices.

- **Chapter 4** considers the shortcomings of current practices related to both theoretical and practical aspects. From this, the concept of time-related claims was defined as a problem that could be solved by a simulation-assisted framework. Using these shortcomings as a basis, a solution was formulated, in form of an alternative approach which would improve the accuracy, efficiency and effectiveness of delay analysis practice.
- **Chapter 5** covers the detialed design and implementation of ForSIM prototype. It also highlights the limitations of the developed prototype and provided recommendations for future implementation and research.
- **Chapter 6** reports on the issue of time claims management in greater details through the application of ForSIM on a real life and hypothetical simple case studies. This chapter also discusses the capabilities of ForSIM in comparison to the daily window delay analysis method.
- **Chapter 7** describes the findings of this research and states its conclusions, contributions, limitations and the recommendations for further research on the subject matter.

Chapter 2. Literature Review

2.1. Chapter Introduction

This chapter provides a review of literature related to the development of project schedules, delay analysis methods, and factors impacting project schedules; additionally, this chapter discuses the different types of simulation modeling paradigms and their application in the construction domain. The discussion on project schedules commences by highlighting principles for establishing the project timelines and benchmarks to measure progress and performance as well as the dvelopment of as-built schedules. A discussion follows on the problem of delays in construction projects, including concurrent delay, float ownership, and time at large. The discussion enumerates the currently available methods for analyzing delay, their limitations, and current research directions to overcome these limitations.

A review of the impact of changes on a construction project schedule is also provided by discussing common productivity factors as well as quantification models for both single and multiple factors. This chapter concludes with discussion of simulation in construction. The discussion introduces computer simulation types, such as: Discrete Event Simulation (DES), Monte Carlo Simulation, and Dynamic Systems. Practical applications are reviewed for feasibility in the domain of construction.

2.2. Development of Construction Projects Schedules

Project scheduling determines and communicates project requirements, procedures, timelines, and resources needed to manage, execute, and control the work (PMI, 2017). The project scope and deliverables are broken down into manageable components with what is known as Work Breakdown Structure (WBS). The WBS helps define the scope of the project carried out during the construction stage to be completed as deliverables (Ahuja, Dozzi, & AbouRizk, 1994; PMI, 2017). Accordingly, the project activities are defined with estimated resources and durations, and are logically sequenced to achieve project completion. Often, contractors are required to submit their preliminary schedule as part of the bidding package and, within a month or two (depending of project size), they must submit the baseline schedule for the project. The baseline schedule reflects their intended plan to execute the project.

There are many techniques available for scheduling project activities. Initially, bar charts were used to generate construction schedules by forming lists of activities along with their start and finish dates plotted on a time scale (Gibson, 2008). More sophisticated scheduling techniques were then introduced, such as: Line of Balance technique, Project Evaluation Review Technique (PERT), and Critical Path Method (CPM) (Ahuja, Dozzi, & AbouRizk, 1994; Newitt, 2008). A description of these techniques and their computation as well as their benefits and limitations are discussed extensively in the literature.

CPM is an industry-wide accepted method for delay analysis; moreover, many forms of commercial software are available that facilitate its computations, including Oracle's Primavera (Oracle, 2019) and Microsoft Project (Microsoft, 2019). CPM is used to logically sequence project activities and identify the shortest time in which the project can be finished (i.e. the critical path).

From a scheduling perspective, total float refers to the allowable time that an activity can be delayed without impacting the project completion. Activities on the critical path have zero total float; non-critical activities have a positive total float. Activities with a total float of zero form a chain of activities that represent the shortest possible time to complete the project and are referred to as the critical path. Any delay to any one of the critical activities will directly impact the project duration and the completion date of the project, as well as the other projects constraints (cost, quality, and scope). The calculation necessary to determine the start and finish date of activities (forward and backward paths calculations) are very simple arithmetic and have been discussed widely in the literature.

Contractors are usually required to submit baseline schedules that demonstrate their intended plan for delivering projects, as well as providing periodic progress updates during the execution phase. The updates are usually provided in different forms, such as daily site reports, monthly progress reports, meeting minutes, updated schedules, etc. This information becomes part of the project contract and is generally used for resolving relevant claims. Ultimately, this scattered information is gathered and transformed into as-built schedules which represent the actual durations and execution sequences of activities following CPM principles. All project changes should be considered when developing such schedules: this includes but is not limited to scope, schedule, and resource allocation changes (Knoke & Jentzen, 1996; Hegazy, Elbeltagi, & Zhang, 2005; Henschel & Hildreth, 2007).

2.2.1. Changes in Construction Schedules

A project schedule can be represented as a system consisting of many work packages and activities, with durations that are subject to changes (Gibson, 2008). These changes could be triggered by different factors that interact and systematically impact activity durations. The impact could be in the form of variance in productivity and/or increase or decrease in scope of work (AACE International, 2004). Examples of change triggers include change orders, weather conditions, and/or any other matter that requires management attention (either contractor or owner) and subsequently results in managerial action or inaction which then affects jobsite conditions. For instance, a delay in a decision could cause stop-and-go work, which in turn could result in distraction, irritation, and/or loss of continuity of learning.

A construction project consists of various elements that interact with one another; however, there is a misconception in dealing with changes – i.e., that a change is a simple additive or deductive process (Lee S. , 2007). When a change occurs, the original sequence of work might need to be altered, eventually leading to work being done out of sequence, all of which may cause productivity losses and delays. Managerial strategies like acceleration might be used to make up for a delay (directed acceleration) or to accommodate increased scope that is added by change orders without a corresponding time extension (constructive acceleration) (Gibson, 2008). Contractually, directive acceleration occurs when an owner directs a contractor to complete a project prior to the scheduled completion date, while constructive acceleration occurs when an owner refuses a time extension request for an excusable delay. Contractors may also voluntarily accelerate the project either to make up for delays caused by their own fault, such as mismanagement or underestimation, or to earn early completion incentives. However, claims for compensation cannot be made for voluntary acceleration impact. The most common form of acceleration is increasing labor-hours either through the use of overtime, shift work, out-of-sequence work or running concurrent operations; however, these might impact productivity negatively (Hanna A. S., Chang, Lackney, & Sullivan, 2005).

Demonstrating the impacts of productivity influencing factors requires comprehensive understanding of the interrelationship between these factors. Some relationships are easier to identify than others. For instance, the relationship between overtime and fatigue is evident, while the relationship between change orders and productivity loss is implicit, and thus harder to identify.

Recognizing all likely relationships is difficult; however, a framework demonstrating the flow of influences from root causes to schedule impact can be valuable (Tsehayae, 2015).

Researchers study these factors in the context of productivity, and they are commonly known as productivity factors; however, these factors are different in nature (Lee S. , 2007). Some of these factors are explicit in meaning, others implicit. The impact of some factors on activity durations can be direct or instantaneous, others can be indirect impacts or after a time lag. The time of occurrence of these factors can be either before the project start, usually at the planning stage (e.g. underestimated bid, unusual weather conditions, labor outflow), or during project execution. Some of these factors can be managed by the project participants, while others may be out of their control (e.g. strikes and force majeure) and result in undesirable consequences such as out-of-sequence work. Some factors simply reflect situations (disruptions), and others are consequence of actions such as change orders, lengthy decision-making processes or response times.

Managerial actions either control changes or cause further disruption to work. Disruption causes poor adeptness, lowered motivation, lost learning curve, and other impacts to workers, which immediately affects productivity. Although reduced productivity may not cause a delay, it often demands managerial responses.

Also, certain factors can be considered in two distinct cases. For instance, weather conditions can be considered to be an external factor in cases where it is beyond anyone’s control, such as uncommonly heavy rainfalls or unexpected freezing temperatures; however, in other cases these can be categorized as disruptive events in the case that delays or changes caused by some party or action resulted in work being pushed back and executed during unfavorable weather conditions.

The impact of change on schedule is noted in this study to provide an emphasis on causation and the fact that multiple factors might be combined to quantify impact of changes on activity durations. While the problems and limitations of quantifying the impact of factors are comprehensively noted in other studies, it is important to note that the redundancy of impact calculation when multiple factors are combined remains as a critical issue. For instance, when overtime and fatigue are considered, summing their impact could result in over-quantification, since the impact of overtime may have been accounted for when quantifying the impact of fatigue.

Although it is not always the case, many schedule delay claims are caused by productivity loss due to disruptions. Analyzing entitlement and, in some cases, impact of lost productivity are the focus of schedule analysis. The relationship can be described as follows: When there is productivity loss during project execution, the durations of impacted activities increase. Consequently, other activities may also be impacted. For instance, increase of duration may result in resequencing of activities to meet planned schedule milestones, or some activities may be pushed into undesired weather conditions. Courts acknowledges that there is no need for contractors to prove their work was extended beyond the contracted completion date in order to claim for compensation of lost productivity (SAUER INC. v. DANZIG, 2000). However, it is likely that contractors would suffer productivity loss if there were re-sequenced activities or a shift due to the weather. There can be a ripple effect on non-impacted activities. The onus, then, is on the claimant to recognize and define the ripple effect, demonstrate entitlement and causation, and quantify as well as document the experienced damages. There is no industry-wide agreement on what method should be applied when quantifying productivity loss impact; developing such a method is not the intent of this research. Rather, this research demonstrates that there is a relationship between labour productivity and projects schedules, and it highlights and discusses some of the methods that can be integrated with the proposed delay analysis framework at the analyst's discretion as the upcoming chapters will show.

2.2.2. Productivity Impact on Construction Schedules

Construction productivity has been a long-term challenge as the parameters influencing productivity are numerous, dynamic, complex, and inconsistent from one project to another (Thomas, et al., 1990; Moselhi, Charles, & Fazio, 1991). Previous studies have identified numerous variables influencing construction productivity, most of which relate to human effort and performance (Arditi & Mochtar, 2000; Ibbs, Nguyen, & Lee, 2007; Jarkas & Bitar, 2012; Nasir, Haas, Caldas, & Goodrum, 2015; Naoum, 2016). Many of the previously developed productivity models focus on one specific condition at a time, including weather conditions, project location, and contract type. The implementation of previous models has been restricted to the data used in their development. Recent studies have sought to collectively quantify the impacts of multiple changes, and many of these employ statistical analysis techniques and artificial intelligence (Lee S. , 2007). The applicability of these studies, however, is limited by the scope of data source and the types of observed trades.

Quantification of the impact of these factors can be grouped into two categories as follows:

2.2.2.1 Single Factor Models

Single factor models are discrete methods that focus on analyzing and quantifying the impacts of one specific factor at a time, irrespective of other factors. A review of the most noted factors and studies is provided in the following sections.

2.2.2.1.1 Overtime

Overtime refers to the extension of working hours beyond the norm. It is one form of acceleration and it is commonly used to complete projects earlier than planned, handle unexpected work, or to complete critical work. One drawback of overtime is the physical fatigue that discourages workers, and which creates a loss of efficiency. Some researchers also noted that management and supporting operations usually do not keep up with overtime through their inability to provide equipment, tools, materials, and so on in a timely manner. Thus, overtime may result in errors, rework, or poor quality of work. Examples of quantification models for the overtime impact are provided by Hanna and Sullivan (2004), Hanna, Taylor and Sullivan (2005) and Somez (2007).

2.2.2.1.2 Overmanning / Trade Stacking

Overmanning refers to either allocating more than typical or optimum manpower to a jobsite or increasing the crew size. Hanna, et al. (2005) argue that the overmanning approach can achieve higher progress rates than overtime without causing productivity loss; however, other researchers argue that this approach results in congestion, supply chain deficiencies, decreases in the learning curve (due to reduced repetition and participation per worker), limited work space, higher accident rates, and higher cost per unit-hour (Gunduz, 2004). Another term often confused with overmanning is trade stacking. The key difference is that overmanning refers to workers within the same trade while trade stacking refers to a situation where different trades work in the same workspace, often due to out-of-sequence work or concurrent operations. Examples of the impact quantification models can be found in Hanna, Chang and Lackney, et al. (2007) and Ibbs (2005).

2.2.2.1.3 Weather Conditions

One of the most notable factors in productivity loss is adverse weather conditions (Moselhi & El-Rayes, 2002). Typical weather conditions are usually considered during the planning stage of projects. Unexpected weather conditions like heavy rainfall, unusual freezing temperature, or any other force majeure incidents can also occur, causing productivity loss. For many reasons such as delay, changes, or scope creep, projects may be forced into continuing during unplanned weather conditions. The impact of weather on productivity is direct and is felt mainly in the areas of the workers mobility, motivation, or physical capacity to complete tasks (Ibbs, 2005). The quantification of weather impact on productivity is relatively easy when compared to other factors. Examples of the quantification models can be found in El-Rayes and Moselhi (2001), Moselhi and El-Rayes (2002) and National Electrical Contractors Association (NECA) (2004).

2.2.2.1.4 Learning Curve

The term "learning curve" refers to many different concepts including but limited to: time reduction curve, improvement curve, experience curve, startup curve, cost reduction curve, and efficiency curve. Although a learning curve does not directly cause productivity loss, it is the main factor causing fluctuation in productivity in any repetitive operations. The concept is based on the theory that performance in repetitive tasks improves due to several factors, such as: better coordination, familiarity with tasks, and effective use of tools and methods. Contractors leverage their learning curve in productivity improvement when bidding on similar activities, while owners leverage it for bids and change order evaluations; it is later used in price negotiation (Raman & Varghese, 2016). Examples of quantification models can be found in Lee, et al. (2015), Grosse, et al. (2015) and Abdulaziz Jarkas, et.al. (2010).

2.2.2.1.5 Change Orders

Leonard et al. (1988) studied the effects of change orders on labour productivity, which is deemed to be a ground-breaking study in attempting a statistical analysis to assess the impact of change orders on productivity. This study is cited frequently in academia as well as in industry (Leonard C. , 1988). Data from 90 projects in Canada were categorized into different sets according to the types of work (e.g. electrical, mechanical & civil), types of construction (e.g. commercial, institutional and industrial), and the major causes of impact. Acceleration, poor scheduling and coordinating, ripple-effect, dimension discrepancies, late delivery, increased complexity, and sequence changes are all identified as the most influential factors with different frequency of occurrence as shown in Figure 2-1.

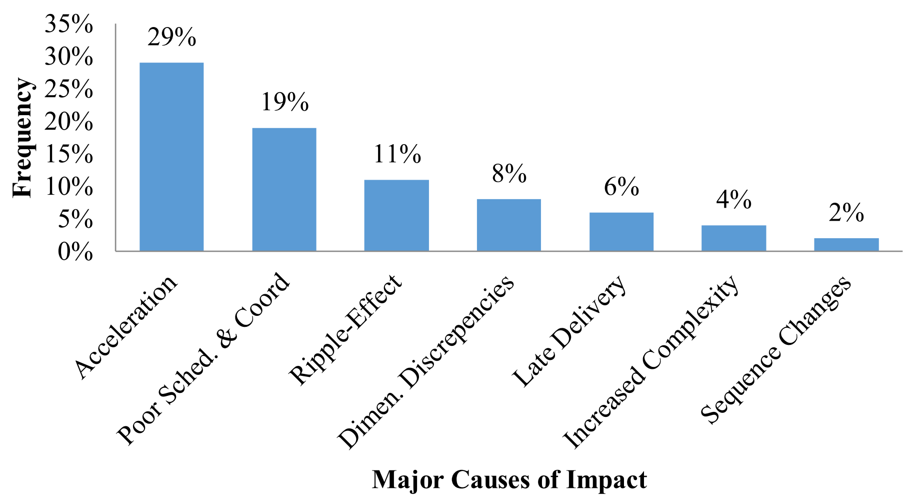


Figure 2-1: Major causes of productivity losses other than change orders (Leonard, Fazio, & Moselhi, 1988)

The authors indicated that contractors can accommodate change orders without affecting the work if the hours total range between 10-15% of the contract hours. Higher percentages of change result in stop-and-go operation, out-of-sequence work, learning-curve-related losses, loss in productive rhythm, demotivation of work force, unbalanced crews, excessive labor fluctuations, and unbalancing of successive operations. The study also identified factors that decrease productivity due to change orders. All of the factors and their frequency of occurrence are shown in Figure 2-2.The study stated that some of the factors are more influential to electrical and mechanical work than to civil and architectural work, such as complexity of the work, interdependency among activities, and intensity of the work. Other factors cited in the literature include, but are not limited to: absenteeism, availability of skilled labor, competition for craft labor, craft turnover, defective engineering, dilution of supervision, material shortage, tools and equipment shortages, poor morale of craft labor, out of sequence work, rework and errors, and site conditions (AACE International, 2004; Ibbs, 2005; Moselhi, Assem, & El-Rayes, 2005; Hazrati, 2016).

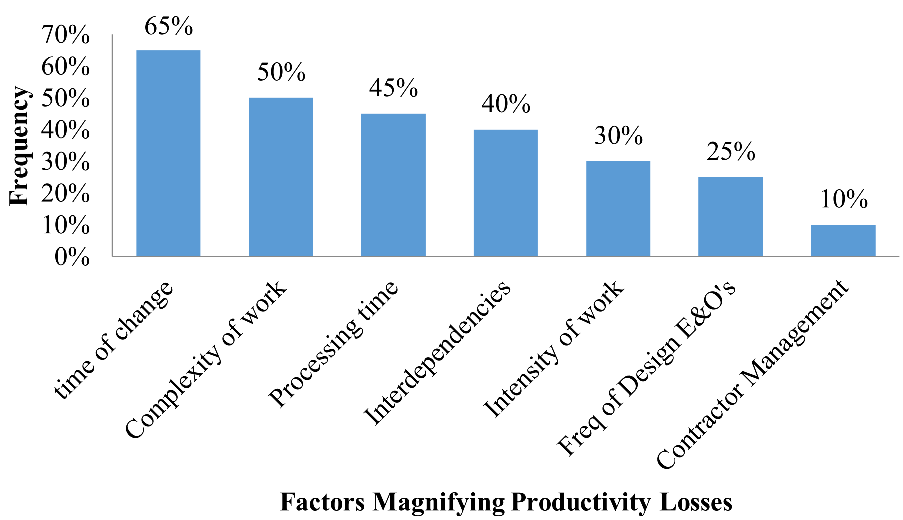


Figure 2-2: Factors negatively influencing change order impact (Leonard, Fazio, & Moselhi, 1988)

Leonard's study had been criticized by many researchers as all of its data comes from projects under dispute, raising concerns on how productivity losses were measured from the sample data (Hanna, Camlic, Peterson, & Nordheim, 2002; Ibbs, 2005; Harmon & Cole, 2006a; Harmon & Cole, 2006b). Although the study indicates data adjustments using methods such as measured mile analysis and modified/total cost approaches, the details of the modification process are not disclosed, and no examples are shown. As such, concerns about its reliability and accuracy are rightfully raised.

Some studies demonstrate that the Leonard's charts are representative and reasonable. A comparison study by McEniry (2007), for example, demonstrates strong similarity between the data points of Leonard to those of Ibbs (2005), strongly supporting the rationality of the Leonard study (McEniry, 2007).

2.2.2.2 Multiple Factors Models

In situations where there are multiple concurrent factors occurring, three core types of model integration can be explored, namely: composition, weaving, and merge.

Composition can be used to accumulate a set of autonomous but interacting models that run in parallel or sequentially, and that capture different components of the productivity system. Singh (2001) provides a case study to show an example of how to utilize existing indices to combine the quantified effects of individual factors. Although the article shows that it is possible to foresee specific types of disruption and estimate their impact, the study falls short in formalizing the composition process.

Weaving can be used to incorporate cross-cutting concerns into the productivity system. Some models may alter the behaviour of others in response to different overarching concerns. In other words, any redundancy in impact caused by productivity factors needs to be tested before determining which factors will be considered. For instance, whereas overmanning and congestion are identified as causal factors for lost productivity in some situations, the impact of overmanning may have already included the effects of congestion; thus, combining both impacts may result in overestimation of the true impact. Likewise, overtime impact probably includes the fatigue impact, so combining these two factors may result in redundant impact calculation.

Merge can be used to build a comprehensive view of a set of overlapping models that capture different perspectives of the productivity impact. Some researchers have tried to develop models that quantify the cumulative impact of multiple productivity factors collectively. Although these studies are limited, the most commonly cited studies include the factor model theory (Thomas & Yiakoumis, 1987), Productivity forecasting model (Thomas & Smith, 1990) and some industry studies that quantify productivity losses due to multiple change orders or various factors induced by the change orders. The studies most commonly referred to include the Mechanical Contractors Association of America (MCAA) Labor Estimating Manual (MCAA, 1994), National Electrical Contractors Association (NECA) Manual of Labor Units (NECA, 2003), and the US Army Corps of Engineering's Modification Impact Evaluation Guide (ACE, 1979). The MCAA and NECA manuals are developed by contractor groups and the Corps manual is developed by an owner (Ibbs, 2005).

2.2.2.3 Methods of Estimating Cumulative Impact of Multiple Factors

When multiple inseparable changes occur, they cause productivity loss in the form of a ripple effect when interdependency exists between changes and the original contracted work. A key condition of the impact multiple changes have is that they are often unexpected at the time of occurrence and can only be recognized retrospectively. This inability for individuals to recognize the full impact of these changes is recognized by courts, which consequently allows contractors to claim cumulative impact claims, even if they have waived the right to claims. This is conditioned, however, upon the owner having initiated multiple excessive changes as main cause cited in the claim. The methods for measuring the impact of such claims are limited and vary in their accuracy.

The traditional methods reviewed include the total cost method, modified total cost method, jury verdict, actual cost method, and measured mile analysis (Long & Lane, 1990; Finke, 1998; Schwartzkopf & McNamara, 2001; Caplicki III, 2003; Sanders & Nagata, 2003). Some of these methods have been used frequently and successfully, while others have been criticized for their lack of reliability and accuracy. Among these methods, the measured mile method has been widely used in the industry and accepted by courts. To overcome some limitations of the measured mile method, some researchers have developed improved methodologies, including: Thomas's baseline method (Thomas & Zavrski, 1999), Gulezian and Samelian's statistical process control method (Gulezian & Samelian, 2003a; Gulezian & Samelian, 2003b), and Ibbs and Liu's statistical clustering method (Ibbs & Liu, 2005).

2.2.3. Prospective and Retrospective As-built Schedules Development

Most of the literature recognizes the value and importance of as-built records for the analysis of delay claims as they can be used to validate as-built dates and evaluate the performance of contractors (Mbabazi, Hegazy, & Saccomanno, 2005; Long R. J., 2018; Avalon, 2014), as well as being used as a reference when developing new project schedules. On the flipside, they can also be used to defend and validate time-related claims, as they form the basis for most delay analysis methods (AACE International, 2011). However, analyzing as-built schedules is difficult for many reasons, including inaccuracy of CPM calculations (Hegazy & Menesi, 2010) and lack of site event documentation (Hegazy, Elbeltagi, & Zhang, 2005), all of which limits the utilization of as-built schedules when analyzing delay claims.

As-built schedules can be categorized either by the time of development or the level of detail (Shrestha & Jeong, 2017). As-built schedules can be developed throughout the construction phase of projects in the form of schedule updates to reflect the progression of completed work to date, also called as-built to date schedules, which are usually used for project controls. The latest project schedule update, also called the final as-built schedule, reflects the actual sequence and duration of project activities. It is this final as-built schedule that is usually used to evaluate project performance and/or to validate delay claims. From the level of detail perspective, as-built schedules can be developed at the project level, reflecting the start and completion date of projects, or at the activities level, reflecting the timeline and sequence of activities. However, experts in this field acknowledge that it is impossible to have a perfect as-built schedule and recommend that both parties agree on the as-built dates prior to claims analysis (AACE International, 2011). The recommended practice is that significant activities should be accurate to within one working day, while the dates accuracy of less significant activities should be 5 working days or less.

As-built schedules are usually developed using existing commercial scheduling tools that rely on CPM principles, such as Microsoft Project or Primavera. However, these schedules are difficult to analyze due to many factors that influence the accuracy and repeatability of scheduling calculations. For instance, CPM only record the latest status of activities (Kahler, 2012), and is incapable of reflecting soft human elements (e.g. fatigue) or managerial actions taken to mitigate, delay or accelerate construction projects (Eden, Williams, Ackermann, & Howick, 2000). CPM is also limited in that it cannot be used to identify alternative emerging critical paths when an unexpected disruption has occurred in the as-planned schedule (Tang, Mukherjee, & Onder, 2013). Additionally, the scheduling flexibility that is offered by existing scheduling tools and the need to accommodate inevitable project changes have led to misleading scheduling practices, all of which results in manipulated schedules. These include the use of complex relationships (e.g. start-to-start, SS, and finish-to-finish, FF) (Lu & Lam, Transform Schemes Applied on Non-Finish-to-Start Logical Relationships in Project Network Diagrams, 2009), excessive use of leads and lags (Wickwire & Ockman, 2000), use of multiple calendars (Scavino, 2003), use of multiple constraints, and out-of-sequence progress (Herold, 2004). All of these misleading practices ultimately result in inaccurate schedule calculation and unrealistic activity durations. When such schedules are used in delay claims investigation, these manipulations may lead to inaccuracies while analyzing delays, determining the responsibility of the different parties and quantifying time extensions. Also, the existing scheduling tools do not determine the critical path on the past portion of the data date. Therefore, the usefulness of as-built schedules is limited to representing the actual dates and sequence in which projects are completed. Although several scheduling alternatives have been introduced, such as the use of simulation based systems (Sawhney, Mund, & Chaitavatputtiporn, 2003), a logic diagramming method (Ponce de Leon, 2008) and critical path segments (CPSs) (Hegazy & Menesi, 2010), their application is yet to be integrated with as-built schedule development.

In general, as-built schedules are developed either by creating an as-built schedule from scratch using progress records or modifying a fully progressed schedule update as needed (AACE International, 2011). A subset of this approach is to create the as-built schedule by fully progressing a baseline schedule. To qualify as an as-built schedule from the delay analysis perspective, the schedule must contain as-built dates that are as accurate as possible, be capable of simulating CPM functionality, and show the delay causation in some form (AACE International, 2011).

To develop an as-built schedule, a collection of activity progress data over time is required. More importantly, if as-built schedules are to be used for delay analysis, a history of events that took place during the project execution phase should be documented and readily available.

Several studies have addressed the development of as-built schedules from contemporaneous and unstructured site records (Knoke & Jentzen, 1996; Kahler, 2012). Such records include daily progress reports, testing records, meeting minutes, change orders, submittal logs and payment records. Through these records, the timelines of activities and milestones (start and finish dates) can be extracted manually, along with inference of activity sequence logic. The extracted data are then entered into a scheduling tool to develop a bar chart that visually presents the as-built record of the project schedule. Elkass et al (1995) introduced a computerized delay claim analysis (CDCA) system that integrates traditional scheduling tools with a delay expert system. The study proposed an approach that exports progressing activities into an editable format that is later manipulated by the user to determine the liability associated with a delay. The updates are then imported back into the scheduling tool and stored as a new schedule (schedule update). The schedules are then used to compare adjusted as-planned work with previous schedules (Alkass, Mazerolle, Tribaldos, & Harris, 1995). A similar tool was later introduced by Al-Gahtani, Al-Sulaihi, & Iqupal (2016), which focused in implementing as-built vs. as-planned delay analysis. The proposed tool was integrated with Primavera and also developed as a web application. The main challenges addressed by previous studies are the lengthy manual process, as well as the need for additional resources to capture and sort the data. Moreover, manual collection of the data has some limitations, because data is often incomplete, and their quality and accuracy depend in large part on the data collector (Hegazy, Elbeltagi, & Zhang, 2005). Elzouni & Salem (2010) developed a pattern recognition approach to measure and monitor schedule progress. The study used neural-network pattern recognition (NN-PR) and statistical pattern recognition (S-PR) techniques, which map the CPM schedule, to classify planned progress patterns at a certain date and use the classification to assess actual progress patterns on the same day.

In attempts to overcome these problems and improve as-built schedule development, other studies have introduced new methodologies to determine a pre-structured set of data to automatically generate as-built schedules. These studies rely on impractical data collection practices, including daily capturing of the percent completed of ongoing activities, emails or interactive voice response (IVR). Hegazy, Elbeltagi and Zhang (2005) have introduced an intelligent bar chart (IBC) that is made of spreadsheet cells in which activity durations are represented as groups of cells rather than bars to facilitate delay analysis. Each cell is then used to store the daily percentage complete for activities, general activity information and other data relevant to delays. Navan and Haskaya (2006) have developed a tool to generate monitoring and control information. The tool relies on information from a computerized daily site report (DSR) that records the number of workers, number of hours spent on activities, material delivery times, the type and number of any equipment used, weather conditions, percent complete, contractors or subcontractors, etc. The tool uses this information to generate actual progress information that is later transformed to schedule updates using scheduling tools (Navon & Haskaya, 2006). The model then compares planned dates with actual performance and issues warnings when there are deviations, so that corrective measures can be taken. It also includes a database to store this information for future use and control purposes. The study presented partial implementation of the model and set the stage for future studies.

In another study, Hegazy and Abdel-Monem (2012) developed an email-based framework for progress tracking. The framework automatically sends daily emails to supervisors requesting as-built information for ongoing activities. The emails are sent in the form of a check list with possible events that are filled in by supervisors. Once the forms are sent back, the system automatically reads the responses and updates the schedule with the recorded as-built information. The framework was later used to facilitate progress tracking and control of linear projects (Hegazy, Abdel-Monem, & Saad, 2014). Further enhancements to the framework were later introduced by the researchers by utilizing a cloud-based interactive voice response (IVR) technology to capture as-built information. Using the same principles, the system captures as-built records by either receiving update calls from supervisors or initiating automatic update calls for ongoing activities. The voice responses are saved as emails which are then read by the system and used to update the project schedule (Abdel-Monem & Hegazy, 2013).

To automate the schedule updating process, Chin et al. (2008) proposed using radio-frequency identification (RFID) technology and 4D CAD models to monitor progress. In this approach, steal components are weighted and marked with RFID tags. Once steel components are installed and the tags are scanned, the progress of the relevant 4D CAD model is measured by comparing the total installed weight to the total planned weight. Although RFID technology proven its usefulness, the manual tagging and scanning process limits its functionality for this application.

To improve data collection efficiency, other studies proposed using digital cameras or laser scanner technologies. One study used digital images and AutoCAD as a means of producing as-built schedules of work progress (Memon, Abd-Majid, Yusoff, & Mustaffar, 2006). In principle, the study simulates 2D images or photos of the construction scene and uses them to make a comparison to the 3D CAD model in order to calculate the progress of the work. The measured progress is then shown in bar-chart format using Microsoft Project. Another study proposed superimposing site camera images on views of 3D models to recognise installed building structural components (Rebolj, Babicˇ, Magdicˇ, Podbreznik, & Pšunder, 2008). The study measures progress through user intervention to extract site images and compare them to the 3D model view in order to determine constructed components. Another study used a fixed position camera to take a sequence of images at different times, with the differences between consecutive images analyzed and compared to the 3D as-planned model (Ibrahim, Lukins, Zhang, Trucco, & Kaka, 2009). A similar approach, also based on recognizing the difference between images, was used by Zhang et al. (2009).

Golparvar-Fard et al. (2009) proposed generating a 3D point cloud from a large number of daily site images and then align and compare it to an as-planned 4D model to identify constructed components. In another study, researchers used a Bayesian probabilistic model to measure the physical progress of structural components along with a continuation of research on calculating differences between planned and actual progress (Golparvar-Fard, Peña-Mora, & Savarese, 2015). However, these studies failed in producing as-built schedules, so they can not be used for delay analysis. This failure is mostly due to the fact that the project schedules are defined at a different level of detail than the building components (e.g. formwork, steel bars, concrete pouring, etc. on the schedule, instead of a column, which is visible as a building component). To overcome this problem, Turkan et al. (2012) proposed an approach that integrates 3D point clouds, 4D CAD models and 3D sensing technologies to automate progress tracking and schedule updating. In this approach, the coordinates of the 4D CAD model are compared with site condition data that are captured using a 3D laser scan to extract as-built objects, measure progress and automatically update the project schedule (Turkan, Bosche, Haas, & Haas, 2012). However, the dates of the updated schedule were found to be incompatible with traditional scheduling software such as Microsoft *Project* or Oracle *Primavera*. Following the same principles, Son, Kim and Cho (2017) used the 3D registration method proposed by Kim et al. (2013), which employs a laser scanner to obtain a 3D point cloud that is later compared with the 4D building information modeling (BIM) to identify the constructed components. The Kim et al. (2013) study also has proposed an as-built status revision process to modify inaccuracies caused by incompleteness of the 3D point-cloud data set (Kim, Son, & Kim, 2013).

Although prior studies mainly focused on developing as-built schedules from existing data or automating data processing, almost all of the proposed solutions focused on the prospective development of as-built schedules that serves the project control aspects of a project. Subsequently, prior studies failed in recognizing the need to automate the retrospective development of as-built schedules. Only one study by Shrestha and Jeong (2017) has focused on automating as-built schedule development for highway projects from previously collected field data. The data was collected by State Highway Agencies (SHAs) using a daily work report (DWR) system and includes ongoing construction activities, equipment types, labour and equipment hours, quantity of work performed, etc. (Jeong, Gransberg, & Shrestha, 2015). The proposed framework filters the data of a certain project and processes activity duration and quantity of the work performed, and evaluates contractor performance and develops a visual as-built schedule accordingly (Shrestha & Jeong, 2017). However, the schedule produced has serious limitations, including a restricted application area, lack of CPM functionality and lack of planned schedule consideration.

2.3. Time Claims Analysis

The duration of construction contract directly affects projects' and stakeholders' profitability. Most standard forms of contracts include provisions that anticipate delays caused by actions and/or inactions of owners, contractors, or events outside the control of both parties. Contractors are often excused from the consequences and/or allowed financial compensation when delays result from circumstances or events beyond their control. Contractual provisions also allow owners to recover liquidated damages from contractors when they fail to deliver projects within the agreed duration. Disagreements in any of these instances lead to a construction claim.

A delay could be defined as the time during which a project execution has been extended or interrupted due to unforeseen events (Bramble & Callahan, 2017). Delaying incidents can originate from different sources including, but are not limited to the following: contractors, owners/employers, design team, subcontractors, unions, forces of nature, and so on (Eden, Williams, Ackermann, & Howick, 2000). Many unique circumstances may arise during a construction contract execution which will increase the duration of any given activity or the entire agreement period. The most common causes of schedules delays may include, but are not limited to: changes in the work, site access restrictions, mismanagement and misadministration, under-estimation of jobs in hand, labor productivity issues, permits and approvals, defective plans and specifications, document review/approval, differing site conditions, financial problems, inclement weather, force majeure events and testing/inspections (Gibson, 2008). A considerable degree of understanding of the construction method is required to assess entitlement of the extension of time in each case. If a delay is granted, it relieves the claimant from automatic deduction of damages and, under some circumstances, provides a right to financial reimbursements.

Keane (1994) defines claims as "the assertion of a right to payment arising under the express or implied terms of contract, other than under the ordinary contract provisions for payment of the value of work." In practice, claims are used by contractors to describe an application for extension of time award, reimbursement of expense and or other losses that arise other than those that exist under the ordinary provisions of a contract. Claims are used by owners to describe an application for liquidated damages concerning defects, mismanagement and so forth.

Semple et al. (1994) studied 24 claim reports and found that the majority of claims involved some delay, and that the delay duration exceeded the original projects duration by more than 100% in many cases. The claim values varied from 30% to 60% of the original contract value.

Claim management is defined as "the process of employing and coordinating resources to progress a claim from identification and analysis through preparation, and presentation, to negotiation and settlement" (Keane P. j., 1994). In the event of failure to reach settlement, arbitration or litigation takes place.

Analysis of a claim is often a study in the relationship of cause and effect, which could be demonstrated in many forms such as 'S' curves comparisons of cost/value recovery against the contract baseline, labor histograms, and cash flow curves (Gibson, 2008). Grounds upon which a claim may be rejected are the failure to show that the damages are directly caused by the event(s) (Hackett, 2000). Essential to establishing the cause and effect relationship regarding delays is the gathering and management of witness-of-fact statements and other supporting documentation. Besides the difficulty of isolating cause and effect, apportioning liability is often unclear (Keane P. j., 1994). For example, the fault of contractor will have a contributory factor from the owner or its representative, and vice versa. Thus, in such cases, responsibility allocation will have to be based on weight of evidence and/or judgement.

Points of contention relative to schedule delay claims are as follows: whether an event impacted the critical path of the project, its root-cause, the delay quantification, and entitlement to a time extension and/or additional compensation. Neither precise determination of delay liability allocation nor delays evaluating methods are specified on most of construction contracts (Kim, Kim, & Shin, 2005). Quantifying a delay's impact on a project's total duration in an accurate, fair and reasonable manner is vital subject when delay claims occur. A systematic approach to measure delays and allocate liability is invaluable. The following is a detailed literature review analysis to identify failings and shortcomings in delays analysis and quantification methods.

2.3.1. Challenging Issues

There are many issues noted in the literature relevant to delay analysis problems. It is easy to identify a cause of a delay and its effect in the case of total work stoppage; a labor strike, for instance. Connecting alleged/proved causes of delay with actual critical effects of a delay in situations of contractors' inefficiency, however, remains challenging. Accordingly, delay problems have been classified into two main situations, namely: simple and complicated situations (Kao & Yang, 2009).

2.3.1.1 Simple Situations

Simple cases result from simple delay problems (independent delay or serial delay), in which liability can easily be attributed to a project participant and further to a single activity. Depending on the liability allocation, delays are classified into three types, namely: Excusable Compensable (EC), Excusable Non-compensable (EN) and Non-Excusable None-compensable (NN). The EC classification describes events attributable to owner's actions or inactions for which the contractor is entitled to time extension and reimbursements. EN describes events that are attributable to neither the owner nor the contractor, and for which the contractor is entitled to time extension only. NN describes events attributable to the contractor's or subcontractor's actions or inaction occur for which the contractor is not entitled to time extension or compensation; furthermore, the owner is entitled to make a claim for liquidated damages (Gibson, 2008). It is crucial for all parties to understand the basis of the agreement and what constitutes compensable or excusable delays.

2.3.1.2 *Complicated Situations*

Complications arise when changes to the critical path(s) occur; when non-critical activities become critical, for example. Other complications arise in a situation of concurrent delays: missing activities from as-planned to as-built schedules, pacing delays, and losing productivity disputes. In such cases traditional delay analysis methods become impracticable to assess damages and time extensions (Arditi & Pattanalitchamroon, 2006). Accordingly, delay analysis methods should consider critical path(s) fluctuation as events evolve on site, including sensitivity to the acceleration or slowdown events that occur during the activity execution (Hegazy & Zhang, 2005).

Other issues include float ownership and utilization, concurrent delay, and time at large. The ownership of float is unclear in most of the standard contract forms; however, there is a common understanding the project owns the float, and all contracted parties can use it (Keane & Caletka, 2015). Contractors argue that they should own the float as it helps them in planning for the project execution, controlling the time and budget, as well as allowing latitude for unforeseen events that may occur during the project. Owners, on the other hand, argue that the float forms an assurance against delays to the project completion, and helps them to accommodate change order-impact. This disagreement in float ownership represents the absence of industry-wide practice; the float issue is a common source of disputes in time related claims. Most construction contracts do not define the ownership and consumption of floats, which is critical for delay analysis. Several studies have proposed alternatives for total float allocation, ownership, sharing. and management (Prateapusanond, 2003; Arditi & Pattanalitchamroon, 2006; De la Garza, Prateapusanond, & Ambani, 2007); however, they do not provide an approach that can be used in schedule analysis.

A concurrent delay occurs when two or more delay events caused by different parties (owner(s), contractor(s) or neither) overlap and prolong the project duration (Arditi & Pattanalitchamroon, 2006; Mohan & Al-Gahtani, 2006). Having a true concurrent delay is uncommon as delays usually occur consecutively unless there are multiple critical paths running in parallel. A closer look at root-causes usually shows that one delay occurred before another, which indicates that one delay is impacting the critical path while the other was using float caused by the first event. Importantly, time extension claims only concern delays that occur on the critical path or a path that has become critical, delaying the completion of the contract.

The time at large refers to situations when an owner causes a delay event and there is no contractual mechanisim to set new completion dates (Gibson, 2008). This does not releive contractors from their duty to complete the work. In fact, contractors have to complete the project within a reasonable amount of time, and owners are no longer able to claim liquidated damages. Most modern contracts now contain clauses that allow extension of time awards; however, completion dates may become at-large due to either improper enforcement of contracts. To determine a reasonable time to complete the project, a delay analysis method such as impacted as-planned, time impact method, or collapsed as-built methods can be used (Gibson, 2008).

2.3.2. Delay Analysis Methods

The delay analysis is generally classified by industry, based on when the analysis is performed, into prospective and retrospective analysis (AACE International, 2011). Prospective analysis is performed during the project execution either prior to the delay or at the time of delay occurrence. To facilitate the evaluation of time extension in this form of analysis, contract provisions typically impose the analysis to be performed in prospective mode through specified methods, often called

Time Impact Analysis (TIA). Retrospective analysis is performed retroactively after the impact is known; however, it may be performed prior to or after the completion of a project. This form of analysis allows the analyst to take advantage of as-built documentation for factual investigation; however, this is often accompanied by a change in personnel: the project scheduler who worked under the prospective mode and the analyst who works in retrospective mode.

The delay methods could also be classified, based on the analyst's interaction with the schedule, into observational and modeled basic methods (AACE International, 2011). In the observational method, the analyst examines only existing scheduling data without making any changes to simulate a specific scenario. A common delay analysis example that falls under this analysis form is as-built vs. as-planned. The modeled method allows the analyst to create schedules that simulate different scenarios with subsequent interpretation and evaluation of each scenario. For comparison, schedules are created by either inserting or extracting activities that represent delay events. The collapsed as-built, and the impacted as-planned events are common examples that fall under the modeled basic method. A distinction of the observational method can be made based on the schedule logic. Static Logic Observation considers only the original schedule logic. Dynamic Logic Observation considers schedule updates that add sets of progressive schedule logic. A distinction of the modeled method can be made based on the modeling approach, depending on whether activities are added to a baseline schedule (Additive Modeling) or subtracted from an as-built schedule (Subtractive Modeling). The impacted as-planned events are an example of the additive modeling method, while the collapsed as-built events are an example of the subtractive modeling method.

There are three types of activities monitored during delay analysis, namely: delayed activity, actual duration activity, and actual time-shortened activity. Most of the focus is on the delayed activity, while the effect of time-shortened activity on the project duration is often ignored (Kim, Kim, & Shin, 2005). The basis for current delay analysis methods is information and evidence of delay(s), usually represented by different kinds of documents, records, and schedules during the construction phase.

Various analysis methods have been developed to facilitate delay analysis, such as global impact, as-planned, impacted as-planned, net impact, time impact, collapsing, isolated delay type, snapshot and window analysis (Mohan & Al-Gahtani, 2005). These techniques can be grouped into two categories 1) non-CPM based techniques and 2) CPM based techniques. Guidance on the application of various techniques has led to the establishment of best practice documents, the most notable of which are the "Recommended Practice on Forensic Schedule Analysis" developed by the Association for Advancement of Cost Engineering International of the USA (AACE International, 2011) and "Delay and Disruption Protocol" developed by the UK's Society of Construction Law (SCL, 2017).

A third source that provides guidelines for best practices for project schedules is published by the US Government Acquisition Office and known as the Schedule Assessment Guide (GAO, 2015). A fourth source for best practices in scheduling is the US Defense Contract Management Agency (DCMA). DCMA has developed and released a 14-Point Assessment Check protocol to be used for CPM schedules that undergo reviews by the agency. The protocol is not published as a standard external document, but rather used internally as a guideline for schedule reviews and as a training guide provided to commercial contractors. Another publication by the American Society of Civil Engineers is the "Schedule Delay Analysis" standard (ASCE, 2017). It provides 35 guidelines for best engineering principles associated with delay analysis of construction projects. While a number of published guidelines have been provided, it is a fact that a single methodology has not been applied or adopted as an acceptable approach to determine proof of liability and damages.

Most delay analysis methods have the capacity to solve simple delay situations, but some are inadequate for solving complicated delay problems. Different techniques give different results (Stumpf, 2000). Selecting the most appropriate methodology depends on accessibility to the project control documentation, time, and available resources (Bubshait & Cunningham, 1998). Arditi and Pattanalitchamroon (2006) proposed a checklist with schedule-type and information-type documents that aid the selection of the as-planned vs. as-built, impact as-planned, collapsed as-build and time impact methods. The windows analysis methods, however, have been recognized as the most creditable methods for delay analysis (Gothand, 2003; Kim, Kim, & Shin, 2005). Discussion of the main available delay analysis methods is provided in the following sections.

2.3.2.1 Impacted As-Planned ("What-if")

The impacted as-planned method, sometimes referred to as the "what-if" method, is among the very first delay analysis techniques to utilize a CPM schedule (Alkass, Mazerolle, & Harris, Construction Delay Analysis Techniques, 1996). In this approach, the claimed delays are "inserted" into a contractor's original as-planned CPM schedule to simulate their effect on the critical path. The original as-planned schedule and the impacted version are then compared, and any resultant additional time is allocated to the delays inserted into the schedule. This approach, however, has several limitations: it ignores the as-built critical path of the project and is predicated on the invalid assumption that the project was built strictly in accordance with the as-planned schedule (Bubshait & Cunningham, 1998). As a result, the discrete "what-if" event fails to account for the entirety of the as-built events and contemporaneous schedule adjustments and logic changes made during the project execution. As a result, the impacted as-planned technique has been characterized as a heoretical approach that overlooks actual job history, and thus, it is recognized as inadequate to evaluate project delays (AACE International, 2011).

2.3.2.2 Collapsed As-Built ("But-For")

To undertake the collapsed as-built method, also referred to as the "but-for" method, a complete project as-built schedule must be developed either from contemporaneous project schedule updates or through an after-the-fact review of project records. The delaying events are then removed from the as-built schedule, thereby "collapsing" the schedule to show what would have occurred on an as-built basis "but-for" the claimed delays (Bubshait & Cunningham, 1998). Although the use of an as-built schedule provides the benefit of utilizing actual durations and sequences of all construction work activities, it remains vulnerable to inadequate or manipulated analysis.

This method is associated with several kinds of subjectivity; creating an as-built schedule relies heavily on the precision and correctness of the analyst's interpretation of project data. The nature and quality of the subjective determinations of the preferential logic (choosing the delay issues to address, creating a fragnet to represent those issues, determining how those fragnets connect and impact the project, and then eliminating the delays in a sequence chosen by the analyst) are all major concerns that arise with the use of a collapsed as-built method to determine responsibility for delays (AACE International, 2011). The collapsed as-built method also has been criticized for (i) failing to consider the as-planned schedule; (ii) failing to look forward, or in a chronological/ cumulative sequence; and (iii) utilizing after-the-fact logical ties or assumptions that may fail to reflect the contractor's actual views during performance (Alkass, Mazerolle, & Harris, Construction Delay Analysis Techniques, 1996).

2.3.2.3 As-Planned Versus As-Built

The as-planned vs. as-built method involves a retrospective analysis of the project record to determine the identity, cause, and effect of project delays. Therefore, a detailed as-planned schedule is required to serve as an analytical baseline schedule. An accurate as-built schedule must also be developed either from the contemporaneous updated CPM schedule or through detailed project records such as daily logs, time sheets, and other similar project records. Both schedules are then compared to identify and scrutinize the differences between the planned and actual progression of the work (Alkass, Mazerolle, & Harris, Construction Delay Analysis Techniques, 1996). A proper comparison allows for the determination of the project's as-built critical path, and the identification and quantification of delaying events (AACE International, 2011).

While this approach is very practical, it is not scientifically precise. The comparison process can be subjective when determining the actual as-built critical path and the extent to which the contractor's as-planned performance was impacted by identifiable time-impacting events. Where there is deficiency in the contemporaneous record keeping, there can be difficulty in reconstructing a fully accurate day-by-day historical as-built scenario, since no one can tell the actual restraints that prevailed at the job (AACE International, 2011).

2.3.2.4 Windows Analysis Methods

The windows analysis method, also known as the contemporaneous analysis method, is similar to the overall approach of as-planned versus as built approaches described above. The key difference is that the windows analysis method divides the project duration, as given by as-planned schedule, into digestible time periods called windows. It then identifies and analyzes delays that arise in each window and determines through the CPM whether their effects are liable to the project owner, the contractor, or to any other party (Hegazy & Zhang, 2005). Windows analysis also enables the assessment of the effect of different rates of progress in different phases of the project. The selection of the window size is usually based on either major project milestones or major delays.

Starting from the planned schedule, each window is analyzed separately by introducing contemporaneous site information on the schedule, including an activity's actual start, actual finish, and delays. Delays are usually introduced as new activities linked to impacted activities. This forms as-built events that stretch to the end of the window. The residual part of the schedule, until the end of the project, remains unmodified (without delays). If the project duration changes, the critical activities are analyzed to allocate liability. If there are concurrent delays, both parties share responsibility and no damages can be covered. This process continues until all windows are analyzed, forming the as-built schedule. At the end of the analysis, the total project delay is the summary of delays in all windows (AACE International, 2011).

Although windows-based analysis methods have many benefits and they have been recognized as being the most credible (Gothand, 2003; Kim, Kim, & Shin, 2005), a set of serious drawbacks have been identified by researchers that can be summarised as follows:

- The as-built schedule is usually developed manually and after the project completion which makes it subject to errors and omissions that hinder the accuracy of the delay analysis (AACE International, 2011).
- The analysis focuses on the critical path(s) that exist at the end of each window, thus, ignoring critical path fluctuations that typically occur as events evolve on site. Consequently, the technique loses sensitivity to delays, accelerations, and slowdowns within the window (Hegazy & Zhang, 2005).

- Contemporaneous schedules and updates should be used as they are prepared, reviewed, or accepted because they are used as the basis for managing and decision-making throughout the project. Although, these schedules might not be perfect, they are the most contemporaneous representation of the project as well as an indicator of all parties' performance. To introduce delay (fragmented) activities into a schedule, however, the analyst must manually and subjectively modify the schedule logic, which may result in inaccuracies.

A modified windows analysis method was later introduced by Gothand (2003). The key difference is that the modified method explicitly assigns delay liabilities to the project participants prior to the analysis through a meaningful negotiation that distributes responsibility of the delay values. To overcome the inadequacy of concurrent delay and acceleration, Kim, Kim and Shin (2005) proposed a delay analysis method using delay section (DAMUDS). The method proposes dividing the delay duration into a "single delay" and "two or more delays". The proposed method evaluates delay sections based on the minimum float of succeeding activities.

The windows-based techniques require intensive computation, and window spans may vary; i.e. short or long periods may be used. It is also important to note that short periods require more computational resources and long window periods fail to account for changes in the critical path(s) as events evolve, and the schedules can be manipulated by constraints and logic changes. Moreover, according to the window size, they usually produce different results.

To overcome these drawbacks, Hegazy and Zhang (2005) proposed a daily window delay analysis that considers one 24-hour day as the unit for analysis. The study introduces an intelligent bar chart (IBC) as a new form of representing progress information combined with delay data. IBC is made of spreadsheet cells in which activity durations are represented as group of cells rather than bars.

Each cell is then used to store the daily percentage complete values for activities, delays, the responsible party and other delay-related data. It then calculates delay liabilities based on the day-by-day delay analysis on critical path(s) along the project duration. Such an approach resolves problems of consideration of critical paths fluctuation that occur as events evolve within the analysis period on construction sites without losing sensitivity to the events of speeding or slowdown (Hegazy & Zhang, 2005). However, the proposed daily window analysis method tends to be time consuming. The daily window delay analysis method was later expanded to consider multiple baseline updates and resource overallocation (Hegazy & Menesi, 2008). Abu-Osbeh (2011) proposed an Isolated Daily Window Analysis Technique (IDWAT) that applies the systematic approach of IDT on a daily window span with the addition of cost-quantification.

2.3.2.5 Time Impact Analysis

The time impact analysis is similar to the windows analysis method; however, it focuses on a particular delay, not on a time period containing delays. The intervening event is applied to an updated schedule that represents the status of the project immediately prior to the event occurring (AACE International, 2006). Upon the immediate occurrence of an impacting factor such as a change or delay, an activity representing the impacting factor is entered into the schedule logic network between the appropriate predecessor and successor. The activity duration is set at zero and the schedule is calculated to (re-)establish the completion date and critical path. The next step is to enter the duration of the impacting activity into the schedule and then recalculate the schedule to see what the result would be in terms of time extensions or changes in the critical path.

Table 2-1 shows source schedules required to implement the basic protocol for each delay analysis methods.

Table 2-1: Source data for the various delay analysis methods

Source of Schedules or Data	Methods				
	2.3.2.1	2.3.2.2	2.3.2.3	2.3.2.4	2.3.2.5
Baseline Schedule	✓		✓	✓	✓
Schedule Updates				✓	✓
As-Built Record		✓	✓		

2.3.2.6 Other Techniques

Alkass, Mazerolle and Harris (1996) proposed Isolated Delay Technique (IDT) that combines the traditional windows analysis approach with the delay scrutinizing ability of the "but-for" technique. It determines a delay's liability to project participants before analyzing the delay events. This method is most appropriate for after-the-fact analysis (Alkass, Mazerolle, & Harris, Construction Delay Analysis Techniques, 1996).

Ibbs and Nguyen (2007) examine how a project may be delayed further due to impractical resource allocation in downstream work. Consequently, delay-liability allocation may be inaccurate. Thus, the authors recommended additional steps to enhance the current window analysis, including: dissemination and consensus of resource allocation practice, development of as-planned CPM schedule considering resource allocation, and updating next-window considering resource allocation (Ibbs & Nguyen, 2007). Although the study considers impractical resource allocation when analyzing delays, it could be improved by scrutinizing resource types.

Nguyen (2007) later proposed a new schedule-analysis technique called FLORA that, as its name suggests, captures changes in Float, Logic, and Resource Allocation. The proposed technique relies on a set of rules that are customizable by the contractual parties. The proposed technique starts by defining the baseline schedule, then allocates total float of all activities to the owner and contractor based on a previously agreed-upon apportioning of the total float. It also follows Al-Gahtani and Mohan's (2007) principle of total float entitlement, which states that the responsible party will be discredited any change of total float on the affected activity, and gain or lose in the total float of successive activities (Nguyen L. D., 2007). Another rule is the codification of current practice such that the contractor will be granted a time extension if a third party caused a delay; meanwhile, the owner gains or loses total float for excusable and non-compensable delays. A detailed list of the rules proposed by FLORA is provided in Nguyen (2007).

A shared weakness in the aforementioned delay analysis methods is their oversight on the dynamic nature of the activities' production rates; they assume a linear relationship between time and the number of produced units. To overcome this problem, Lee and Diekmann (2011) propose a method called the delay analysis considering production rate (DAP), which incorporates the learning curve effect. First, they determine the type of production curve for the activities delayed. Then, they calculate learning and production rates. Activities' learning rates are established and converted to a man-hour estimate in order to calculate the activities' production rates for three sub-phases, namely: learning, production, and closing. Production rates are distributed over the activities being reviewed before using window analysis, or the "but-for" method, to determine liability and quantify delays (Lee & Diekmann, 2011). Not only does DAP over-simplify the production computation, but it also does not consider productivity changes due to many other factors influencing productivity. Klanac and Nelson (2004) also emphasised this weakness by stating that identifying the factor causing productivity variance - of the many factors influencing productivity

- is critical in delay claims analysis when determining liability and remains challenging when using the DAP rate.

The industry as led by AACE international, on the other hand, classifies and discusses the methodologies for forensic schedule analysis with a stated desire to minimize disagreements over schedule-implementation and to provide a unifying technical reference for the forensic application of CMP (AACE International, 2011). Moreover, AACE international identifies the various methodologies employed in litigation for cost recovery in lost productivity claims (AACE International, 2004). These include, but are not limited to: Earned Value Method, Comparable Work Study, Comparable Project Study, and Measured Mile Method. Among the above-mentioned techniques, the Measured Mile Method is considered the most accurate as it uses the actual data of contractor's performance, which brings creditability to its calculation (Williams Ibbs, 2012). Importantly, it requires utilized man-hours, comprehensive cost reports, and installed quantity to implement the calculation.

The author notes that the current delay analysis literature available is very limited when compared to other research areas such as productivity and safety. This is mainly due to the sensitivity of the subject and availability of research data. Therefore, the development of new analysis methods is also lacking despite the increased number of claims noted in the construction industry.

2.4. Simulation in Construction

Shannon (1975) defines simulation as a process of designing a model for real system then conducting computer-based experiments to either understand its behavior or evaluate different strategies for its operation (Shannon, 1975). The construction industry has been using simulation for designing, planning, and analyzing construction operations (AbouRizk S. , 2010). It is commonly used in research to study large, complex systems not suitable for conventional analytic approaches.

2.4.1. Computer Simulation Modeling Paradigms

Over the past three decades, various types of simulation methods have been developed to cope with different systems behaviors, including but are not limited to, Monte Carlo simulation, discrete event simulation (DES), continuous simulation and agent-based simulation. The following section provides a brief description of these different simulation modeling paradigms.

2.4.1.1 Monte Carlo Simulation

Monte Carlo simulation is a technique that is utilized to model uncertainty and it is suitable for the analysis of stochastic and static systems or processes (Mitchell, 2017). Typically, predicting the behavior of such systems is difficult as they produce different outputs for the same inputs, moreover, due to their static nature, the outputs are contingent on the inputs values at the time, irrespective of previous and future input values. Hence, Monte Carlo simulation has the capability to cope with solving problems that are related to complexity and randomness.

2.4.1.2 Discrete Event Simulation

DES models the behavior of complex operations as a discrete sequence of events that typically take place at given time intervals where in the occurrence of an event triggers a change in the state of the modeled operation (Lu, 2002). A system is usually modelled through number of variables that also reflect its state. As the simulation time only advances when the next event is due to occur, it is logical to conclude that DES are event driven systems (Bandyopadhyay & Bhattacharya, 2014). Typical domains of DES include: customer waiting time, hauling operations, and management of parts inventory. DES include the following main elements:

- **Events**: An event is an occurrence that impacts a process or system by causing changes to its state at specific time interval. In a model of a customer-serving system, for instance, a customer order (an event) can be simulated by releasing an entity into the model.
- **Entities**: An entity in a simulation environment refers to a unit of transaction. The creation and movement of entities are controlled by the modeler. As entities route through the model, they respond to events by migrating from one state to another.
- **Simulation clock**: The simulation time can be measured through different units as deemed suitable for the system being modeled. In DES, the simulation clock skips to the start time of next event as the simulation advances.
- **Control components**: These include: (1) an initialization routine, which configures the model prior to the simulation execution (at time 0); (2) a timing routine, which schedules event occurrences and types as well as advancing the simulation clock; (3) event routines that define the event's logic, constraints, resources, and so on; (4) the main program, which controls the execution and order of routines.
- **Random-number generators**: Depending on the system being modeled, various kinds of random variables are generated through pseudorandom-number generators. The use of pseudorandom numbers is very beneficial as simulation models are typically used to test different scenarios and produce different statistical results.

2.4.1.3 Continuous Simulation

Unlike DES, continuous simulation represents systems whose states continuously change. Variables define the state of system change continuously at constant time intervals, such that the modeller creates artificial events or pseudo-events to analyze and the behaviours and state of the system over time. Accordingly, continuous simulation is referred to as time-step simulation, wherein the time-steps are equal in size (Bandyopadhyay & Bhattacharya, 2014). There are two forms of continuous simulation, namely: dynamic systems and system dynamics. In dynamic systems, the state variables change continuously in synchronized fashion and, unlike other systems, they are not intensely inter-related. Thus, they do not have feedback loops within them. System dynamics, on the other hand, are used to understand the behaviour of a system over time. The main component of system dynamics is to model the relationships between variables and to observe their influence on the behaviour of a system over time using elements like stocks, feedback loops, flows, and time delays (Sterman, 2001).

2.4.1.4 Agent-Based Modeling

In contrast to DES and system dynamics, agent-based simulation centres on individual components within a system (agents) and focuses on their behaviour and their interactions (Railsback & Grimm, 2011). It combines elements of complex systems, multi-agent systems, game theory, computational sociology, and evolutionary programming. Although there is no unified definition of an agent, there is a common understanding of them as independent, autonomous, decision-making components in a simulation system. Agents have various characteristics including, but are not limited to, autonomy, adaptability, cooperation, proactiveness, mobility, learning, and responsiveness (Bandyopadhyay & Bhattacharya, 2014).

2.4.2. Applications Areas in Construction

Traditionally, the approach used to model construction processes has been discrete event process interaction simulation. Researchers have used it to apply “link-node” methodology (Teicholz, 1963) and queuing theory (Gaarslev, 1969) to study earth-hauling systems. The first application approach to address management of construction processes was CYCLONE; introduced by Halpin (1973), which relies on a simple diagram flow methodology, and which facilitates the modelling of repetitive processes to identify output productivity and potential imbalance in the use of key resources. This approach is used in modelling construction operations, such as concrete batch plants (Lluch & Halpin, 1982) and tunnelling (Martinez & Ioannou, General-purpose Systems for Effective Construction Simulation, 1999). The development of CYCLONE resulted in development of several simulation approaches, many based on the CYCLONE methodology. Others follow more generic simulation approaches.

Similar approaches were proposed to optimize earth-moving operations and to minimize costs by designing optimal fleet configuration and considering the dispatching time required to move the fleet from one site to another (Marzouk & Moselhi, 2004; Zhang H. , 2008; Mohamed & Ali, 2013). Moreover, researchers used tracking technologies to capture detailed motions of trucks and excavators and to enhance the accuracy of identifying the state of equipment (Vahdatikhhaki & Hammad, 2014). Global Positioning Systems (GPSs) were also used to collect data from receivers attached to equipment, using them as an input to the simulation model (Alshibani & Moselhi, 2012).

Other modelling systems, such as *Simphony*, offered advantages for use in industry by enabling increased modeling and simulation capability to facilitate more complex model development;

providing more flexible user interfaces and explicit modelling of simulation entities and resources, and allowing user-written code to provide extensibility and hierarchy in model development. Special Purpose Simulation (SPS) (Hajjar & AbouRizk, 1996) modeling, and the Construction Synthetic Environment (COSYE) (AbouRizk & Hague, 2009) are modelling environments that use a set of icons, associated with different construction processes and predefined by designers, to represent various construction resources and resource-flow path indicators to build the simulation model.

Ebrahimy et al. (2013) modelled the supply chain of a real-life tunnelling construction project to capture and analyse variables affecting productivity using the *Simphony* environment. Moreover, Al-Bataineh et al. (2013) used *Simphony* to develop a special purpose simulation for tunnelling applications to explore different construction scenarios during the planning and execution stages.

Hybrid simulation, which considers both strategic and operational aspects, can produce complex models better attuned to construction projects than non-hybrid models. Simulation development has also focused on integration of simulation with other tools, particularly visualization. Zhang et al. (2013) integrated AutoCAD models with *Simphony* process models for visualization purposes. Ali et al (2014) developed an earth-moving simulator that incorporates different construction influencing factors to generate realistic operation behaviors. A distributed simulation approach, based on High Level Architecture (HLA) standards and COSYE, was used to model and visualize earthmoving operations realistically and quantify some of the performance indicators such as trucks' fuel consumption, emissions, and production rates continuously throughout the simulation in graphical and statistical fashion.

Other researchers have used simulation approaches to develop training tools to control heavy duty machines, such as a PC-based excavator simulator (Ni, Zhang, Yu, Zhao, & Liu, 2013) and a 3D physics-based excavator simulator (González, Luaces, Dopico, & Cuadrado, 2009) that simulates terrain excavation, loading and unloading processes, and events such as excavator slippage on sloped terrain using real-time simulation techniques. Current research focuses on integration of 3D modelling with real-time updates for a four-dimensional approach, as well as hybrid modelling for incorporating discrete-event approaches with system dynamics. Rahm et al (2013) proposed a model for a tunnel boring machine (TBM) that considers the effects of geological conditions and accounts for the influence of wear on its performance.

Some researchers have used simulation algorithms to address scheduling and resource leveling problems. One study explored how an Interactive Construction Decision-Making Aid (ICDMA) schedule-simulation platform can improve the scheduling process (Tang, Mukherjee, & Onder, 2013). The study argues that CPM cannot be used to identify alternative emerging critical paths when unexpected disruption occurs in the as-planned schedule. The research used ICDMA to identify activities most likely to become critical and concluded that scheduling based on production is better equipped for capturing the critical changes as compared to schedules based on time. Another study explored the use of agent-based modeling for scheduling resources for multiple projects. Araúzo et al. (2009) propose a multi-agent system for online dynamic scheduling that completes the following: it allocates resources dynamically for a multi-project environment, considers project value when deciding what projects to be accepted or rejected, and also discovers the most valuable resources to be added to the firm. For their study, Araúzo et al. represent projects and resources as agents and use auction-inspired mechanisms for agents to negotiate resources (Araúzo, Pavón, Lopez-Paredes, & Pajares, 2009).

Tang, Cass & Mukherjee (2011) argue that regardless of the construction strategies used, different scheduling approaches impact the project greenhouse gas (GHG). The study applied two construction strategies (Control and CatchUp) to complete highway construction projects using both CPM and Linear Scheduling Method (LSM). The Control strategy aims at managing schedules with minimum actions in dealing with interruptions, while the CatchUp strategy focuses on managing schedules to minimize delays. When using the CatchUp strategy, both scheduling practices showed good performance in reducing GHS emissions. When using control strategy, however, CPM showed a better performance (Tang, Cass, & Mukherjee, 2011).

Despite the wide usage of simulation in construction processes, its application in claims analysis is very limited. DES use tends to be focused on modeling different scenarios under different conditions so that changes in time and productivity can better be analyzed and evaluated. For instance, AbouRisk and Dozzi (1993) used DES during a dispute-mediation process to verify extra cost claims. Two simulation models were developed, the first modeled and estimated operation cost at the time of contracting based on the construction method specified in the contract. The second modeled and estimated actual operation costs. Man-hours required to complete the operation under the two scenarios were then used as the bases to estimate a reasonable cost to be awarded to the claimant. A similar approach was followed by Al Malah et al. (2013) to demonstrate and analyze the conflict between the as-planned and the as-built conditions at the construction site for a tunneling project. The authors first created a stochastic as-planned model to represent the time required to complete the project during the planning phase. They then added the impacted processes to the original duration. The required time extension was estimated by comparing as-built data to the impacted model (Al Malah, Golnaraghi, Biok, Elfaizy, & Zayed, 2013).

Systems Dynamics models have also been used in claims analysis processes because the use of concepts and arrows in qualitative models provide clearer argument routs and makes it easier to understand than the quantitative models (Howick, 2003). Cooper (1980) used SD to settle a $500 million claim in the Ingalls Shipbuilding's case against the US Navy. William et al. (1995) also used SD to study the impact of design changes and delay on the project costs. Williams, Ackermann, and Eden (2003) introduced an approach for structuring a delay and disruption claim using cognitive maps and system dynamics. Specifically, the approach demonstrates causality, responsibility, and quantum of over-spend/time over-run of a claim. The cognitive maps are generated through interviews with the project team members by analyzing a draft of the claim document, all of which can be used to identify the disruptive triggers and to model the lines of arguments from causes to consequences. The authors emphasized making a detailed explanation of the triggers to enhance the understanding of their meanings and their interrelationships. When two triggers overlap, the study noted two additional phenomena (Williams, Ackermann, & Eden, 2003). The first is called the "portfolio", where the overall effect of many factors is larger than their individual sum. In such a case, clarification is required on how the magnitude of the overall effect is larger than the sum of the individual effects. The second is called "feedback." Feedback describes the phenomenon when tracking the immediate consequences of individual factors to subsequent consequences reveals positive and negative feedback loops. Once the SD model has been built representing the project as a bid, all the disruptive events are modeled by replicating the cognitive maps. The model is run twice: the first run replicates how the project should have occurred (all triggers are switched off), and the second run shows the impacts of a subset of triggers upon the project plan. The model can also be used to show the effect of individual triggers as well as their combined effects to demonstrate what would have been the effect had these triggers not occurred. Thus, the difference between the planned run and disrupted run becomes the total claim.

While SD can capture soft human elements and managerial actions, it is incapable of capturing detailed operational issues at the activities level (Rodrigues, 2000). To overcome this limitation, integration with CPM might be required so that the weaknesses of SD would be covered by the CPM (Howick, 2003).

2.5. Summary and Conclusion

A comprehensive literature review was presented in this chapter. Topics covered include: project scheduling principles used in the construction industry to properly set timelines for project completion. This chapter also covers the inevitable changes that usually occur during project execution, such as: severe weather conditions, learning curves, and change orders as well as their implications in terms of time extensions and liability. The causes of changes were expansively studied, and their impacts on the project schedule were discussed. Although the quantification of change impacts is not the focus of this research, a review of quantification models was conducted. As it is presented in the following chapters, quantification models could be integrated with the proposed framework for delay analysis purposes.

An overview of the delay analysis methods was also presented describing procedures, limitations, and solutions proposed by other researchers. The review concluded that window delay methods are the most reliable and accurate analysis methods; however, they still have some limitations that were overcome in this study through an introduction of a new delay analysis approach. The chapter concluded with a review of simulation modeling paradigms, their types, and application in the construction industry.

Chapter 3. Critical Review of the Limitations in Time Claims Practice

3.1. Chapter Introduction

In Chapters 1 and 2, the issues associated with claim management in general and delay analysis in particular were discussed and identified. This derived as a result of researching existing academic and professional literature.

This chapter contrasts and expands on the findings of the above research. The current research has demonstrated that existing delay analysis practices have several shortcomings that prolong the analysis process, inflate analysis cost, lead to inaccurate results, and constrain their use by industry practitioners.

This phase of research involved further investigation of the problems/issues faced in claim management and delay analysis in order to identify particular problems for which solutions could be developed. Ultimately, this approach led to the formulation of the proposed simulation-assisted approach to forensic schedule analysis and delay assessment for use in the construction industry.

3.2. An Overview of Limitations

According to the literature, claims have become an essential part of construction projects. It is therefore logical that claims management should also become part of the overall management process: furthermore, due to the large sum of money at stake, this aspect of the project must be given equal priority. In addition, there is a noticeable lack of criticism noted in the literature involving the role of claims management in reaching a satisfactory conclusion; however, there is clearly space for improving the practicality of the process by focusing solutions on at least some of the more problematic aspects of claims management.

There are many claim types that arise during construction projects; however, one of the most noted topics in both the literature and industry practice is delay to the progress of contracted work. As delay claims are both the most frequently occurring claim type and likely to significantly benefit from improvement (Gibson, 2008), this research concentrates on addressing the shortcomings in delay claims and providing concrete practical solutions, ultimately yielding considerable cost benefits.

It is therefore the theoretical and practical basis of shortcomings in delay analysis process that this chapter seeks to identify and describe under the description of issues in time claims practice. Through a detailed analysis of the literature, the following two pertinent areas of limitation were identified.

1. **Claim Administration**

   In brief, this area concerns the difficulties claimants encounter when managing a time claim process. This touches on all aspects of the administration process, including documentation, delay identification, and analysis skills, as well as processing time, all of which contributes to disintegration in the management process. It also includes the critical matter of substantial expenditure during the claim resolution process.

2. **Technical Analysis**

   This area encompasses the difficulties associated with the quantification process related to time claims. This encompasses all technical and applications issues, such as CPM application, as-built schedule development, practicality of the process, accuracy of results, and modeling techniques and tools.

While the above-mentioned issues are clearly not an exhaustive list of the problems that arise in delay analysis practice, they are identified as the factors which most contribute to shortcomings in the analysis of delay claims. These issues are explored in greater detail in the following sections.

3.2.1. Claim Administration

Claims are generally understood to be simple disputes over facts. While, in principle, the facts may appear to be relatively straightforward to establish, the surrounding circumstances and documentation are often not clear. For delay claims, in particular, obtaining evidence is a necessity; this evidence gathering is often followed by thorough analysis by experts. A major area of concern with regards to claim administration is the often lengthy and costly process before a conclusion can be reached, from the initial claim identification through data capture and organization to evaluation and submission of the claim.

Several issues may arise during the execution of a project that cannot be resolved among the project participants. These issues could have positive (acceleration) or negative (delay) impact on the schedule, all of which must be supported by factual evidence. Typically, the resolution of such issues results in time extension and/or compensation through additional requests for additional costs, which are referred to as claims. If such claims are granted, the issues are resolved. However, unsettled claims lead to disputes, and restrict the route of resolution, often involving a third party through alternative dispute resolution (ADR) mechanisms such as mediation, arbitration and litigation, all of which result in a lengthy process and substantial cost expenditures prior to reaching a conclusion (Fenn, O'Shea, & Davies, 1998; Hackett, 2000; Gibson, 2008).

As previously discussed, the claim management process includes four main stages, namely: delay identification, impact quantification, causation demonstration and claim documentation. For delay claims, events that impact the project schedule are identified and then their criticality is assessed. Delay identification requires individuals with sufficient knowledge of the contracted work, including scope, responsibilities and the agreed contract terms, in conjunction with identification of any variation that may occur or any activity that is viewed as extra, which would then require contract adjustment (Keane & Caletka, 2015). It also requires project scheduling skills, as the criticality of events is determined through CPM calculation, since delay claims can only be pursued when an event impacts the critical path of a schedule.

When there is an event that potentially could have an impact on a project schedule, a claimant should document all aspects of the event to prove occurrence, timelines, entitlement, damages and retain all supporting documents. However, events impacting a project schedule vary in nature and complexity, and when they occur, they are often captured and documented inadequately. This is mainly due to the fact that there is no standardized set of attributes used to document events. Although one could argue that most of impacting events are usually documented in the contemporaneous records of projects, the form in which these events are documented neither guarantees comprehensive documentation of all prerequisites needed to perform delay analysis nor supports an efficient delay analysis process.

If a decision is made to pursue a claim, the claimant analyzes the project documentation with respect to occurring issues and investigates what to include in a claim document to substantiate his or her case. The claimant should understand the grounds of the claim and be very familiar with the available project documents, including schedules, letters, drawings, etc. However, by nature, a huge volume of documentation is usually generated during the course of a construction project.

This is further compounded by the diverse nature of the documents. For example, there is tender documentation, followed by construction documents (including design drawings), control and management documents, and, finally, cost control documents. Thus, when events related to the claim take place on even a moderate scale, say, for instance, a $5 million infrastructure project over a two-year period, the extent of documentation that may need to be reviewed can be daunting. This is particularly true for the case of retrospective analysis.

Many document management systems (DMS) are being used to store, track and organize project documentation, such as SharePoint, WorkflowMax, Procore and Skysite (Astor, 2017). Most of these systems are designed to improve access to project information and reduce time spent on filing and searching for documents through use of a centralized system. Although some systems are capable of producing reports, claim evidence requires careful presentation, because without the proper organization of contemporaneous records needed to establish the claim, even simple claims would lead to an expensive process. While establishing chain of events and documentation may seem to be an easy task, there are notable cases where evidence documentation related to a clear-cut claim has been presented in a confused or incomplete state.

The outcome of the identification process is the statement of claim, in which all alleged events are outlined, along with the supporting documents. For delay claims, analysts are mainly concerned with a matter of what event impacted the project schedule, or what caused a given delay to the project completion or any other milestone date, the time of occurrence, the impact of event on the project schedule and the responsible party (Keane & Caletka, 2015). Such information is not readily available through existing project control measures or the DMS, and it must be extracted meaningfully to be used in the damage quantification process. Therefore, time and resources are required to review and analyze records thoroughly when pursuing delay claims which costs money that many claimants cannot afford and deny themselves opportunities for potential compensation. Perhaps it is the nature of the problem and lack of a standardised format for documentation that discourages project entities from adopting a disciplined approach to record keeping.

For reasons already given, including the quantity and diversity of construction documents and the failure to have organized data, the ready availability of evidence to prove causation is lacking. The consequence is a lengthy and costly process to prove a claim. In other words, current project and document control practices do not provide a direct link between impacting events, their context, and the responsible parties, all of which is mandatory for delay analysis.

Another issue is that the impact of events on a project schedule can either be certain, uncertain, or expressed mathematically. For instance, the impact of activity stoppage due to safety concerns or a delay in material delivery is usually known and easy to quantify. However, in retrospective situations where there is no accurate contemporaneous record available, the extent of the impact of such events is uncertain and can only be expressed in the form of a range (for instance, two to three days). The mathematical models used in these cases are similar to the productivity loss models discussed in Chapter 2 of this thesis. A good example is the occurrence of severe weather conditions: to determine the impact of weather conditions, an analyst needs to use an impact curve and quantify the productivity loss, depending on the weather condition at the time, and then re-estimate the duration of impacted activities or preferably add activities to the schedule to reflect the corresponding productivity loss. One issue resulting from adding activities to the schedule to reflect the impact of an event is that it requires logic modification, which makes it a subjective process. Therefore, depending on the type of the event, the impact quantification stage itself may have two distinct substages: these are the quantification of the impact of events and then integration of impacts into the schedule to assess the overall impact of the events on the schedule.

A further problem is that, depending on the time at which a delay is analyzed and perused (either prospectively or retrospectively), various delay analysis methods can be used, all of which often require extensive knowledge and expertise. Therefore, third-party experts are often involved. This change of personnel potentially can result in knowledge loss, an additional review process of contemporaneous records and inaccuracy in the analysis process. Thus, this disintegration in delay claims management further results in a lengthy, costly and inaccurate process: moreover, it further complicates the issue of demonstrating causation, especially in concurrent delay situations, as some of the impact might be lost during the process. Therefore, it is logical to conclude that any effort to integrate this process would be invaluable.

3.2.2. Technical Analysis

This issue concerns the difficulties associated with the quantification process of a delay claim, including the shortcomings of tools and techniques used for the analysis and inaccuracy of the outcome. Once a delay claim is identified and pursued, the next step is to quantify it in terms of a time extension and damage compensation. The process uses a cause-and-effect approach to determine the full effect of the claimed activity on the contracted work.

CPM has proven to be the most effective technique for project management despite its many weaknesses that are extensively noted in literature. It used by practitioners to manage all aspects of a project, including planning, execution, control, and progress tracking to increase the accuracy of a project's timeline, cost estimate and resource utilization, and to gain insight into existing and potential problems (Ahuja, Dozzi, & AbouRizk, 1994).

In assessing current and past accepted industry practices and standards, it has been generally established by various construction claims experts, government agencies and organizations that using the CPM as a tool for delay analysis is acceptable, subject to a number of principles. Levin (2016) summarizes the basic principles set out by various US courts and boards which are used as industry guidelines when undertaking a delay analysis. These principles are as follows:

1. The baseline and update schedule have been established as reasonable and accurate.
2. The schedule has been updated and maintained during construction in accordance with the specifications
3. The analysis is employed in an accurate and consistent manner in accordance with acceptable forensic scheduling theory, including adjustments for contractor-caused and concurrent delays.
4. A cause –and-effect relationship between actual events and delays to the job is shown.

A key limitation of applying CPM to construction schedules is that schedules are often generated manually by using scheduling tools. Those tools are capable of intensive CPM computations and offer sophisticated scheduling flexibilities, however, this has led to misleading scheduling practices and also resulted in manipulated schedules. These practices include, but are not limited to, missing logic, late date scheduling, actual date manipulation, and out-of-sequence activities, as well as excessive use of leads, lags, constraints and negative floats. When such schedules are used in delay claims investigation, these manipulations may lead to inaccuracies in analyzing delays and quantifying time extensions, all of which add to the existing functional limitations of current delay analysis techniques that are noted in this study. Moreover, traditional schedueling tools only reflect the latest status of activities progress and do not capture how an activity evolved throughout the course of a project. More importantly, most of the tools do not demonstrate the critical path of the project of completed work which is critical for delay analysis as entitlement and compensation are only granted for delay that associated with the critical path of the project.

A point that should be noted at this stage is that scheduling tools utilize CPM to provide time and cost management solutions throughout project execution, not to measure impact of events responsible for delays and acceleration. The absence of practical alternatives, the intensive computation required by CPM, and the large amount of information that needs to be processed during the delay analysis process compels industry practitioners to use available scheduling tools.

Reiterating the first principle, there is a requirement to demonstrate that baseline schedule and updates are reasonable and accurate. Baseline schedules demonstrate the contractors' intent, based on their knowledge of the project at the pre-contract stage, and therefore, form the basis for assessing project progress. As far as contracts are concerned, delay claims usually involve a progress comparison with respect to the original (baseline) schedule. In this respect, CPM provides a great degree of detail, as it requires contractors to consider their proposed construction procedures and method. Generally, when more detail is included in a construction schedule, it is a better reference point from which variations and delays can be measured.

In reference to the second principle, there is a requirement to demonstrate that the schedule was updated and maintained during construction in accordance with the specifications. Most construction contracts require contractors to constantly update schedules, document progress and notify owners of any changes. One major concern is that as the project progress, contractors inevitably make changes by reactively resequencing activities, occasionally adding and/or removing a considerable number of activities included on the schedule, accelerate and/or deaccelerate the progress of activities, and, in doing so, either risk, or divert from, the logic set in the baseline schedule. Schedule logic may change throughout the project due to one of, or a combination of, the following factors: (1) scope changes (increase or decrease in project scope), (2) activity resequencing, or (3) incorporation of delays into the schedule. When delays occur, impacting events are usually modeled as fragnets in the schedule. To do so, the scheduler or analyst needs to identify an appropriate logic for these fragnets in order for them to be linked with the impacted activities. Consequently, logic modification of the planned schedule is required to incorporate impacting events. The result of applying such modifications to a schedule is that a new critical path may be developed that differs from the critical path included in the planned schedule.

A relevant point of discussion is the developmenet of as-built schedules that are commonly used to analyze performance and validate claims. Previous research focused on either 1) manually developing as-built schedules from unstructured project data (Knoke & Jentzen, 1996; Kahler, 2012) or 2) automating the as-built schedule development process (Mbabazi, Hegazy, & Saccomanno, 2005; Chin, Yoon, Choi, & Cho, 2008; Rebolj, Babicˇ, Magdicˇ, Podbreznik, & Pšunder, 2008; Golparvar-Fard, Peña-Mora, & Savarese, 2009; Ibrahim, Lukins, Zhang, Trucco, & Kaka, 2009; Zhang, et al., 2009; Turkan, Bosche, Haas, & Haas, 2012; Hegazy & Abdel-Monem, 2012). The first approach is impractical, tedious, and time consuming, because it requires a substantial effort to thoroughly review mass project documentation to sort and determine events that occurred during the project (Hegazy & Ayed, 1998), and it often suffers from inaccuracies due to lost information (Memon, Abd-Majid, Yusoff, & Mustaffar, 2006; Elazouni & Salem, 2010). Moreover, a standardized process for extracting meaningful data from the scattered project data is lacking, and consequently this results in a significantly prolonged process and augmented cost. A rule of thumb in claims preparation is that 70% of the time is spent on searching for and organizing information, while the analysis process takes the remaining 30% (Alkass, Mazerolle, Tribaldos, & Harris, 1995). This demonstrates the undervalued importance of as-built schedules by practitioners and absence of systematic methods to generate as-built schedules (Hegazy, Elbeltagi, & Zhang, 2005).

The second approach relies on tracking technologies (digital cameras, laser scanners and radiofrequency identification [RFID] sensors) and building information models (BIMs). Such technologies can be used to identify variation between actual and planned progress, so correction measures can be taken for either schedule recovery or expenditure adjustment. Although this approach can improve the efficiency of collecting as-built data from construction sites, the as-built schedule development was secondary, as most of the research focus was on progress monitoring and project controls. Additionally, switching to these new systems would be an expensive process, because their application imposes new means of data collection and restricted project control tools.

The current state of the art practice, represented by the previously discussed studies on as-built schedule development and delay analysis, has a number of gaps in knowledge that hinder the efficient utilization of as-built schedules for delay claims analysis. The methods reviewed do not meet the increasingly tight timelines for delay claims and the need to integrate heterogeneous project data sources and schedule updates, complying with CPM principles. It also worth to note that there are no means for considering the unvailaility and inaccurcy of project data records when developing as-built schedules. For instance, when extracting activities duration from contemporaneous project records, there might be contradicting timelines reported in different sources of information. Current approachs fall short in addressing this uncertainty of activities duration which lead to inaccurate as-built schedules and delay analysis conclusions. Table **3-1** summarizes the capabilities of existing research and indicates the identified gaps in each of the approaches (highlighted in grey).

Table 3-1: Summary of previous studies

							As-built Features							
	Main Research Focus						Basic		Enhanced/Advanced					
									Automation					
Study	**As-built schedule Development**	**Progress Monitoring**	**Site-data Records**	**Payment**	**Communication**	**Delay Analysis**	**As-built dates**	**CPM Functionality**	**Prospective**	**Retrospective**	**Data Uncertainty**	**Events Traceability**	**Critical Path Demo**	**Data Structure**
(Elkass, Mazerolle, Tribaldos, & Harris, 1995)	✓					✓	✓	✓						✓
(Knoke & Jentzen, 1996)	✓					✓	✓							
(Hegazy, Elbeltagi, & Zhang, 2005)	✓	✓	✓			✓	✓	✓	✓			✓		✓
(Memon, Abd-Majid, Yusoff, & Mustaffar, 2006)	✓	✓					✓	✓	✓					
(Navon & Haskaya, 2006)		✓					✓	✓	✓					
(Chin, Yoon, Choi, & Cho, 2008)		✓					✓							
(Rebolj, et al., 2008)		✓			✓		✓	✓	✓					
(Zhang, et al., 2009)		✓		✓			✓	✓	✓					
(Elazouni & Salem, 2010)		✓					✓							

							As-built Features							
	Main Research Focus						**Basic**		**Enhanced/Advanced**					
									Automation					
Study	**As-built schedule Development**	**Progress Monitoring**	**Site-data Records**	**Payment**	**Communication**	**Delay Analysis**	**As-built dates**	**CPM Functionality**	**Prospective**	**Retrospective**	**Data Uncertainty**	**Events Traceability**	**Critical Path Demo**	**Data Structure**
(Kahler, 2012)		✓					✓							
(Turkan, Bosche, Haas, & Haas, 2012)		✓					✓	✓	✓					
(Hegazy & Abdel-Monem, 2012)	✓	✓	✓		✓		✓	✓	✓					✓
(Abdel-Monem & Hegazy, 2013)	✓	✓	✓		✓		✓	✓	✓					✓
(Hegazy, Abdel-Monem, & Saad, 2014)	✓	✓	✓				✓	✓	✓					
(Al-Gahtani, Al-Sulaihi, & Iqupal, 2016)						✓	✓	✓						
(Shrestha & Jeong, 2017)	✓	✓					✓			✓				✓
(Son, Kim, & Cho, 2017)	✓	✓					✓	✓	✓					

Previous studies failed collectively to provide all the desired features of as-built schedules which would ultimately add to their value in claims analysis. Since all such information required for as-built schedule development is already available in different forms, automatic generation of as-built schedules can be achieved if standardized organization of these data is established, coupled with a systematic integration approach.

The third principle involves a requirement that the analysis is employed in an accurate and consistent manner in accordance with acceptable forensic scheduling theory, including adjustments for contractor-caused and concurrent delays. Many delay analysis techniques have been developed addressing challenges such as concurrent delay, critical path fluctuation, and liability allocation (Kao & Yang, 2009).

One of several approaches that is widely recognized and used by the construction industry is window delay analysis, nevertheless, it has some flaws. The technique requires intensive computation and the window spans may vary in short and long periods. Long window periods fail to account for changes in the critical path(s) as events evolve, and schedules can be manipulated by constraints and logic changes. A study by Hegazy and Zhang (2005) addressed the critical path fluctuation flaw by proving that smaller window spans would result in more accurate delay analysis. Furthermore, the study proposed a daily window delay analysis technique using an intelligent bar chart (IBC) that is made of spreadsheet cells in which duration of activities are represented as group of cells rather than bars (Hegazy & Zhang, 2005). Each cell is then used to store daily percent complete values for activities, delays, responsible parties and other data related to any delay.

The proposed practice is designed to be used on a day-to-day basis as the project evolves, which makes it suitable for prospective delay analysis. The researchers acknowledged that the proposed

IBC is not a substitute for the traditional means of site data collection. Moreover, it is important to note that construction activities vary in nature (e.g. design activities, management activities, etc.), therefore, measurement procedures could be different and may require a different skill level. Thus, regardless of the subjectivity and potential inaccuracy in estimating percent completion of activities, a daily estimation would necessitate additional resource deployment from both the contractor, to estimate the progress, and the owner, to verify the estimate. Likewise, if this technique were to be used for retrospective analysis, reconstruction of the project schedule with daily records would be a resource-intensive and costly process. Therefore, a simpler solution that can maximize the utilization of currently available tools and practices would be invaluable and contribute greatly to delay claims practice.

There are further problems related to the method: the researchers acknowledged that the proposed method needs refinement, as it still falls short in addressing some major delay issues, including, but are not limited to, considering partial daily delay, owner-requested versus contractor-owned acceleration, and apportioning delays at the subcontractor level (Hegazy & Zhang, 2005). The study also acknowledged that the reliance on spreadsheets makes it only suitable for small and medium-size projects, and that large and complex projects would need a more powerful method for implementation. Despite all these drawbacks related to window delay analysis techniques, the literature review reveals that relatively little has been published on the subject of using alternative techniques, such as simulation, to manage construction claims and dispute resolution, despite the proven computation and accuracy benefits of simulation in other applications.

The fourth principle involves demonstrating whether a cause-and-effect relationship between actual events and delays to the schedule is shown. Many of the existing delay techniques fulfill such requirements at the owner and contractor level, including the daily delay method. However, establishing causation and apportioning delays at the subcontractor level is yet to be investigated.

At this point, it might be useful to note the following interim conclusion – that is, that considering the improper application of CPM and shortcomings of delay analysis methods, leveraging technology advancements to design and customize a CPM-based delay quantification framework is indispensable.

Another problematic issue that forms a key point of most disputes is liability allocation between the involved parties: each party involved blames the other, and presumably completes a delay analysis and submits an alleged claim. For instance, in a situation where a delay in design completion of non-standard products occurs, a contractor would claim that the owner's actions caused the delay to the design completion, while the owner could claim that the design submission was unsatisfactory and, therefore, resulted in a prolonged design process. Such issues are usually resolved through the involvement of experts in the subject matter, and a verdict passed by a ruler (referee or arbitrator, etc.) could potentially involve shared liability. However, a scenario such as this could be further exacerbated when there are multiple points of dispute. Therefore, current delay analysis practices limit the rulers' options to either accept the outcome of an analysis as-is, request reanalysis of claims based on a reallocated liability, or make a conclusion based on their judgement.

Another relevant issue besides liability allocation is that current delay analysis practices mainly focus on quantifying time extension. Although these two elements are key in resolving time-related claims, the analysis is not expanded to include other aspects, such as having independent events analysis that is independent of the schedule analysis. For instance, available delay analysis techniques do not analyze the magnitude of an impact at the event level, which is more important in concurrent delay analysis situations. Such an approach would offer professional ruling on claims a new means for their ruling and allow project participants to learn from the claim process for future projects.

3.3. Deductions

Following the review of literature in Chapter 2 and discussion of issues presented in this chapter, a summary of the immediate deductions relating to the delay analysis issues is set forth as follows:

3.3.1. Administrative Issues

Need for specific delay analysis expertise

- Delay identification requires sufficient knowledge of other contracted work to recognise variations and potential schedule manipulation, and scheduling skills to assess the impact on project schedule. Moreover, depending on the timing of the delay analysis (prospective or retrospective) and the availability of contemporaneous records, there are many delay analysis methods available with different degrees of complexities. The implementation of any of these methods requires extensive knowledge and expertise, which often requires the involvement of different parties than those involved in the project (third-party experts) which can, subsequently, result in prolonged and costly delay analysis.

Lack of standardized data documentation structure and organization processes

- Project control practices have been continuously developed, yet they do not truly align and support the claims management process. Records gathered during the execution of a project are organized in a way that does not align with the delay analysis process. Delay analysts still need to review project documents to extract delay information, identify delay events and quantify their impact. This, consequently forms an unavoidable data organization process and adds significant cost and time to the analysis process. The identification of events that impact a project schedule is not an easy task, because events vary in nature and complexity. Moreover, when such events are identified, there is no standardised set of attributes that ensures adequate and efficient documentation of each event.

Disintegrated management process

- Delay identification and quantification processes are isolated and usually treated as independent processes accomplished by third party experts; mainly due to the skills and expertise required for the analysis process. This disintegrated approach impedes the process of demonstrating causation, which in turn drives up the cost of the process and leads to problems concerning the sourcing of data.

3.3.2. Technical Issues

Inadequate testing and use of alternate technologies

- Advancements in simulation techniques have been occurring for decades, mostly related to the advanced computational capabilities essential to model the calculations of CPM. However, these capabilities have not been fully utilized by either researchers or practitioners for the delay quantification process, despite the proven benefits associated with CPM modeling.

Inefficient and inaccurate development of as-built schedules and analysis of time claims

- There are many challenges associated with the development of as-built schedules and time claims analyis that include 1) lack of uncertainty modelling for inaccurate or unavailable project data records, 2) lack of a structured approach for automated retrospective project data integration with project schedules updates used by delay analysts to either test different delay scenarios or verify and quantify delay claims, 3) a relatively long as-built schedule development time compared to the short decision making window that governs most construction contracts, 4) lack of activities progresss documentation associated with traditional scheduling tools, i.e. how an activity evolved throughout the course of a project, and 5) lack of a demonstrated critical path of completed work

Subjective interaction with schedules

- As project progress, inevitable modifications to the project schedule are made to reflect progress, acceleration or delays, resulting in deviation from the project plan. However, some of the delay analysis methods requires retrospective interaction with projects' schedule to model delays which is undesirable and questionable during a delay analysis process. Pursuing alternative means of change modelling without altering project schedules is invaluable.

Impractical solutions

- Although researchers are successfully developing new tools and forcing new requirements as a part of implementing analysis solutions, these tools and requirements sometimes exacerbate the problems and do more harm than good. This is a very true in claims management, as disputes are usually expensive to manage, complicated, and accompanied by many existing challenges, including data availability, accuracy of data collection, and subjectivity, among others. Any additional demands from industry practitioners contribute to the identified problems. A more practical approach would involve less complexity and would, furthermore, present opportunities for improvement. A simulation-assisted modelling approach, comprising all essential stages, from initial data gathering and organization through to liability allocation, would greatly improve the delay claim process. It is this approach that has been adopted in this research.

Inconsideration of partial delays

- The duration of delays to construction activities vary in length. Some delays last for long periods, (days, weeks, or even months), while some last for hours (e.g., windy conditions during a crane lift). Current delay analysis methods do not accurately consider such short periods of delay, as they are either ignored completely or represented as a full day.

Failing to allocate liability at the micro-level

- Usually delays are apportioned among the owner, contractor and external reasons (i.e., at the macro level). All contractors and their subcontractors are grouped under the term contractor, without directly allocating the delay to the incumbent contractors and/or subcontractors. This further complicates the process of establishing a link between the liable party and the party who is required to compensate for the delay.

Restricted forms of delay analysis

- Currently, available delay analysis techniques mainly focus on liability allocation and time extension quantification, which limits both the ability of a ruler to evaluate the claim and options to reach conclusions efficiently and accurately. Moreover, none of the available analysis methods allow for event-based analysis, which would be beneficial to both claim rulers and project participants.

3.4. Summary and Conclusions

This chapter concludes the background research portion of this study. The contrast between literature review and industry practice has been completed to identify issues related to the current practice of delay analysis that are leading to inefficiencies and inaccuracies in the quantification process of time-related claims in the construction industry.

This review and analysis reveal that there are clear shortcomings in the current practice, prompting a need for a new approach to the management and analysis process of time-related claims.

Chapter 4. A New Simulation-Assisted Framework for the Analysis of Time Claims

4.1. Chapter Introduction

Chapter 2 set out in detail the findings of the literature review of current delay and time extension problems in the construction industry, as well as the existing analysis methods and their limitations. It also discussed the limited use of simulation in addressing time claims analysis and how productivity impacts construction schedules. In Chapter 3, the academic and practical aspects of current delay analysis practice were contrasted, identifying inherited issues. The key problem areas were generally classified under two main headings, namely: administrative and technical issues. Problem areas were further presented as deductions at section 3.3.

This Chapter states a composite problem that is defined and derived by the deductions of the critical review of time-claims practice and uncovered shortcomings. It also proposes a framework to incorporate the finding of state-of-the-art research and industry practices to provide a comprehensive solution to time claims problems, including: information overload, accuracy, and efficiency required to analyze construction schedules.

4.2. Problem Statement

This research has revealed that time claims are complex and have become an inevitable part of construction projects. Together with the increased complexity of construction projects and tight deadline demands, this situation is expected to remain unchanged.

The failings and shortcomings of the overall management, analyses, and assessment of time claims, as well as the need for improvements, are formulated as a problem with a simulation-assisted framework proposed as the solution.

The problem is defined under two key issues identified earlier in our investigation, namely: claims administration and technical analysis issues. External factors contributing to the defined problem include sensitivity of the subject, lack of knowledge on how claims evolve (understanding the potential implications of simple actions made on a project), how they are analyzed and settled, along with inadequate availability of real project data for researchers.

4.3. Proposed Solution – A Simulation-Assisted Framework

This section proposes a solution to the defined problem in the form of a new simulation-assisted framework for time claims analysis, which seeks to address the administrative and technical issues identified earlier. This framework seeks to eliminate the deficiencies of current practice.

In order for the framework to achieve its goals, its design is based on knowledge-discovery principles. This begins with data organization in which raw data are prepared to extract meaningful information (targeted data) through to knowledge discovery by virtue of a unique data mining process based on various simulation algorithms.

Many of the proposed framework's components are similar in principle to the traditional approaches in terms of analysis and evaluation in connection with delay assessments.

The key differences between the proposed framework and the existing delay analysis approaches are as follows. In the proposed framework heavy emphasis is placed on integrating the main components of the delay management process, including delay identification, impact quantification (converting lost productivity into delay duration), analysis and evaluation into a simulation-assisted system.

From the technical perspective, the proposed framework addresses the critical interface between the documentation and organization of the contemporaneous data processes, and the claim management process—a significant departure from the current practice. The proposed framework also addresses the matter of liability allocation, and analysts' interaction with schedules for delay analysis purposes.

4.3.1. Conceptual Architecture

The proposed solution takes the form of a **Forensic Schedule Information Modeling** framework for analysis of time claims; abbreviated hereafter as **ForSIM**. The development of ForSIM is based on the concept of time-step simulation where the analysis result of a time-step forms the basis for the successor time-step. It is composed of four main components: (1) data organization and filtration, (2) initialization and data pre-processing, (3) simulation-assisted data integration and transformation and (4) analysis and results compilation. Figure 4-1 illustrates a high-level structure of ForSIM.

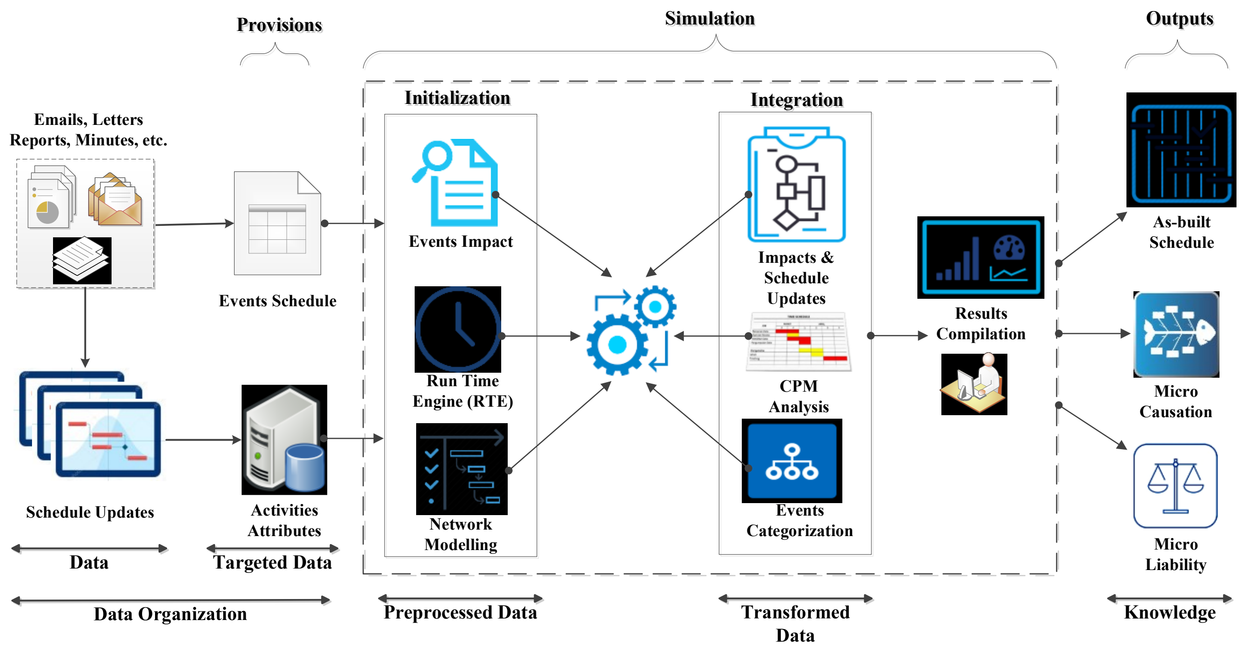


Figure 4-1: High-level architecture of ForSIM framework

The dynamics of schedule changes are modeled by extracting schedule activities and their logic based on a predefined time-step of one entity, integrating the impacts of the events relevant to the entity into the CPM computation, and lastly analyzing the data and providing results. To enable this process, conceptual entities are generated that represent time units such as minutes, hours, weeks, and so on.

It is important to note the distinction between an entity and an event. While an entity is an object of time unit, an event is an instantaneous incident that change a state of project schedule, analysis outcome, and/or the occurrence of other events.

The entity movement is facilitated through two main constructs, 1) an *entity information model* that contains relevant information of events and schedule activities, and 2) an *entity lifecycle model* that defines possible routes which an entity can go through a schedule network. Detailed description of these constructs is provided in Sections 4.3.3.2 and 4.3.3.3 of this thesis.

4.3.2. Provisions

While gathering and presenting evidence is a vital element in claims management, delay analysts are often overwhelmed with information. Construction projects, by nature, generate huge amounts of documentation. The sheer amount of documentation alone makes the analysis process daunting, particularly for retrospective analysis. The provisions of ForSIM help in establishing formal means of data documentation and organization, so a more focused analysis can be executed. ForSIM relies on data from three sources, which serve as inputs: the baseline schedule, schedule updates, and the schedule of events. Transforming these inputs into the acceptable framework specification is based on a combination of actions from the analyst, along with automated verification and synthesis algorithms. A detailed description of these sources follows.

4.3.2.1 Baseline Schedule and Schedule Updates

The role of the baseline schedule in construction management cannot be underestimated. It represents a time-frame that provides the start and finish dates for all project activities, taking their relationships, constraints, and other project characteristics into consideration to reach a certain project objective. It is important to note that baseline schedules are based upon the knowledge at the pre-contract stage. If the baseline were contrasted with the 'as-built schedule, then a factual progress record of could be provided. Notably, it is incorrect to base a delay claim analysis on a schedule that was not adhered to, or that could not be adhered to.

Claims usually compare actual events (what happened) with baseline(s) (what was intended to happen). ForSIM utilizes the baseline schedule as initial reference to measure time extension or acceleration and to allocate liability and support the as-built vs. as-planned analysis. The baseline schedule is used to model the planned sequence of activities, estimate activities' duration, logical constraints, and project calendars, which are all used to calculate the start and finish dates of activities as per the CPM computation. ForSIM also supports available schedule updates to reflect inevitable schedule changes. For instance, if changes are made to a schedule (such as change to logic, activities' duration, constraints, and so on), all of these changes will be reflected on the simulation model at the time the changes are made. It is important that schedules used in the analysis adhere to the best scheduling practices.

4.3.2.2 Schedule of Events

Organizing project data, particularly data related to claims, would make that data more useful. Organized data results in better understanding of the claim under investigation, considerable time saving, as well as focused analysis. The framework proposes using a well-structured event schedule designed to capture the information required to analyze construction schedules.

The Schedule of Events (SoE) lists all events that might impact the project schedule, including but are not limited to: approved time extensions, unsettled time extensions requests, daily site events, and so on. Impacting events are sorted by reference to the date of occurrence, duration, impacted activities, and liable parties for the delay. ForSIM requires certain attributes of an event to be captured in a firm format for it to be considered as an event. Descriptions of these attributes are listed as follows:

- **ID:** Each event is assigned a unique ID once it is entered into the event schedule. At the initiation, identifiers are also used to track events and configure their impact quantification.
- **Description:** A detailed account of the event that describes its circumstances. A well described event would help the claim analyst to better understand the event, resulting in a well-informed quantification.

- **Cause:** A concise description of the event's cause in a few words; brief but comprehensive. Ideally, it should provide the analyst with a high-level categorization of delay events.
- **Quantification type:** ForSIM support the following three types of impact quantification:
  - **Fixed:** The event's impact assumed to be certainly known; this method is used where contemporaneous records of the event's impact on the schedule are available and undisputable.
  - **Uncertain:** The event's impact is assumed to be uncertain; this quantification type is used where contemporaneous record of the event's impact on the schedule is unavailable, inaccurate or contradictory and can only be captured in distribution form.
  - **Formula:** The event's impact is modeled as a mathematical model that expresses the relationships between different variables. In previous studies, many quantification models have been developed where each model quantifies the impact of a certain factor, in a specific context, and under specific circumstances.
- **Start time:** This refers to the specific starting time for the event occurrence. Considering the time-step concept adopted in this framework, the start time refers to the time on which the event had occurred.
- **Parameters:** There are various factors influencing productivity and activities duration. Many models quantifying the impact of each factor have been developed and require certain parameter inputs. Having identified which factors to consider and model, the actual data (inputs) required for predicting the production ratio is captured under the Parameters' column. Considering the three quantification types supported by ForSIM, the parameters are filed as follows:

- ***Fixed***: the parameter reflects the duration of the event as per the time step unit, e.g. hours, days, weeks, etc.
- ***Uncertain***: the parameters reflect the inputs required for the selected distribution by the analyst.
- ***Formula***: the parameter(s) reflect the input variables specified by the analyst when setting the formula.

➢ **Responsible parties:** The person or entity responsible or liable for event's occurrence. ForSIM supports the cases where there is more than one party liable for the event. Notably, the SoE is designed for delay quantification from the claimant's perspective. Disagreement between responsible parties is a different issue.

➢ **Impact type:** An event could have different types of impacts on the schedule. ForSIM defines and models two types of impact that are either Global or Task-specific.

- ***Global Impact***: refers to an event that impacts the whole project. This case is modeled by integrating the impact of the event into all the activities occurring on the modeled time instanse. For example, if there is a labor strike on a project, all the project activities will be impacted.
- ***Task-specific***: this refers to an event that impact certain activities. This case is modeled by integrating the impact of the event into the activities that are only occurring on that modeled time instanse out of predefined activities. The predefined activities are captured by listing their IDs in the field under the **Impacted Activities IDs** column. For example, if there is a design change to a structural element, all of the associated occurring activities will be impacted.

- **References:** This refers to source documents supporting the occurrence of events. This helps in organizing and retrieving project files later used in demonstrating entitlement.
- **Issue Date:** This refers to the date in which supporting documents of events are issued. Construction contracts usually include provisions for when claims notices are submitted, otherwise, claim entitlement could be dismissed. Therefore, this attribute could be used to filter out non-excusable events.

The SoE could be implemented in variety of ways; however, it must be in a computer- interpretable format such as a database, Excel sheet, and so on. Table 4-1 depicts a populated sample of the SoE. It is also important to note that the currently included attributes concern delay events, and the SoE can be extended to other attributes as necessary (e.g. cost, additional resources, equipment, and so on).

Table 4-1: Snapshot of the schedule of events (SoE)

#	Description	Cause	Quantification Type	Start	Parameters	Impact Type	Resposible Party	Directly Impacted Ativities ID	Reference	Issue Date
1	Unsafe site conditions	Weather	Uncertain	1/20/18 12:00 AM	1,4	Global	Contractor A, Constractor B	N/A	Daily site report	20-Jan-18
2	Change in the building layout to accommodate extra excavation	Design Change	Fixed	2/5/18 12:00 AM	5	Task-specific	Owner	10, 12, 15	Change Order No. 5	02-Feb-18
3	Removal of contamintated soil	Different site condition	Fixed	3/15/18 12:00 AM	6		Consultant X	N/A	Geotechnical report	14-Mar-18
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

4.3.3. Simulation

Construction schedules are constantly subject to changes, depending on internal and external factors, such as planned activities, resource availability, approvals and weather conditions. As such, a time-step simulation approach would be suitable to model the dynamics of CPM networks. It is reasonable that entities may represent time units. The entity could represent any unit of time (hours, days, weeks), based on the desired level of abstraction. This poses certain modeling requirements, including: (1) that each entity must be distinct and represent unique and active event(s), and (2) there must be capability to route through Active activities, so that duration adjustments can be made where applicable. The Active status of an event or an activity refers to the occurrence of the event or activity at that entity instance. These requirements will be addressed in the following sections through detailed explanation of the simulation components.

4.3.3.1 Initialization

The initialization starts with interpreting and storing the framework's required inputs. All the information stored in the project schedule and SoE are captured and preprocessed, so it can be manipulated through libraries written in programming languages, such as Java and .Net for delay analysis purposes. The initialization would depend on the programming language used as well as specific qualities (type, storage class) of the attribute (object). The initialization, as shown in Figure 4-2, includes quantifying the impact of events, defining the network structure, and setting up the time-step simulation.

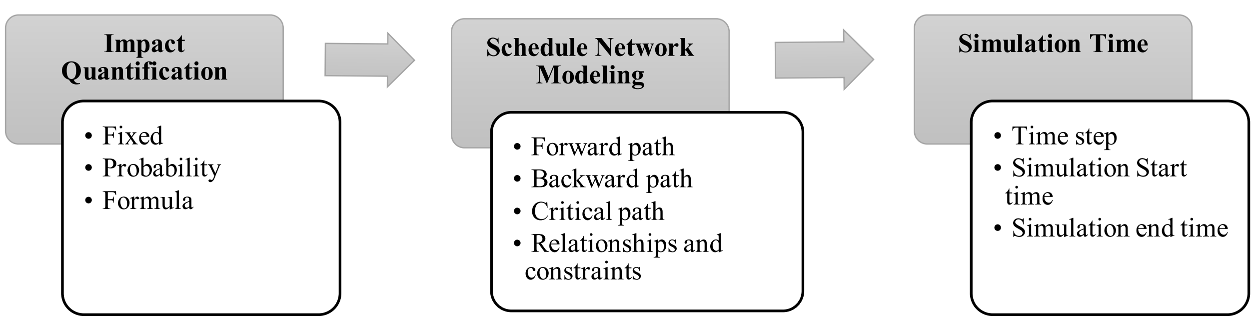


Figure 4-2: Initiation process

ForSIM supports three ways of quantifying an event's impact: fixed, formula, and probability. Events with fixed impact do not require impact quantification as the impact is assumed to be known. Events with probability impact are those that have uncertain impact durations; accordingly, ForSIM supports using probability distributions such as uniform, triangular, or beta distributions to capture uncertainty of the event's impact. Methods like Monte Carlo simulation or the Inverse transformation method can be used to quantify these events. For events with impacts that can only be expressed formulaically, ForSIM enables the analyst to define the quantification model and then compute the event's impact. To avoid subjectivity issues, the quantification models could be set or agreed upon prior to the project start, and perhaps outlined in the Project Agreement (PA). At the end of the initialization the calculated impacts of events are used to calculate the end dates of events. At time zero ($\tau 0=0$), the starting simulation date and time are initiated as the earliest start time in the project schedule. Then, the simulated time will be incremented by a predefined time-step throughout the simulation of the entire schedule. As it has been noted in previous research (Hu, 2013), using large time-steps results in fast but inaccurate/unstable simulations. Using small time-steps leads to more precise simulations but takes longer to process.

The CPM is the foundation of ForSIM, and for most other delay analysis techniques. Activities information that are embedded at compiled time ($\tau 0$) are used at the initialization to model the network of the project and perform CPM calculations. The modelled CPM is executed at the initiation stage to set up the delay measurements, which include identifying the critical path activities and thus their calculating the project duration.

The outcomes of this impact initialization are the final impact duration of all events listed in the SoE and their calculated end dates, which refer to the specific finishing time for the occurrence of the events.

4.3.3.2 Entity Information Model

Entities in the simulation model are initiated equally by default. In order to make them representative of distinct times, some key events and activities information must be carried by the entities. This often refers to descriptive attributes such as event ID, cause, and impact. To enable entities to carry both event and activity-related information, an integrated entity information model (EIM) is designed. Figure 4-3 illustrates the components of an information model, which include (i) simulation run-time data; (ii) impacting events data, and (iii) other project control data. The EIM is a record type where each of the fields is either a record of an attribute or collection of attributes.

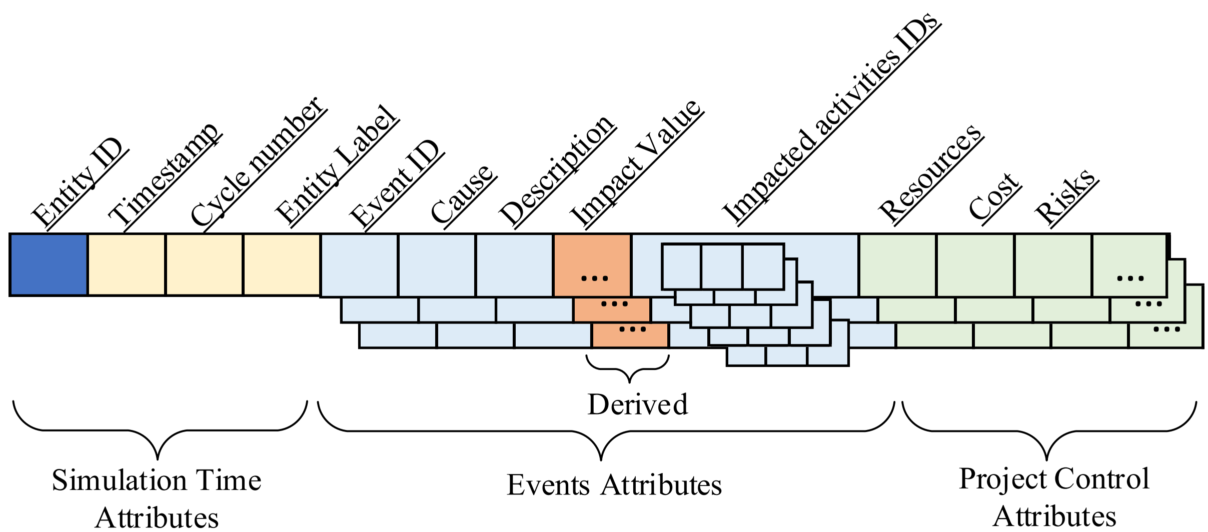


Figure 4-3: Entity information model

As sown in Figure 4-3, the EIM is broken into three categories. The *Simulation time* attributes holds information about the simulation time of an entity instance, including the most current simulation timestamp as per the entity instance, cycle number, and the entity instance label (working or non-working day). The *event attributes* hold information about the occurrence impacting events relevant to the entity instance, including event ID, cause, description, impact value (derived), impact type, and applicable impacted activities ID. A given event occurrence might be relevant to multiple entity instances; in such cases, events' attributes will be recorded on all the entities. This means the event span is larger than an entity instance. Nesting events is supported and executed in parallel. When there are multiple events relevant to an entity instance, EIM will contain records of all events, route through all active activities, and accordingly trigger change to their duration. The *project control* attributes are currently not implemented in ForSIM; however, they are shown to demonstrate how the information model can be expanded to hold other information such as resources, cost, and risks.

4.3.3.3 Entity Lifecycle Model

Figure 4-4 shows the topmost levels, referred to as stages, of the entity lifecycle. The entity lifecycle model specifies the activities that an entity can be involved in as the entity routes through its lifecycle. It is specified using *stages,* where each stage consists of one or more *guards*. A guard is a condition (possibly a triggering event) that, when activated, enables entities to route through the network model and then trigger changes into the activities' duration. The guard's conditions range over the information model of the entity instance and are expressed using if/then rules. When these rules are evaluated to be TRUE (satisfying the condition under consideration), the guards become OPEN, allowing a set of associated actions, (changes to activities' duration) and other rules to be executed. For instance, if there was an Active Event at an entity instance, the Events' Schedule guard would become OPEN, allowing the entity to pass through to collect records of that Active event.

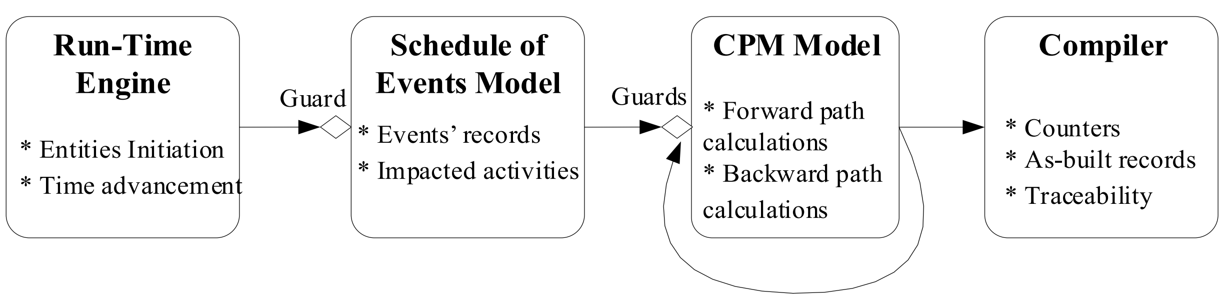


Figure 4-4: Entity life cycle model

4.3.3.3.1 Run-time Engine

The time-step simulation allows both events that occur at specific times and periodic events to be modeled. The run-time engine (RTE) is responsible for controlling the simulation execution, creating the simulation environment, initiating entities with a timestamp, cycle number, and label, as well as advancing the simulation time. At time zero (τ0=0), the starting simulation date is initiated as the smallest early start time in the project schedule. In other words, the simulation sets the starting simulation date as the earliest start time (ES_i) of the first activity in the project. The simulated start date will then be incremented by one entity throughout the simulation of the entire schedule.

4.3.3.3.2 Schedule of Events Model

In order to reduce the modeling complexity of an event so that it will be easy to integrate into the project activities, one approach is to break the event into smaller events (events slicing), which are referred to as E-bites in this framework. The event slicing transforms events into E-bites by using the entity span as slicing criteria to identify E-bites relevant to an entity instance. All E-bites inherit the attributes of their parent events. The generation of E-bites starts by defining the slicing criteria, which are the time spans represented by the entity instance. Each E-bite is tagged with a timestamp and includes a Boolean attribute, which holds its status. This is initialized at CLOSE and becomes ACTIVE once its guard becomes OPEN. The guard status changes as per the status of its parent event. For example, if an entity was released and a parent event was active, the guard becomes OPEN. This means the entity will route through the event's schedule and its information model will be updated as per the attributes of the parent event.

4.3.3.3.3 Network Model

Initial values of activities attributes (ID, name, duration) embedded at compile time ($\tau0$) are used to model the network of the project. ForSIM relies on basic CPM principles discussed at length in the literature, including modeling precedence relationships, leads and lags, calendars, as well as both forward and backward passes computation through the schedule network. As schedule updates become available, they are used to update the activities attributes and execution logic. Modelling the aforementioned principles could be done programmatically in variety of ways, depending on preference. ForSIM is mainly concerned with having a fully functional CPM calculation of the project attributes, regardless of the modeling approach. The modelled CPM is executed at the initiation stage to establish the planned project timelines. The framework supports continuous critical path identification and calculation at every time-step, as delay is only measured against critical path activities at the time. It is important to note that executing the CPM at the initialization is also a vital step in verifying the modelled network.

A similar approach to the events slicing is used for the schedule activities where the durations of activities are broken down into smaller activities, referred to as A-bites. Each A-bite represents an entity span ; its status attributes change as per the release of a matching entity. The Network model, however, has a guard for the network and guard for each activity. The network guard becomes OPEN once the status of a parent activity becomes ACTIVE, which allows the entity instance to route though the Network model. The activity guards become OPEN only when the network guard is OPEN, and the status of the A-bite becomes ACTIVE. In such a case, the entity routes through the parent activity and triggers changes to its duration as per the attributes of the relevant E-bites.

The final portion of the entity lifecycle model is the compiler, described in section 4.3.4.

4.3.3.4 Data Integration

As shown in Figure 4-5, the integration process starts by advancing the simulation time from day zero ($\tau 0$) to the starting simulation date *(τ_1)*. The RTE then releases the first entity instance tagged with working or non-working labels as per the project calendar. When an entity instance is released, it may result in a series of changes in the status of parent events, E-bites, parent activities, and A-bites becoming ACTIVE. Guards become OPEN or CLOSED.

When τ_1 is a non-working day, the entity routes to the compiler without triggering any changes in the CPM network model; otherwise, the simulation explores the event's schedule to check if there is any ACTIVE event relevant to the entity instance through an event-to-event sequence. In such a case, the event's guard becomes OPEN, allowing the entity instance to route through the event's schedule. When there is an ACTIVE E-bite, the simulation updates the EIM; otherwise, the entity simply routes to the compiler. For ACTIVE E-bites with global impact type, the impacted activities field in the EIM will be updated to include all the ACTIVE A-bites. Also, for ACTIVE E-bites with a task-specific impact type, the impacted activities field in the EIM will be updated to include the ID of the impacted activities regardless of their status.

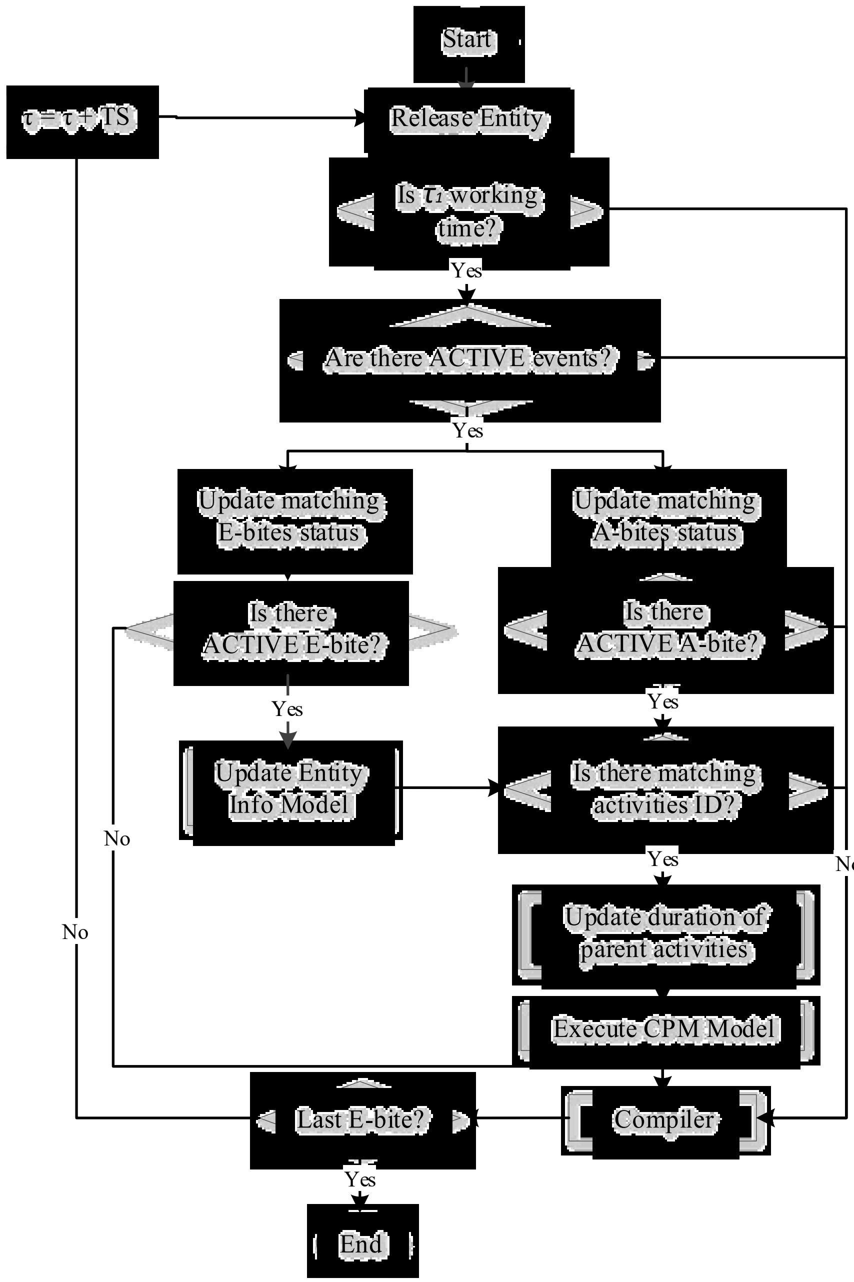


Figure 4-5: Data integration process

The entity instance then transfers to the network model stage. When there is an ACTIVE parent activity, the network guard becomes OPEN, allowing the entity instance to route through the network model. The activity guards become OPEN when there are ACTIVE A-bites, which allows the entity to trigger changes to the duration of parent activities as per the impact field of EIM. Durations of all Active parent activities are updated simultaneously, and the CPM model will be accordingly executed. Thereafter, the entity routes through the compiler and the simulation advances to the next time step (TS) by following the same updating process. Thus, it shifts from one entity to the next until it passes the timestamp of last ACTIVE E-bite. If at any time during the simulation a guard has CLOSED status, the entity routes to the compiler without triggering any changes in the network model. It is important to note that an activity's duration is only updated to a maximum of one entity span (a time-step). The update could either be positive or negative.

4.3.3.5 Network Criticality Analysis

Once the impacts of all active events at an entity instance are applied, the CPM is executed to analyze the impact of events on the critical path in comparison to a calculation of the previous entity instance. Changes in activities' durations may result in either extension or compression (acceleration) to the project schedule, or formulation of an entirely new critical path(s). The simulation, therefore, re-identifies the critical path of the schedule and the overall project duration. If the CPM execution results in no changes in the critical path, active events would be labelled as non-impacting events and the simulation would advance its time to the next entity instance. When changes to the critical path exist, however, ACTIVE events are labeled as impacting events and responsibility (liability) counters are initiated for every unique associated responsible party. When there is extension to the critical path, active events are labeled as delay events, and would undertake further categorization as discussed in section 4.3.3.6; however, when there is compression to the critical path, ACTIVE events associated with reduced activities duration are labelled as acceleration events.

4.3.3.6 Delay Events Categorization

Delay events fall into one of three fundamental categories: excusable compensable, excusable non-compensable, and non-excusable. To categorize delay events, the claimant must be set at the beginning of the analysis. This framework can be used by any party involved to determine liability of other parties. To enable an event's categorization and liability allocation, the claimant must be set at the initiation of the simulation model. The rules for delay-event-categorization can be implemented, for instance, through conditional statements.

4.3.4. Outputs / Compiler

ForSIM imitates the dynamic of the project schedule without committing real resources. As a result, it extracts useful and sometimes hidden information from large project data and documentation. The outputs of ForSIM are described in the following sections.

- **As-built Schedule and Time Award:** One of the simulation outputs is an as-built schedule, which is a result of incorporating all the impacting events into the durations of the base schedule's activities. Then, a comparison of the as-built schedule and the baseline schedule is presented in a graphical and statistical fashion. Time extension or acceleration is quantified by subtracting the simulated project duration from the planned project duration.
- **Micro-Liability Allocation:** Each delay event has one or more responsible parties who are all traced and assigned with liability counters. Liability is computed throughout the simulation, and the counters are continuously updated and presented at the end in tabulated and statistical fashions.

- **Micro-Causation:** Unlike establishing causation traditionally, the proposed system establishes the cause-and-effect at the events level. Through the use of simulation, impacts of events that have caused change to the project's critical path are quantified and traced separately. As such, the impact of each event (time extension or acceleration) are automatically presented in statistical fashion.

4.4. Validation of ForSIM

The verification and validation of simulation models is extremely important, so it can be used within the academia and industry. Therefore, many methods were proposed for developing valid and credible simulation models (Law, 2006; Martinez, 2009; Lucko & Rojas, 2009). As recommended by these studies, the verification and validation process of ForSIM was carried as continuous process throughout the development process.

Due to the large complexity of the ForSIM, it was undertaken progressively through a stepwise approach using different techniques as follows:

4.4.1. Content Validation

Content validity is a non-statistical examination of the model content to assess whether it is a representative sample of the systems of interest (Anastasi & Urbina, 1997). Simulation studies commence with abstraction of a real-world systems or process. The precision of the modeling process determines the validity or invalidity of the model. The first aspect of abstraction pertains to the fixation of the model boundaries that involves determining which constructs of the system to include in the modeling process. The selection of ForSIM's constructs was guided by the research objectives and underlying assumptions. This phase of the validation process was carried carefully to ensure ForSIM is valid with respect to its content.

4.4.2. Constructs Validation

After ForSIM boundaries were defined, the selected constructs were mapped to a time-step simulation paradigm. Constructs validity concerns with assessing the appropriateness of the simulation method used to model the abstracted constructs. This process requires domain experts to confirm the design and analysis of ForSIM. To ensure the validity of ForSIM constructs, the following steps were followed:

- Simulation and construction knowledge acquisition through readings, courses and projects undertaken by the author throughout the research.
- Design representation; a number of design aids were used to represent and communicate ForSIM design such as flowcharts, algorithms, activity charts and concept schematic layouts.
- Scrutiny of ForSIM design by the research supervisors and colleagues within the group construction research group. This was a continuous process that led to significant improvements to ForSIM throughout its development.

4.4.3. Face Validation

Face Validation is a technique used to assess whether a model appears to be suitable or unsuitable representation of the process of interest. ForSIM conceptual design was validated through discussions with professors in the research group, experts in the field of delay claim analysis as well as a lawyer, all of whom provided feedback on the validity of ForSIM based on its face value. The subject matters confirmed the reasonableness of ForSIM design and modeling approach.

4.4.4. Results Verification and Validation

ForSIM prototype is being developed and studied in several ways. The prototype model was tested with complex scheduling scenarios, including leads, lags, different relationship settings (Finish-to-Start, Start-to-Start, Finish-to-Finish, Start-to-Finish) and various constraint settings (Finish No Earlier Than, Finish No Later Than, Must Finish On, Must Start On, Start No Earlier Than, Start No Later Than).

As indicated earlier, ForSIM calculates start and finish dates of activities using CPM principles and are driven by the activities duration and constrains as established in the planned schedule. To validate ForSIM, the modeled planned start and finish dates outputs are closely compared to those from the planned schedule dates. Each scheduling scenario was verified and validated independently, and then the validity of all scenarios together was made. The comparison confirmed that ForSIM CPM calculation is valid under all the tested scheduling scenarios with exception of one scenario that is the use of different working calendars within the project. A comparison example is shown in Section 6.2.3. Lastly, to verify the data integration process and delay analysis, event traceability during ForSIM execution was used to observe changes to activities' durations and timelines as well as delay liabilities. An example of a simulation log for tracing changes to project timelines is discussed in Section 6.3.2.

4.5. Summary and Conclusions

This chapter considered the academic knowledge and practical aspects of time claims analysis, the inherent shortcomings therein, and has defined such deficiencies as a problem that in need of improvement. To improve construction delay analysis practices, advancements in simulation can be explored and tested.

A promising solution to the defined problem was proposed in the form of a **Forensic Schedule Information Modeling** framework, abbreviated as ForSIM. ForSIM integrates various schedule-related factors under one environment, using simulation to analyze construction time claims and allow analysts to make well-informed judgements. ForSIM also simultaneously quantifies the time extension and/or acceleration award and provides feedback for the delay analyst in graphical and statistical fashion. The framework was comprehensively described. This systemized and automated approach to the modeling, analysis, and quantification of time claims is based on research, analysis, and assessment of state-of-the-art research as well as industry practice, and will be beneficial to disputing parties. Additionally, the verification and validation appoach followed was also discussed.

The detialed design of ForSIM framework and algorithms used to develop ForSIM prototype are discussed in Chapter 5.

Chapter 5. ForSIM Prototype Model Development and Implementation

5.1. Chapter Introduction

Chapter 4 describes the research problem and provides conceptual design of ForSIM framework as promising solution. The architecture of the siulation model, inputs and outputs were all discussed along with high level of the simulation flow.

This Chapter describes the development of ForSIM concept proving prototype to support scenario experiments and implementations. The current implementation of the framework supports both the automated generation of as-built schedules and time claims analysis. The prototype model uses Excel for the event schedule and MS Project for the planned schedule, as well as front-end data processing through Visual C# .Net. MS Project data is manipulated and transferred automatically to the simulation using an MPJX library.

5.2. Detailed Design and Implementation of ForSIM

The implementation of the ForSIM prototype is based on a .NET framework and is written using the C# computing language. It also uses MPJX library to model project schedules (Packwood Software, 2018) as it provides a set of facilities to allow project information to be manipulated in the .Net environment. Specifically, through the use of MPJX, ForSIM supports Microsoft Project's (MPP) schedules format, which is Microsoft's proprietary way of storing the project data. The framework could also be extended for other scheduling formats.

As proof of concept, the Event's Schedule is made using Microsoft Spreadsheet. To document each project event, the attributes requied are extracted from the project contemporanous records and entered into the spreadsheet in the same order shown in Table 4-1. For fields that require multiple variables (parameters of the probability distributions, IDs of impacted activities, and names of responsible parties) the current implementation enables analysts to simply list all the variables separated by a comma(s): [,].

The author emphasizes that since the schedule of events is independent from the simulation model, it can be implemented in any other computer interpreting format (e.g. database) as deemed suitable for the project under consideration.

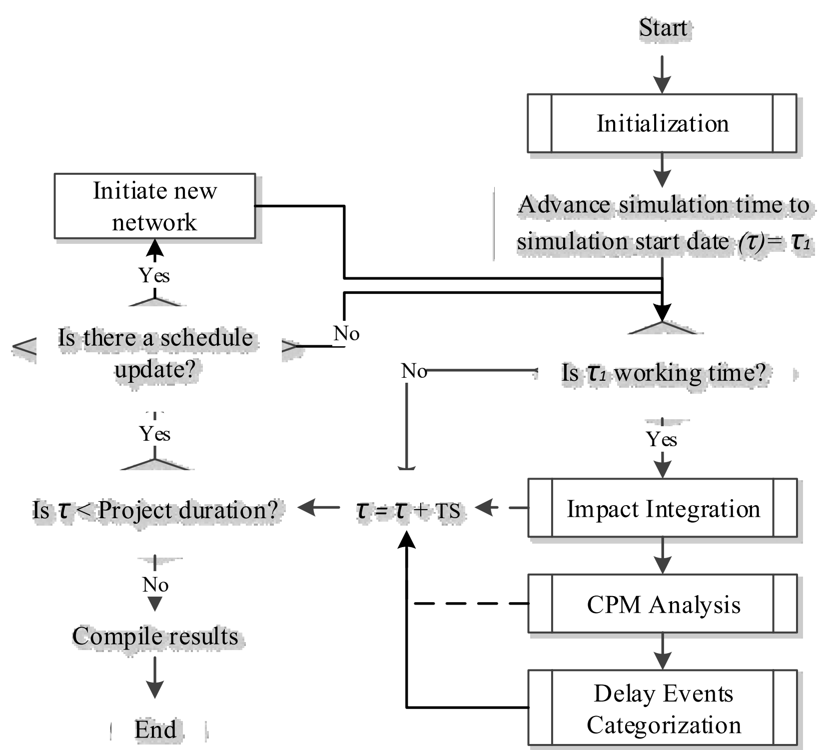


Figure 5-1: System workflow

The overall simulation architecture, as shown in Figure 5-1, is composed of four main components that include initialization, impact integration, CPM network analysis, and events categorization.

In the current implementation of ForSIM, entities are chosen to represent days as they are the most common time unit currently used by scheduling practitioners in the industry; however, the author also emphasizes that smaller time units can also be represented.

Through these constructs, each entity will have a life cycle that starts by traversing into the model, causing various changes to schedule activities, and triggering re-execution of the CPM algorithm.

5.2.1. Initialization

The initialization of ForSIM begins by declaring the claimant. The claimant is then used to set the benchmark for analyzing and categorizing liabilities of other parties involved in the project. The initialization, as shown in Figure 5-2, follows three main processes: impact quantification, network modeling, and time-step initialization and advancement.

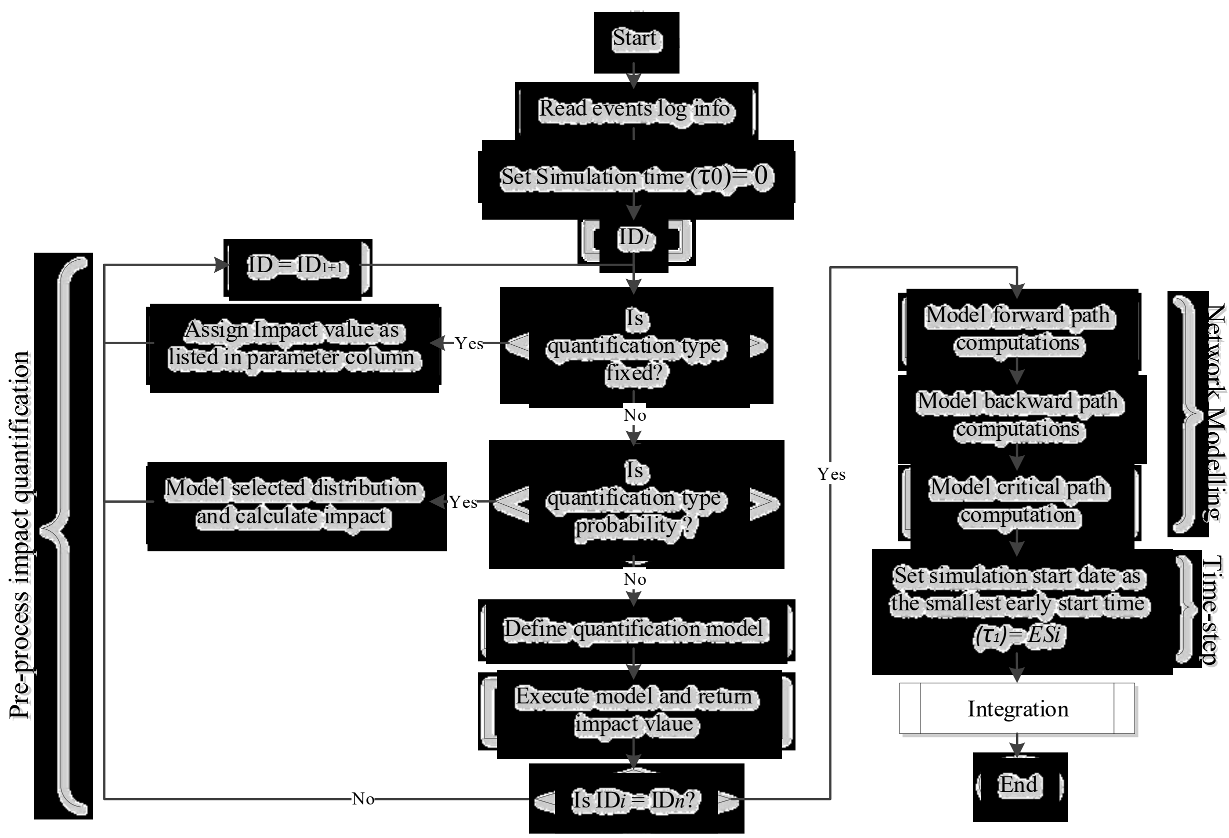


Figure 5-2: ForSIM initialization algorithm

5.2.1.1 *Impact Initialization*

As previously mentioned, ForSIM supports three ways of quantifying impact: fixed, formula and probability. The impact of events with fixed quantification type is known and their values are assigned as listed under the parameter column in the delay log, while events with formula and probability impact types require computation to determine the value of the impact.

At initialization, the impact is calculated of those events with undetermined impact values. When uncertainty exists in an impact of event (uncertain impact value), a probability distribution can be used to reflect uncertainty. Although, there are many probability distribution generators that can be used, identifying or examining the accuracy of these methods is not the focus of this research. ForSIM prototype supports a continuous uniform distribution to represent the impact where all the outcomes (in a range between a minimum and maximum impact values) are equally likely. The distribution is defined by two parameters: a and b. These parameters are the associated minimum and maximum duration of an event's impact. This scenario is usually caused by a lack of accuracy in data capturing, or inability to determine the exact impact of events. In such case, ForSIM calculates the impact value as the mean of probability distribution.

For the impacting events in which their quantification is expressed as formula, the ForSIM enables the claim analyst to set up the impact quantification formula through a user interface. The framework leaves the choice of the quantification model to the analyst's discretion by enabling the analyst to express the model mathematically. From delays analysis perspective, it is recommended to use higher-level factors as they can easily be identified and linked to responsible parties. Low-level factors do not necessarily prove one party is responsible for the event, as it may be that these factors are themselves not the cause of the event, but rather the consequence of higher-level factors. For instance, congestion reduces productivity. Congestion, however, can be caused by several different triggers like poor coordination, concurrent operations, and overmanning. Once the analyst defines a model that best reflects the impact of each unique event, the simulation then computes the impact and returns its value for each event based on the configuration set by the analyst.

5.2.1.2 Network Modelling

ForSIM relies on basic CPM principles, which include modeling precedence relationships, leads and lags, calendars, both forward and backward passes, computation through the schedule network, and critical path identification.

At compile time (τ0), the MPJX library is used to read the attributes of the project activities, including: task ID, name, duration, precedence relationships, as well as leads and lags which their values are all stored in dictionaries. The precedence relationships between the activities are modeled by an integer matrix, shown in Figure 5-3, whose row and column indices indicate the set of the project activities (elements of *X* and *Y)*.

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}$$

Figure 5-3: Integer relationship matrix

This relationship matrix is used to programmatically model the forward and backward passes calculations as per the formulas described in Section 2.2 of this thesis. Upon initiation, these calculations are executed to identify the critical path and set the benchmark of the project timelines accordingly. The calculation results should match the timelines of the project baseline.

5.2.1.3 Time-step Initialization

The simulator component is responsible for controlling the simulation execution, creating the simulation environment, extracting relative activities and their logic based on a pre-defined time-step, integrating delays occurring during that time step into the schedule, and lastly analyzing the data and providing results.

At time zero ($\tau0=0$), the starting simulation date is set as the earliest start time (ES_i) of the first activity in the project. The simulated date will be incremented as per the entity span size throughout the simulation of the entire schedule. As it has been noted in previous research, using large time-steps results in fast, but inaccurate/unstable, simulations. Small time-steps lead to more precise simulations, take more time. ForSIM prototype is developed using an entity instance of one day as prof of concept, however, the author emphasis that a smaller time-step can be modeled.

5.2.2. Impact Integration

Impact integration is the process of updating project activities to reflect the impact of occurring events and, subsequently, investigating whether they had positive or negative impacts on the overall schedule. The integration process starts by advancing the simulation time from day zero ($\tau0$) into the starting simulation date ($\tau1$).

At τ_1, the simulation explores the SoE to see if any active events (occurring at the date being simulated) take place during this time interval through a next-event (or event-to-event) model. When an active event is identified, the simulation updates the duration of impacted activities according to the type of the impact and its quantified value. For events with a global impact type, durations of all active activities (ongoing activities under simulation) are updated according to the quantified impact. For events with a task-specific impact type, only the impacted activities associated with the event are treated as ACTIVE activities. Their durations are updated accordingly. Thereafter, the simulation advances to the next active event, and follows the same updating process. Thus, it shifts from one event to the next until the last ACTIVE event. All active events that take place during that interval are treated as if they occurred simultaneously, and the duration of impacted activities is updated accordingly. It is important to note that activities' durations are only updated to a maximum of the entity span. The update could either be positive or negative. Figure 5-4 shows the proposed algorithm for impact integration.

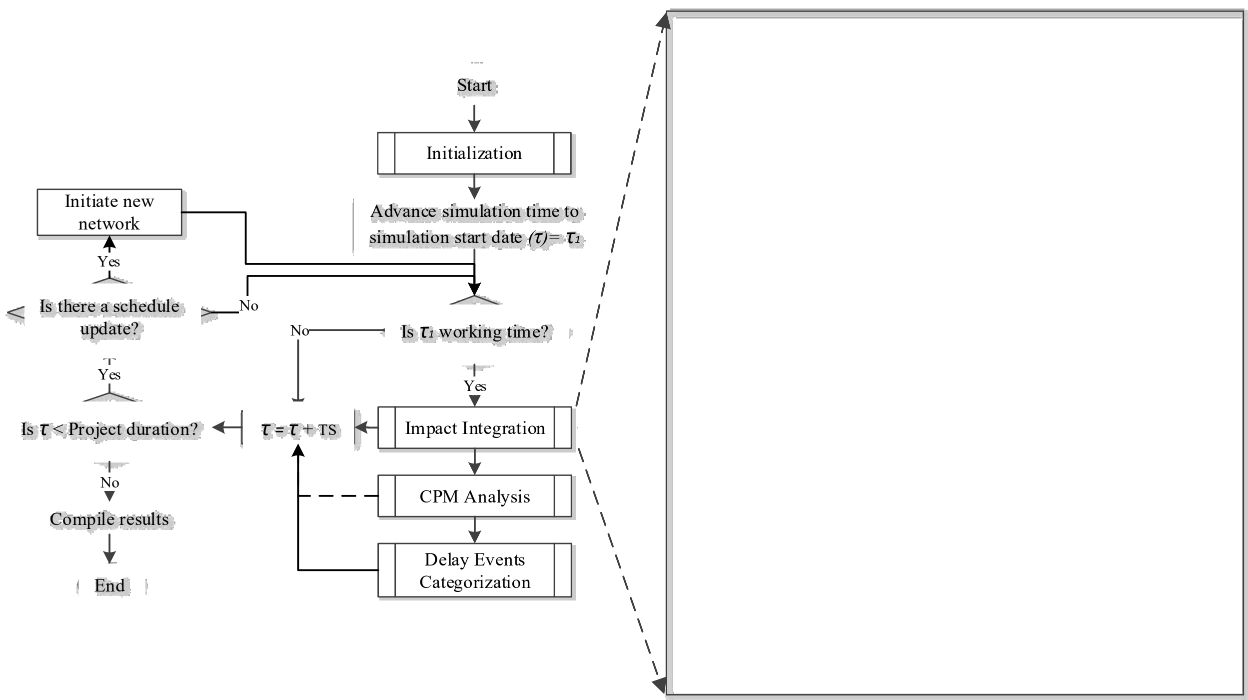


Figure 5-4: ForSIM impact integration

5.2.3. Network Criticality Analysis and Events Categorization

Once all active events' impacts at an entity instance are applied, the CPM is executed to identify the project's critical path and to analyze the impact of changes, if any, on the overall project schedule. If there are no changes to the project duration when compared to the calculation of the previous entity instance, ACTIVE events are labelled as non-impacting events. However, if there are changes to the project duration, each active event will be labelled as either a delay or acceleration; moreover, liability counters will be initiated for every unique responsible party. A delay refers to the situation where there is in increase in the project duration while acceleration refers to the situation where the project duration is decreased. Illustration of the proposed process is shown in Figure 5-5.

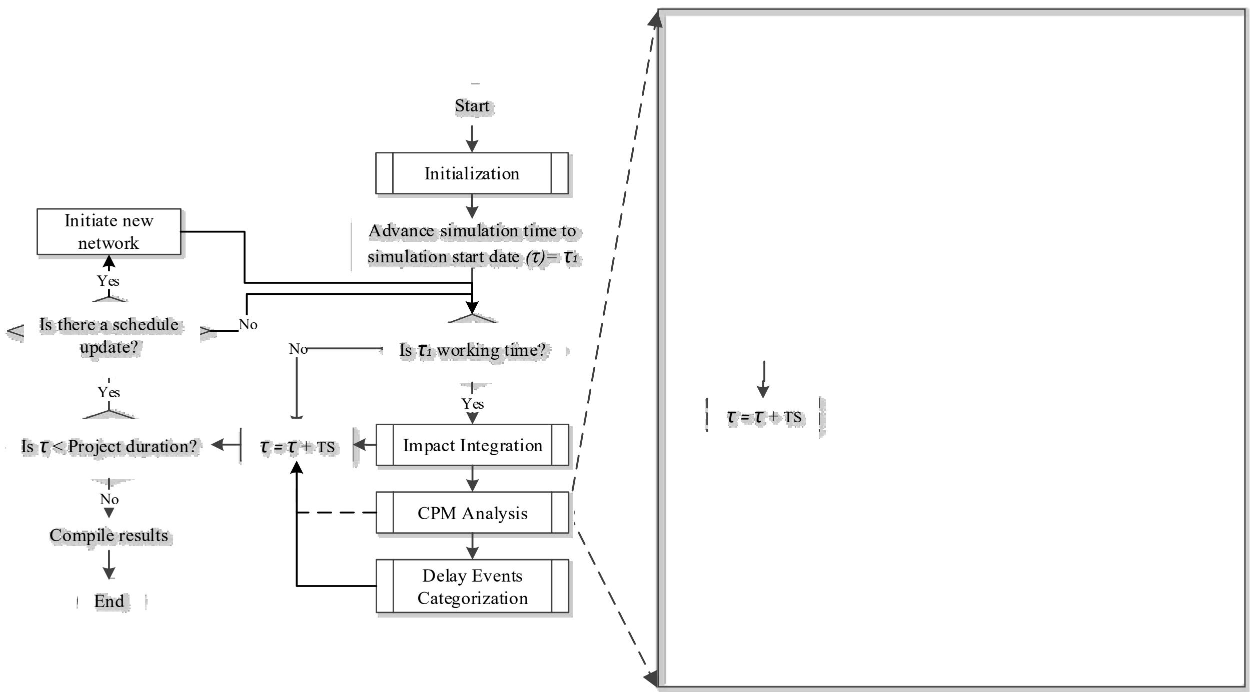


Figure 5-5: ForSIM Network Criticality Analysis

Temporary liability counters are initiated for responsible parties associated with any of the delay events. By using the claimant declared at the initialization of the simulation model as the benchmark, delay events are checked then against three scenarios. First, if the claimant was not listed as the responsible party of an event, then the event will be categorized as excusable and compensable. Second, if there were multiple parties responsible for an event and the claimant was one of them, then it will be categorized as excusable but not compensable. In such a case, the framework assumes equally shared responsibility between responsible parties associated with the event. Lastly, if the claimant was the solely responsible party of an event, then the event will be categorized as not excusable. This categorization process continues for all delay events; however, it is important to note that liability is allocated to a maximum of the entity span. Figure 5-6 shows ForSIM categorization process of delay events.

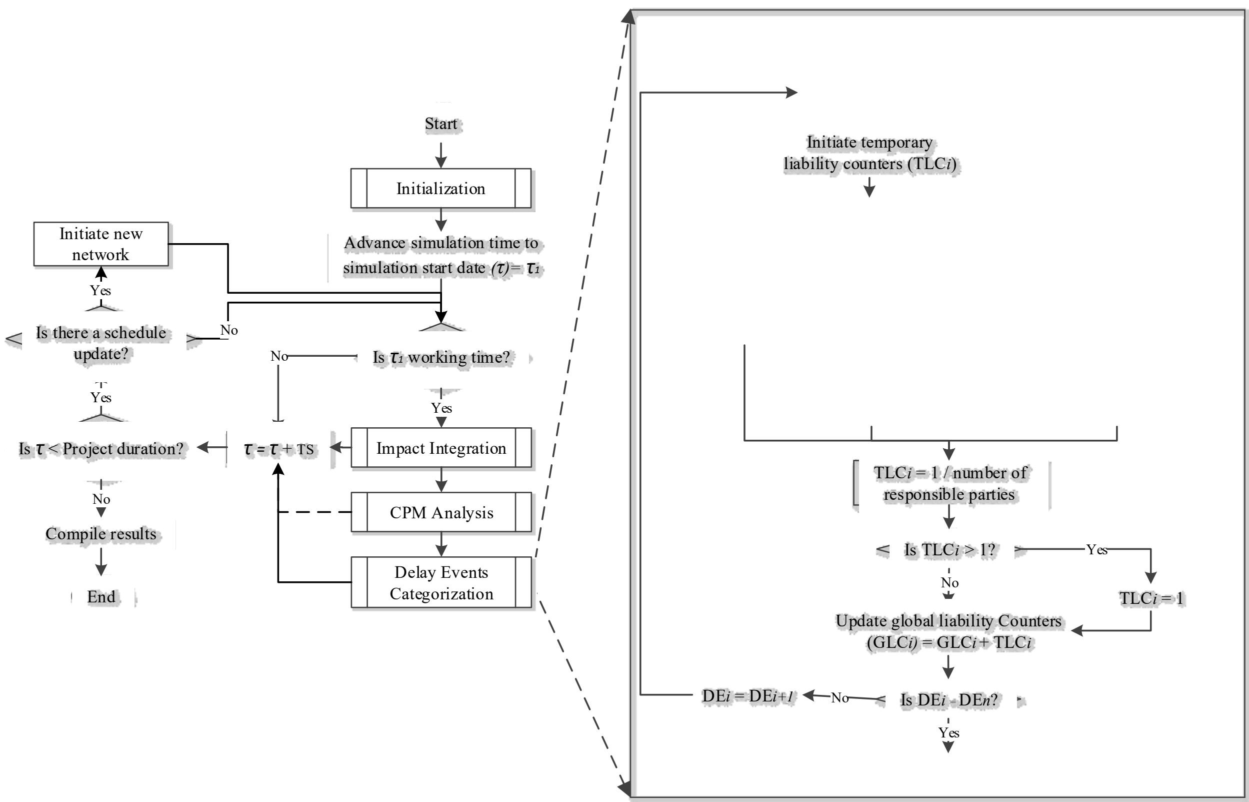


Figure 5-6: ForSIM delay events categorization algorithm

The integration process continues by incrementing the simulation time to the next time step and repeating the impact integration, criticality analysis, and event categorization processes at every time interval. Finally, the simulation is terminated when the simulated date is beyond the end of the last impacting event.

5.2.4. Outputs

The last stage in the entity lifecycle is the compiler responsible for capturing the information recorded in each EIM, for compiling the results of the CPM, and for identifying the critical path at every interval. Once the simulation is complete, the compiler uses this information to generate the as-built schedule, which is a result of incorporating all of the impacting events into the durations of the base schedule's activities. The planned and simulated timelines for each activity are recorded along with the history of the evolved events relevant to the activity. Then, a comparison is visualized of the as-built records and planned schedule of critical activities in a graphical and statistical fashion. The compiler also traces the liabilities of all responsible parties listed in the schedule of events a long with cauastion of each event as per their criticality to the project schedule.

Lastly, these detailed algorithms were translated into a prototype model that made up the envisaged design. ForSIM was then tested with hypothetical cases as well as real-life projects, as shown in Chapter 6. To verify its results and demonstrate its merit, simulation features such as events-trace will be used to confirm that the logical sequence of events matched the intended sequence.

5.3. ForSIM Prototype Limitations

It is important to note that ForSIM prototype is developed as a proof of concept. The developed prototype has some limitations that can be summarized as follows:

- The developed prototype is based on a spreadsheet for the event schedule and MS Project for schedules. Future implementation could be based on more user-friendly interface of the events schedule. Moreover, to support large projects, a database could be developed and used to document events attributes in more efficient manner. The prototype could also be expanded to support different project schedules formats such as Primavera.

- The prototype only supports uniform distribution for modeling uncertainty of events' timelines, and for simplicity, it uses the mean as representation of the event duration. Future implementation should include other probability distributions and further investigation on which quantiles to be used for representing uncertainty of events' duration
- The developed prototype currently supports schedules with one calendar due to technical difficulties with MPJX library. Although this is an implementation limitation that can easily be addressed in the future, it is important to note that it might impact the analysis result.
- The prototype does not model resource constraints on activities progress. Previous research highlighted the dynamic availability of resources might impact delay analysis conclusions. Therefore, future research should focus on integrating resource constraints and the dynamics of their availability in flexible time units and quantifying their impact on the project schedule
- As noted in this research, the impact of productivity on schedules is noted in this study to provide an emphasis on causation. As ForSIM enables analysts to model different productivity factors, quantify their impact using mathematical models and integrate their quantified impact on project schedules, the selection of the mathematical models is left at the analysts discretion. To avoid over-quantification of impact, the analyst should investigate the interrelationships and dependencies between the factors in consideration when analyzing the impact of events related to productivity lose.

5.4. Summary and Conclusions

This chapter provides detailed description of ForSIM design and implementation by transforming the conceptual design into algorithms. Each of the simulation constructs was described separately as per the simulation flow from initialization and impact integration to analysis and results compilations. This chapter also discusses the simplifications made in the course of developing the prototype of ForSIM prototype. Most of these manifested as limitations in the capabilities of ForSIM prototype and served as basis for future implementations and recommendation for further research.

The findings of the trial runs for the ForSIM prototype, and their integration into real construction projects are discussed in Chapter 6.

Chapter 6. Application of ForSIM for As-Built Schedules Development and Time Claims Analysis

6.1. Chapter Introduction

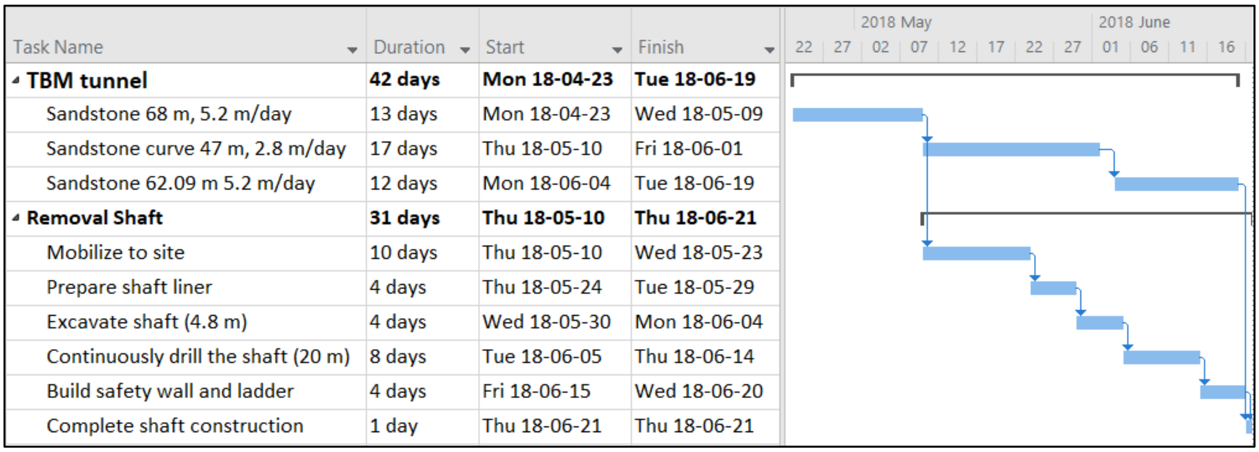
Chapters 4 and 5 present the conceptual and detailed design of ForSIM framework. In order to evaluate whether ForSIM would work effectively, it was necessary to test and validate ForSIM prototype. The evaluation comprised trial runs in two real life case studies, the results of which were discussed, analyzed, validated and are commented upon on this chapter. The first case study is used to demonstrate ForSIM's capabilities in developing as-built schedule of a tunneling segment and the second case study is used to test ForSIM on a time claim scenario. For reasons of confidentiality, the names of parties involved in these case studies and the actual project context of the claim scenario are not identified in this thesis.

This chapter also includes discussion of two simple hypothetical case studies to demonstrate inaccuracies in the other delay analysis techniques.

6.2. Automated Development and Analysis of As-Built Schedules Using ForSIM – A Case Study

To verify the framework functionality, the prototype model has been applied to a number of hypothetical case studies with various scheduling scenarios. Initial results have shown that the framework has several benefits due to the added features for as-built schedules. To demonstrate the observed benefits, the prototype has been applied to a segment of a real-life tunneling project.

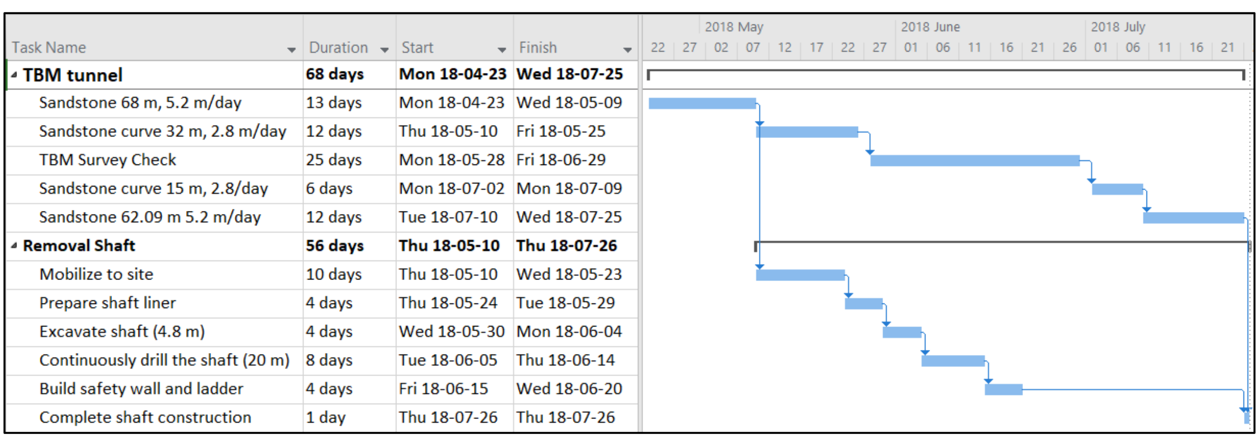
The segment includes the excavation of a 162-meter tunnel using a tunnel boring machine (TBM) and construction of a removal shaft. This segment was expected to be completed over 44 working days (59 days including weekends). The breakdown of activities involved in this segment and their estimated durations were defined in MS Project, as shown in Figure 6-1.



Task Name	Duration	Start	Finish
TBM tunnel	**42 days**	**Mon 18-04-23**	**Tue 18-06-19**
Sandstone 68 m, 5.2 m/day	13 days	Mon 18-04-23	Wed 18-05-09
Sandstone curve 47 m, 2.8 m/day	17 days	Thu 18-05-10	Fri 18-06-01
Sandstone 62.09 m 5.2 m/day	12 days	Mon 18-06-04	Tue 18-06-19
Removal Shaft	**31 days**	**Thu 18-05-10**	**Thu 18-06-21**
Mobilize to site	10 days	Thu 18-05-10	Wed 18-05-23
Prepare shaft liner	4 days	Thu 18-05-24	Tue 18-05-29
Excavate shaft (4.8 m)	4 days	Wed 18-05-30	Mon 18-06-04
Continuously drill the shaft (20 m)	8 days	Tue 18-06-05	Thu 18-06-14
Build safety wall and ladder	4 days	Fri 18-06-15	Wed 18-06-20
Complete shaft construction	1 day	Thu 18-06-21	Thu 18-06-21

Figure 6-1: Planned schedule of the tunneling segment

Another project schedule, as shown in Figure 6-2, was later provided by the contractor to accommodate a TBM alignment check that took 25 days and was accepted by the owner as contemporaneous evidence providing as-built information for evaluating schedule delay and changes in the critical path.



Task Name	Duration	Start	Finish
TBM tunnel	**68 days**	**Mon 18-04-23**	**Wed 18-07-25**
Sandstone 68 m, 5.2 m/day	13 days	Mon 18-04-23	Wed 18-05-09
Sandstone curve 32 m, 2.8 m/day	12 days	Thu 18-05-10	Fri 18-05-25
TBM Survey Check	25 days	Mon 18-05-28	Fri 18-06-29
Sandstone curve 15 m, 2.8/day	6 days	Mon 18-07-02	Mon 18-07-09
Sandstone 62.09 m 5.2 m/day	12 days	Tue 18-07-10	Wed 18-07-25
Removal Shaft	**56 days**	**Thu 18-05-10**	**Thu 18-07-26**
Mobilize to site	10 days	Thu 18-05-10	Wed 18-05-23
Prepare shaft liner	4 days	Thu 18-05-24	Tue 18-05-29
Excavate shaft (4.8 m)	4 days	Wed 18-05-30	Mon 18-06-04
Continuously drill the shaft (20 m)	8 days	Tue 18-06-05	Thu 18-06-14
Build safety wall and ladder	4 days	Fri 18-06-15	Wed 18-06-20
Complete shaft construction	1 day	Thu 18-07-26	Thu 18-07-26

Figure 6-2: Updated schedule of the tunneling segment

Ideally, as-built schedules will have been prepared and maintained prospectively during project execution as it is often easier to compile contemporaneous records when progress can be physically verified. In the absence of contemporaneous as-built schedule, the primary sources of contemporaneous records required to retrospectively construct an as-built schedule include, but are not limited to, monthly reports, subcontractor reports, meeting minutes, valuations/application for payment/invoices, site diaries, photographs, etc. The level of detail required for an as-built schedule depends on the level of detail of the baseline/planned schedule and the purpose of the analysis. Once the as-built data have been collected, they are typically represented in a spreadsheet to show the start and finish dates of each activity, including activities that are included on the as-planned schedule and those added subsequently. Sources of documentary evidence which identify start and finish dates, and/or the duration of activities should also be properly recorded to provide an audit trail of the data relied on to prepare the contemporaneous record. Once this data is compiled, it is usually imported into project planning software and integrated with the as-planned schedule to provide a better understanding of project performance.

6.2.1. Automated Development of As-Built Schedule

To develop the as-built schedule for the case study, ForSIM relied on daily progress reports and monthly progress reports that were available from the project. These contemporaneous records were organized and sorted as per the format and attributes of SoE. This process helps with organizing the scattered project information, and subsequently, enables the automatic development of as-built schedules at any time; prospectively and/or retrospectively. The framework, then, automatically integrates the contemporaneous records with the preliminary schedule that was developed by the contractor at the start of the project as per the data integration algorithms discussed in Sections 4.3.3.4 and 5.2.2. In modelling the project schedule and logic changes, the framework also considers the updated schedule that was issued at a later date to accommodate the alignment check on the TBM. As the simulation progress and once a schedule update became avalabile, the schedule netwrok, activities durations and schedule constraints are updated as per the schedule update while preserving analysis results.

The system flow to generate the as-built schedule for the project can be explained in five steps. The user executes ForSIM, and once the graphical user interface (GUI) opens as illustrated in Figure 6-3, the user sets the total float value that is to be used as criterion for identifying critical activities (1). The user also chooses the event schedule file in .xlsx format (2) and the planned schedule for the project in .mpp format (3). In the case where schedule updates are available, the user can choose all the schedules at once, and a pop-up window opens in which to specify the dates on which each schedule was made available (4). Then, by clicking the run button (5), the proposed system automatically executes the simulation model, integrates events into the schedule, updates the activity timelines (start and finish dates), records impacting events for each activity and identifies critical activities for the whole project, including both completed activities and activities remaining. After the process is complete, all this information is compiled and presented in a statistical and graphical fashion using a GUI.

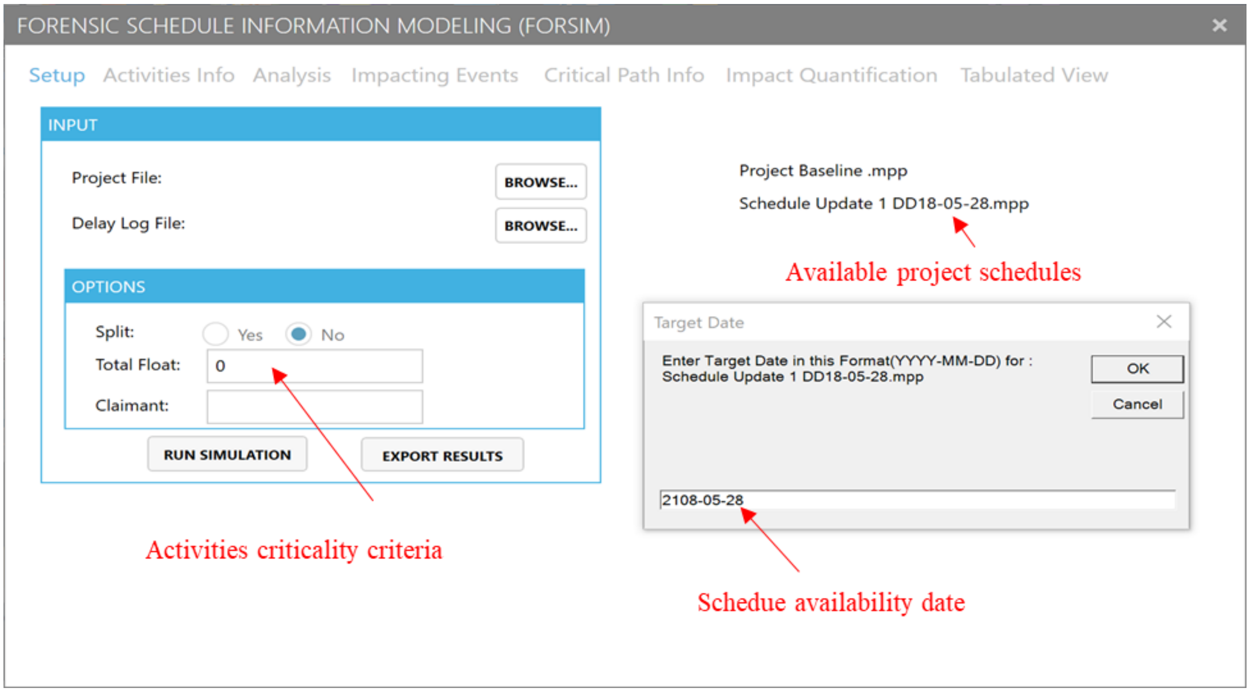


Figure 6-3: Start page on GUI of proposed framework

The activities information window provides a tabular view of the project activities on the left and the information associated with a selected activity on the right (Figure 6-4). The predecessor and successor tabs on the bottom right show the active relationships driving the calculation, while the impacting event tab shows the events that have impacted the activity, if any. As can be noted from Figure 6-4, tunnelling through the first 68m of sandstone was impacted by three events which resulted in a five-day increase to the planned duration.

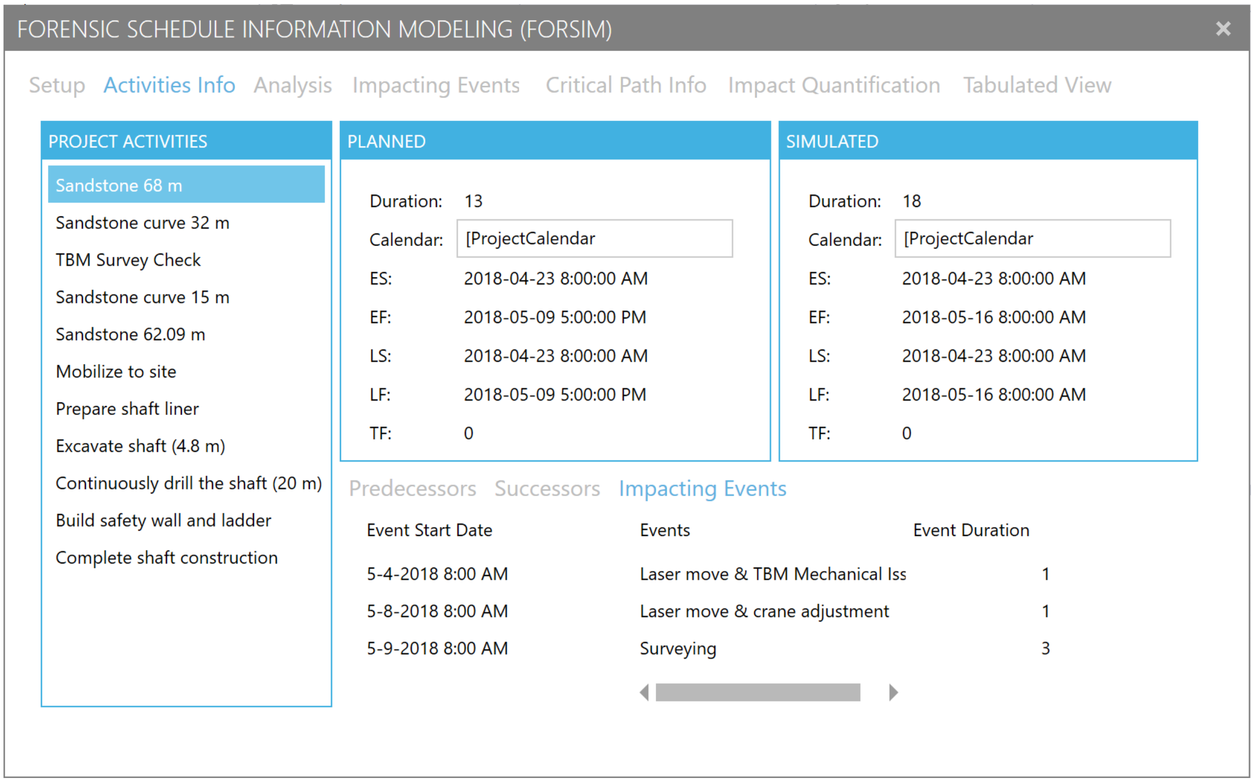


Figure 6-4: Simulated activities information for the tunneling segment

6.2.2. Delay Analysis Facilitation

One of the main objectives when analyzing delay claims is establishing a factual matrix and a precise chronology of events that impacted the project activities, and subsequently, the overall project schedule. A review of the as-built schedule provides an overall view of the delays to the project from the planned start date to the finish date. To analyze the activities of the as-built schedule, it is important to identify the critical activities that drive the schedule. However, critical activities on the past portion of the date on which the schedule status is being reported (data date) cannot be identified through the use of conventional scheduling tools, consequently, the critical activities of an as-built schedule are called controlling activities and are identified either through the baseline schedule or schedule updates. In the absence of schedule updates, the identification of controlling activities becomes a subjective process that is based on the opinion of the project participants. To overcome this problem, ForSIM is capable of CPM functionality and demonstrating critical activities of completed work.

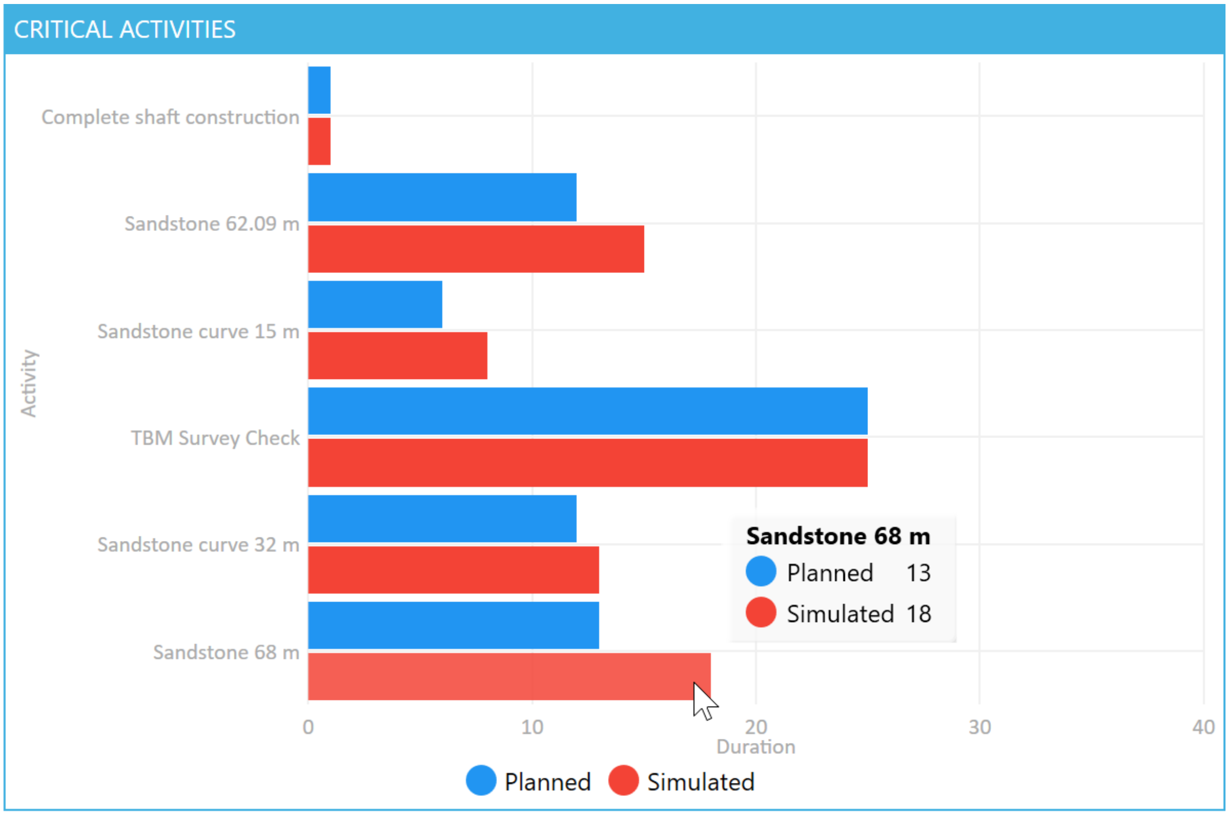


Figure 6-5: Illustration of the critical activities of the tunneling segement

The Critical Path Info window, as shown in Figure 6-5, illustrates bar charts for the critical activities at the time of analysis. For each activity, the planned duration and simulated duration are plotted with blue and red bars, respectively. Details of the planned duration and simulated duration of an activity can be observed by hovering a cursor over the desired activity bars. This helps analysts identify and isolate critical activities with large delays and allows for more focused delay analysis.

One form of analysis is based on an as-planned versus as-built schedule delay analysis method. It is a retrospective approach used to compare the baseline, or as-planned, construction schedule against the as-built schedule. The as-built schedule reflects the progress of all activities and milestones throughout the project and provides verification of the driving activities that make up the critical path of the schedule. ForSIM facilitates as-built vs. as-planned analysis by automatically providing activity information (e.g. planned and actual date) along with a detailed documentation of events that impacted activity progress, in one way or another.

Some of the other observed benefits of the proposed approach to the as-built schedule development include:

- ***The method takes into account the uncertainty of event timelines***. Previous studies show that the data capturing process is subject to inaccuracies that usually result from human factors (e.g. work load, experience, fatigue, etc.), the unavailability of contemporaneous records and conflicting information regarding the progress of an activity due to inaccuracies and inconsistencies between the contemporaneous records available for a project. More specifically, in the case of this case study, some daily site reports were not available. This was mainly due to the fact that some reports were never sent, or, in some instances, the wrong reports were sent (for instance, the report of the previous date was sent as second time, resulting in duplicate reports). This negligence resulted in uncertainty with the timelines used when developing the event schedule. In these cases, the proposed framework, as it is based on simulation technologies, enables the use of distributions to model the uncertainties associated with the timelines: for this case study, uniform distributions were used.
- ***The method limits the level of scheduling skills required for the development of as-built schedules.*** Developing realistic as-built schedules requires experienced schedulers to review project documentation and establish the activity execution sequence. The current system

eliminates this subjective process and in contrast helps inexperienced schedulers to have a better understanding of projects;

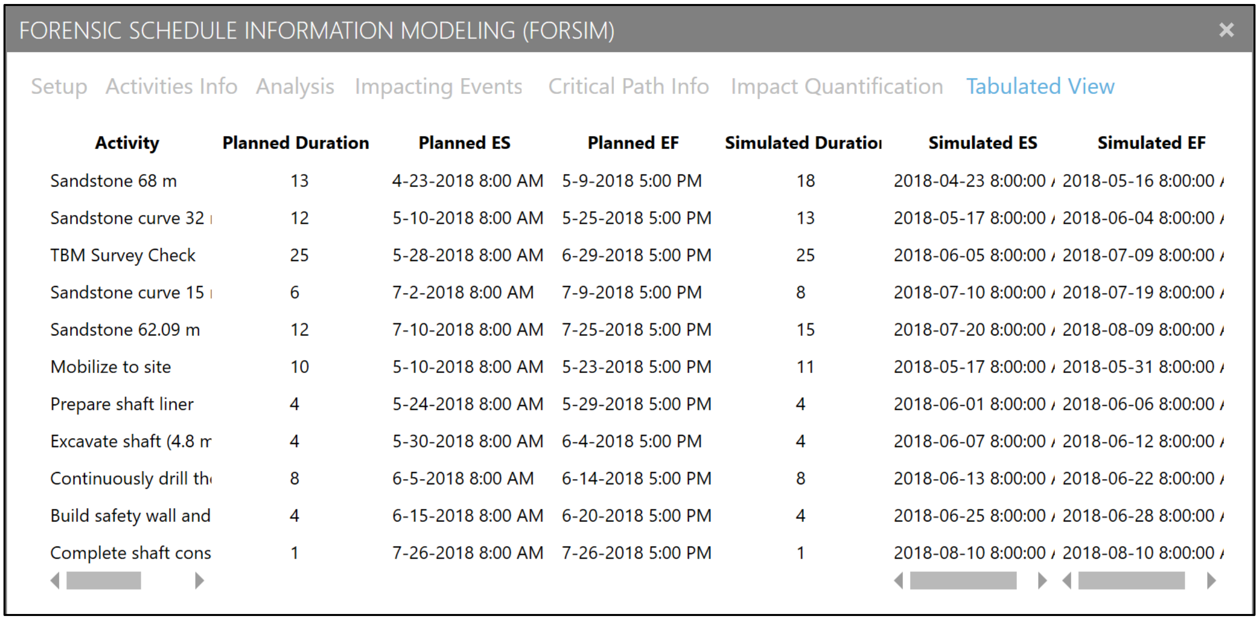
- ***The proposed method limits the need for balancing between purpose of analysis and as-built schedule preparation cost***. Typically, delay analysts are constrained by the need to strike a balance between the objective of the analysis and the cost of preparing an as-built schedule. For instance, in the case of retrospective delay analysis, the time required to identify the start and finish dates for all activities on a large schedule is disproportionate in terms of the cost and time required, especially when delay events impacted a small portion of the activities. Practically, therefore, analysts compromise by collapsing activities that are pertinent to the analysis process into a single activity or bar when illustrating as-built schedules. When such a balance is made, analysts are required to demonstrate that the omission of identifying actual dates of non-critical work was not intentional to avoid contradictory or negative evidence that does not support the conclusion of the analysis. On the contrary, the proposed framework eliminates the need of this subjective and judgmental balancing process by enabling analysts to focus on identifying the actual dates of events that might have impacted the project schedule rather than wasting the effort on identification of actual dates for all activities. Similarly, this approach eliminates the difficulties of identifying conclusive start and finish dates for activities. This assures higher accuracy of the as-built schedule and enables a more focused analysis process.
- ***The proposed method offers an objective approach to as-built development:*** Traditionally, as-built schedules are created either from scratch or a fully progressed schedule update and then modified or augmented as needed. Both approaches require analyst interaction with the schedule, which makes the development process subjective and easily to manipulate. To this

end, the proposed framework eliminates any interaction with the schedule by fully progressing the planned / baseline schedule with contemporaneous records while simultaneously modelling the dynamics of schedule changes.

The proposed modelling approach would potentially enable other forms of delay analysis. More specifically, future research will address current problematic areas related to window-based delay analysis techniques currently used in industry and improve the overall analysis process.

6.2.3. Results Verification and Validation

To validat ForSIM's results, as discussed in Section 4.4.4, a comparison between the simulated planned dates with those on the baseline schedule and schedule update can be drawn. The tabulated view window in ForSIM, as shown in Figure 6-6, provides a tabular view of tunneling segement activities, reflecting both the simulated project plans and as-built records. As it can be noticed, the planned timelines of the "Sandstome 68 m" activity as well as as the planned early start date of "Sandstone curve 32 m" activity are matching with those indicated in the baseline schedule (Figure 6-1) mainly because the simulation model was initialy based on the baseline schedule. Once the schedule update became availabe, ForSIM updated the network model to reflect schedule changes (TBM alignement check). Consequently, it can be noticed that the planned timelines of remaining activities are matching with those indicated in the updated schedule (Figure 6-2).


FORENSIC SCHEDULE INFORMATION MODELING (FORSIM)

Setup Activities Info Analysis Impacting Events Critical Path Info Impact Quantification Tabulated View

Activity	Planned Duration	Planned ES	Planned EF	Simulated Duratio	Simulated ES	Simulated EF
Sandstone 68 m	13	4-23-2018 8:00 AM	5-9-2018 5:00 PM	18	2018-04-23 8:00:00	2018-05-16 8:00:00
Sandstone curve 32	12	5-10-2018 8:00 AM	5-25-2018 5:00 PM	13	2018-05-17 8:00:00	2018-06-04 8:00:00
TBM Survey Check	25	5-28-2018 8:00 AM	6-29-2018 5:00 PM	25	2018-06-05 8:00:00	2018-07-09 8:00:00
Sandstone curve 15	6	7-2-2018 8:00 AM	7-9-2018 5:00 PM	8	2018-07-10 8:00:00	2018-07-19 8:00:00
Sandstone 62.09 m	12	7-10-2018 8:00 AM	7-25-2018 5:00 PM	15	2018-07-20 8:00:00	2018-08-09 8:00:00
Mobilize to site	10	5-10-2018 8:00 AM	5-23-2018 5:00 PM	11	2018-05-17 8:00:00	2018-05-31 8:00:00
Prepare shaft liner	4	5-24-2018 8:00 AM	5-29-2018 5:00 PM	4	2018-06-01 8:00:00	2018-06-06 8:00:00
Excavate shaft (4.8 m	4	5-30-2018 8:00 AM	6-4-2018 5:00 PM	4	2018-06-07 8:00:00	2018-06-12 8:00:00
Continuously drill th	8	6-5-2018 8:00 AM	6-14-2018 5:00 PM	8	2018-06-13 8:00:00	2018-06-22 8:00:00
Build safety wall and	4	6-15-2018 8:00 AM	6-20-2018 5:00 PM	4	2018-06-25 8:00:00	2018-06-28 8:00:00
Complete shaft cons	1	7-26-2018 8:00 AM	7-26-2018 5:00 PM	1	2018-08-10 8:00:00	2018-08-10 8:00:00

Figure 6-6: Tabulated view of simulated activities information

Moreover, the simulated as-built timelines can be validate at activities level by comparing events information with simulated timelines. For instance, the “Sandstome 68 m” activity, as shown in Figure 6-4, was impacted by three events that contributed to total of 5 days of delay to its planned completion date. It is also noticable that the durations of unimpacted activites remain unchanged while the start and finish timelines were automatically updated based on the modeled CPM calcuation. These comparisons show that ForSIM can successfully generate as-builts schedules. It also provides schedules analyst with information needed for better understanding of projects execution. It is important to note that ForSIM is currently limited to one calendar per schedule due to technical difficulties with the MPJX library which can easily be addressed in future implementation of ForSIM.

6.3. Time Claims Analysis Using ForSIM – A Case Study

In order to assess the effectiveness of ForSIM, the prototype was tested on an abstract scenario drawn from an actual case study. For reasons of confidentiality the actual project context, names of disputing parties and all other bodies involved in the project will not be identified in this thesis.

The results of the trial run were analyzed, evaluated, and discussed, along with a description of the process and controls employed. It should be noted that while ForSIM may be used both prospectively and retrospectively, throughout the trial run it was solely used for retrospective analysis to identify the causes of a contract period overrun, quantify their impact and allocate liability in compliance with research objectives.

The construction project involved the design-build construction of a distribution facility, with an additional storage facility. The scope of work was broken down into two contracts, accordingly, the owner (the "Owner") entered into a contract with a civil and structures contractor (the "Civil and Structures Contractor") and another contract with a systems contractor (the "Systems Contractor"). The project was planned with one year of construction. Unfortunately, the project did not progress as either of the parties expected, as it experienced about two months of delay. The Systems Contractor submitted a claim attributing the delay to numerous actions by the Owner, which can be summarized as follows:

- *Delays attributed to site access*: The contract set forth specific milestone dates for the Civil and Structures Contractor to achieve certain construction objectives. The Contractor was supposed to finish work on the storage facility by the end of July 2019 and then hand over the site to the Systems Contractor to perform his work, however, the Contractor failed to complete the work and hand over the site as per the milestone set by the contract.

- *Delays attributed to the design review process*: The design process consisted of two packages; a civil and structures design and systems design. Each of these packages included a three-stage review process, 60%, 90% and 100% final design submissions. The review process focused on general conformance with contract requirements, and was conducted through a structured framework of workshops, review periods of three weeks for each submittal, and acceptance and closeout process. As is typical in projects, the 60% design requirements called for a high-level overview of the conceptual and provisional design. The documents would become more detailed as the 90% and 100% final design review phases progressed. The Systems Contractor alleged that the Owner's actions, including setting different expectations for the design level of details, failure in administrating the review process and late submission of design comments, were the causes of the delays.
- *Delays attributed to scope changes*: During the course of the project, the Owner decided to expand the size of the storage facility, which necessitated additional expansion to the storage facility. The Systems Contractor alleged that this scope increase impacted the design and procurement process.

The Civil and Structures Contractor also alleged that severe winter weather conditions caused productivity loss for the testing and commissioning activities.

The Owner submitted a counterclaim for liquidated damages, alleging that the reasons for the delay and additional costs incurred by the Owner were mainly attributable to management and coordination issues caused by the Systems Contractor. The Owner noted that management and coordination of resources and subcontractors, frequent changes to key personnel, inexperienced workers and poor performance were key reasons for the delay.

6.3.1. Analysis and Results

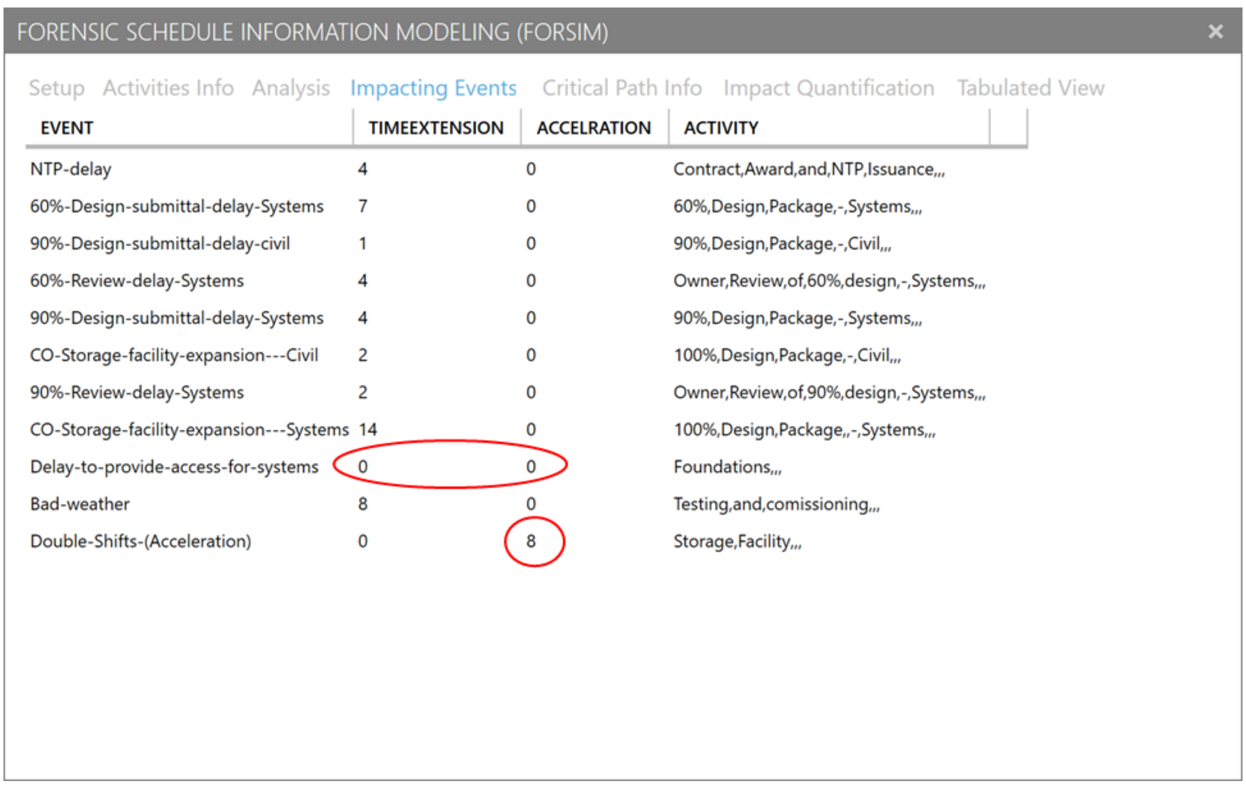
As previously noted, ForSIM requires the development of the SoE, therefore, the initial analysis focused on identifying events that were relevant to the points of dispute.

There was only one project schedule available for the analysis. Therefore, the analysis relied on the baseline schedule, contemporaneous records and project contracts to identify delays attributed to the design, all of which were used to progress the baseline schedule accordingly. Delays attributed to the Systems Contractor were identified by using design duration as specified in the baseline schedule as a benchmark, and then, in the absence of an as-built schedule, contemporaneous records were used to identify delays to the design activities beyond the timelines set in the baseline schedule. A similar approach was used to identify delays that were attributed to the Owner for the time spent on the design review process beyond the three-week period set in the project contract, delays attributed to contractor performance, and delays that were beyond the control of any of the parties involved in the project. As shown in Table 6-1, events that are relevant to the dispute were extracted and recorded in the format used by ForSIM.

Table 6-1: Extracted events relevant to the case study

Event	Responsible Party	Start Date	Modeled duration (days)
Delay in issuing Notice to Proceed (NTP)	Owner	2019-01-01	5
Delay in submitting 60% Systems design package	Systems Contractor	2019-03-18	20
Delay in submitting 90% Civil design package	Civil Contractor	2019-04-08	10
Delay in providing comments on the 60% Systems design package	Owner	2019-04-29	(5, 6) Uniform
Delay in submitting 90% systems design package	Systems Contractor	2019-05-21	5
Change Order (CO) for storage facility expansion – Civil design update. The CO granted an extra 14 days for the 100% design submission.	Owner	2019-05-21	14
Delay in providing comments on the 90% Systems design package	Owner	2019-06-18	4
Change Order (CO) for storage facility expansion – System design update. The CO granted an extra 20 days for the 100% design submission.	Owner	2019-08-01	20
Delay in providing access for systems installation	Civil Contractor	2019-08-27	10
Accelerating storage facility construction by working two shifts	Owner, Civil and Structures Contractor	2019-12-15	10
Severe winter weather condition	Weather	2020-01-15	Formula

Figure 6-7 shows a breakdown of the impact of each of the events on the project schedule. As can be noted from the figure, ForSIM distinguishes between two types of impact: time extension and acceleration. The impact of each event was incrementally traced according to its criticality for the schedule. At every entity instance (time step), ForSIM examines the impact of events, if found, on the critical path of the schedule. A negative impact is reflected as a time extension, while a positive impact is reflected as an acceleration. Through this detailed breakdown of events, ForSIM can be used as a new project control mechanism to demonstrate the schedule impact at the events level, which can be used to analyze and verify contractor performance during the project.



EVENT	TIMEEXTENSION	ACCELRATION	ACTIVITY
NTP-delay	4	0	Contract,Award,and,NTP,Issuance,,,
60%-Design-submittal-delay-Systems	7	0	60%,Design,Package,-,Systems,,,
90%-Design-submittal-delay-civil	1	0	90%,Design,Package,-,Civil,,,
60%-Review-delay-Systems	4	0	Owner,Review,of,60%,design,-,Systems,,,
90%-Design-submittal-delay-Systems	4	0	90%,Design,Package,-,Systems,,,
CO-Storage-facility-expansion---Civil	2	0	100%,Design,Package,-,Civil,,,
90%-Review-delay-Systems	2	0	Owner,Review,of,90%,design,-,Systems,,,
CO-Storage-facility-expansion---Systems	14	0	100%,Design,Package,,-,Systems,,,
Delay-to-provide-access-for-systems	0	0	Foundations,,,
Bad-weather	8	0	Testing,and,comissioning,,,
Double-Shifts-(Acceleration)	0	8	Storage,Facility,,,

Figure 6-7: Breakdown of event impacts

The events breakdown shows that despite the 20 days of delay to the 60% system design submission, as indicated in Table 6-1, it only contributed to a total of 7 working days of delay to the project. The main reason for this minimal impact is that the 60% system design submission activity was not a critical task when the delay occurred, and this only became critical during the last working days of the design. Also, the model shows that the delay in providing access for the systems installation did not have an impact on the overall project schedule asshown in Figure 6-7, therefore, the Systems Contractor is not entitled to any time extension. On the contrary, working double shifts during the construction of the storage facility led to an eight-day acceleration to the project completion. Figure 6-8 illustrates the impact of these events on the critical path of the project at the time of the analysis. It specially shows the changes in planned duration of the project critical activities as the project progressed.

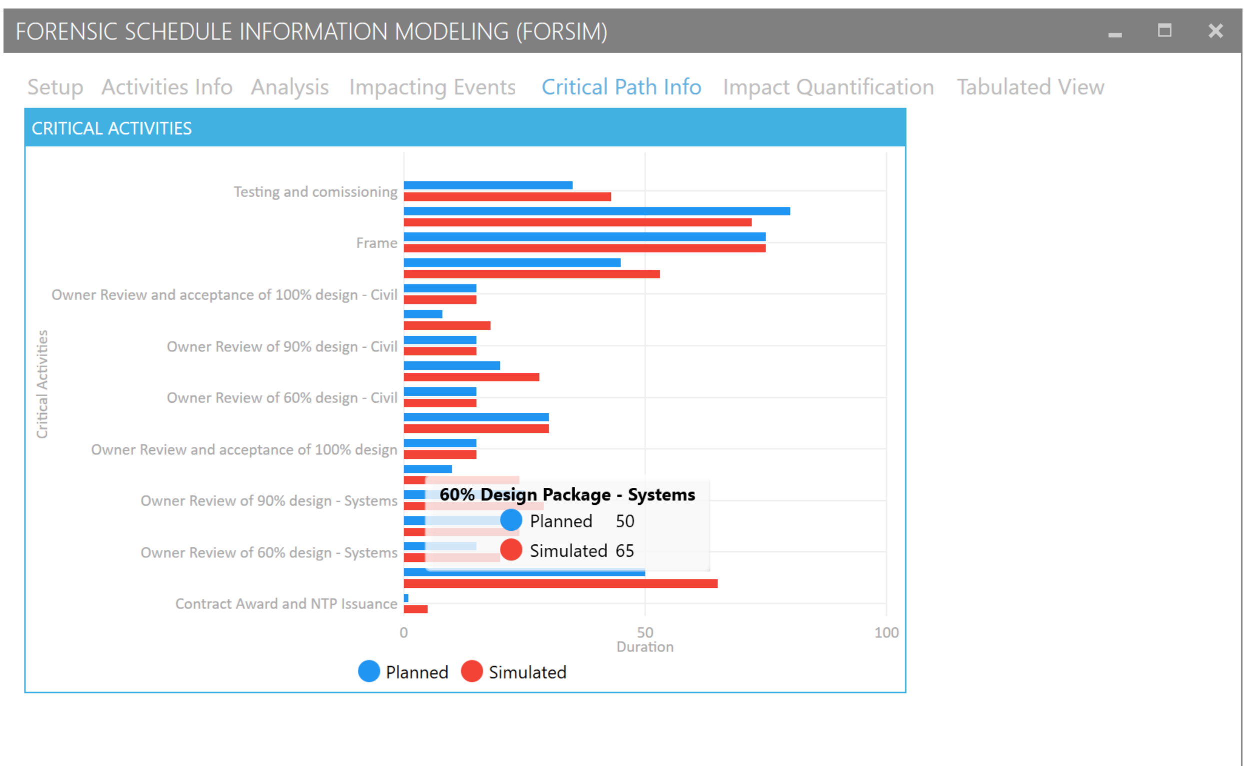


Figure 6-8: Critical activities comparison

Figure 6-9 and Figure 6-10**Error! Reference source not found.** show the liability impact from both the Systems Contractor and Owner perspectives while simultaneously quantifying the liabilities of all parties involved in the project (micro liability allocation). It is important to note that the liability allocation represents working days while the delay shown represents calendar days. This was implemented intentionally to demonstrate that even a small impact associated with an event could have severe consequences: for instance, a delay that shifts the project to the off-construction season could impact the project substantially.

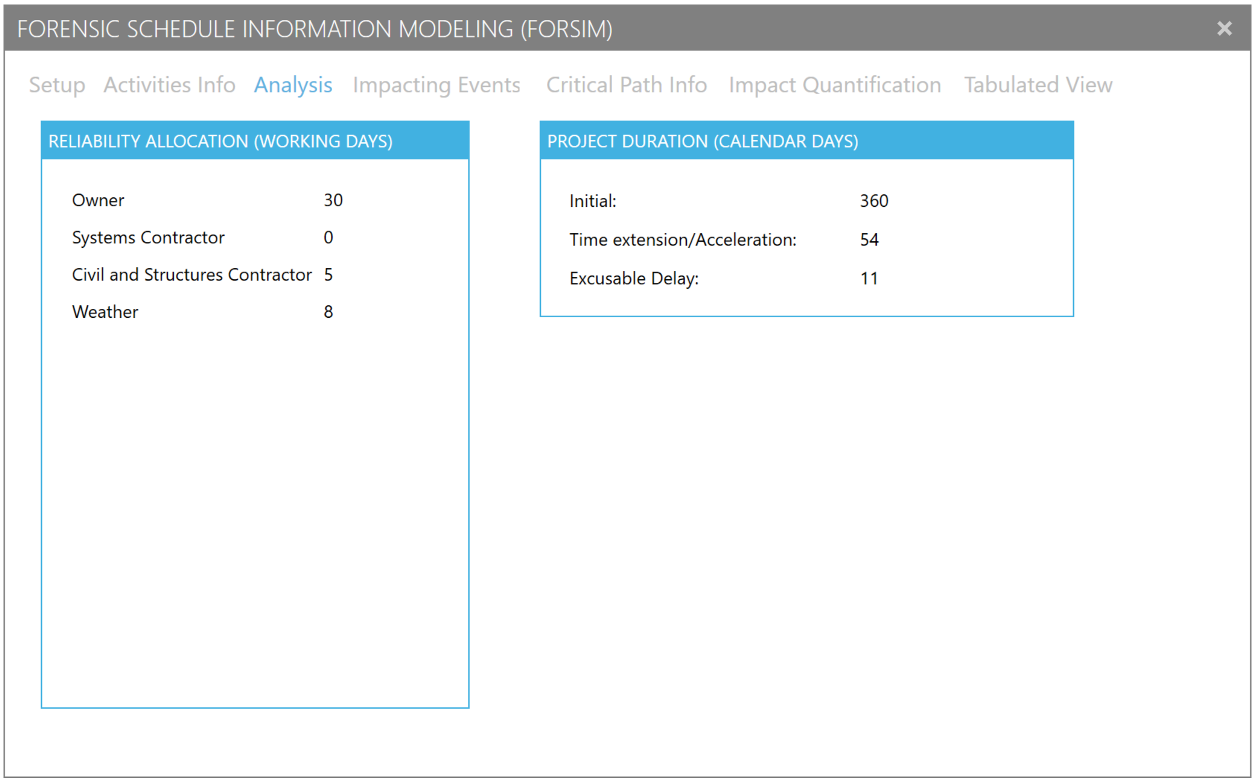


Figure 6-9: Liability allocation from the Systems Contractor's perspective

From the Systems Contractor perspective (Figure 6-9), the results show that the project encountered 54 days of delay beyond the planned completion date of the project. It also shows that, out of the 54 days of delay, the System Contractor was only responsible for 11 days of delay, leading to an entitlement of a 43-calendar-day time extension attributable to other parties involved in the project and bad weather conditions. However, the results in Figure 6-10 also show that the Owner's actions resulted in 18 days of excusable delay to the project.

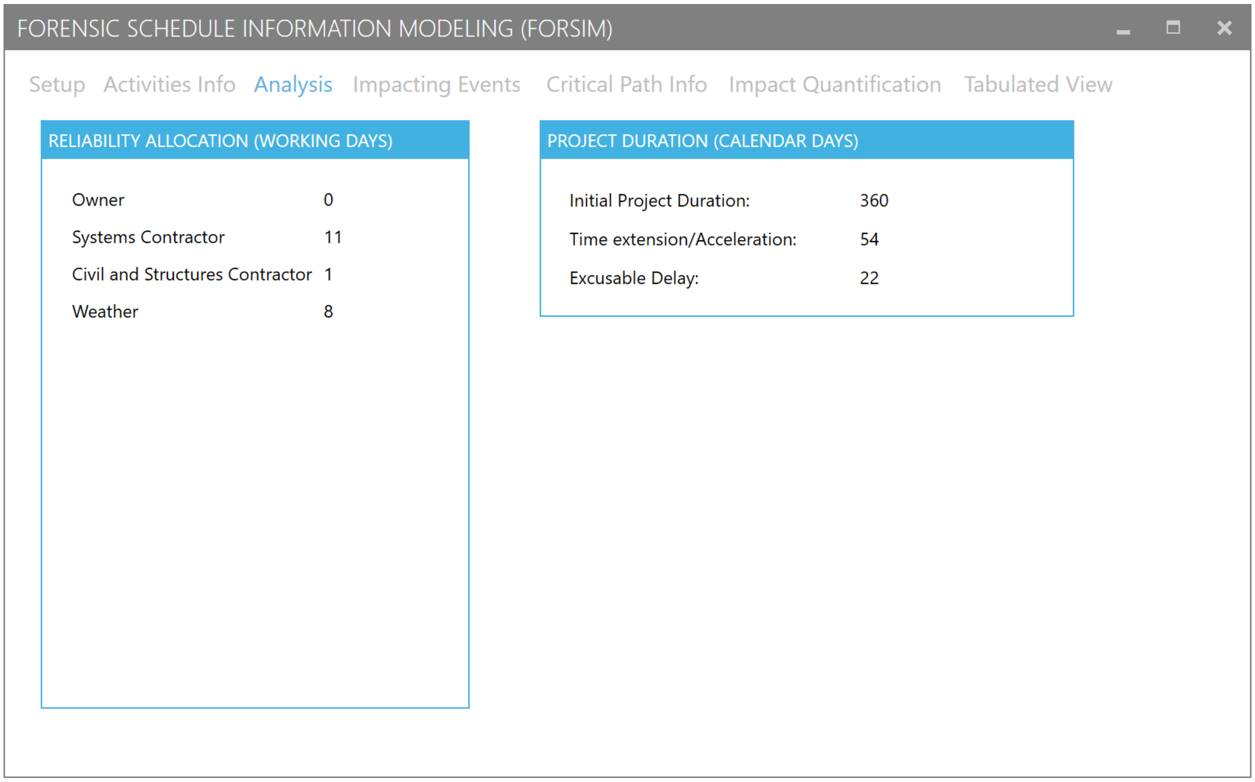


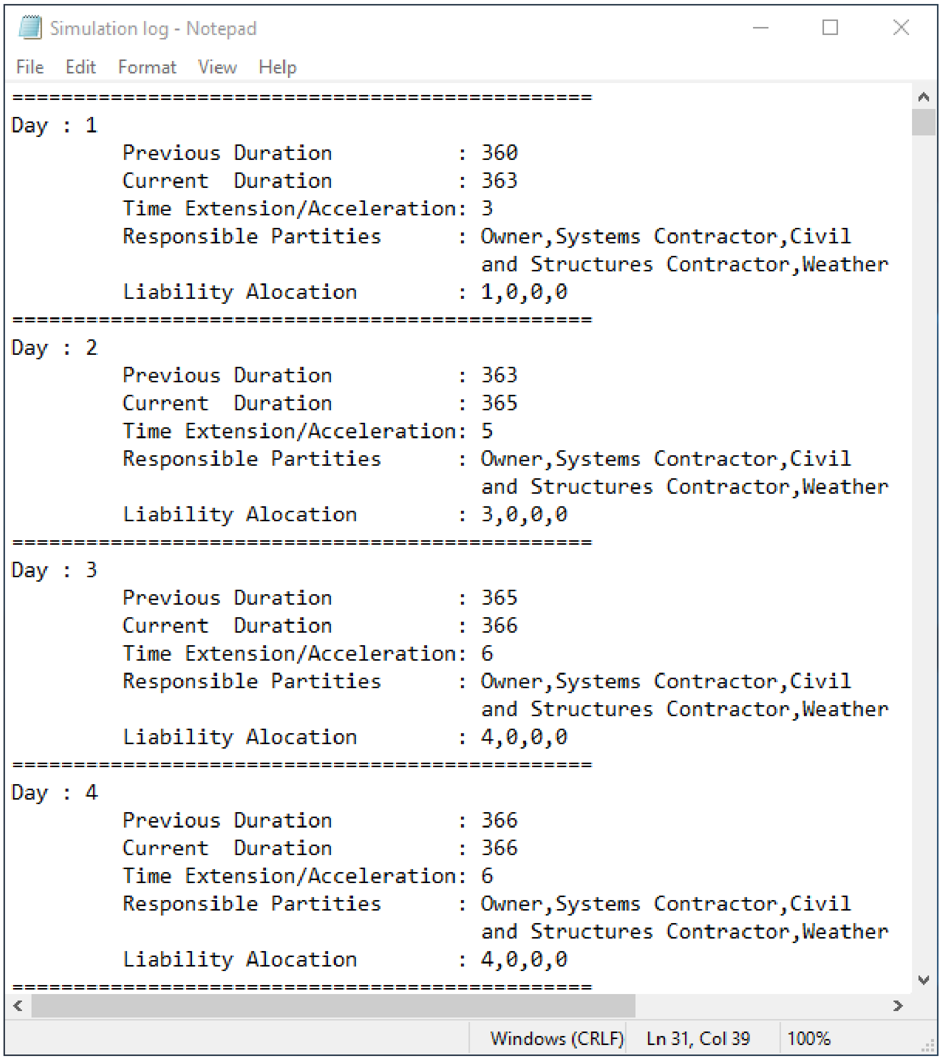
Figure 6-10: Liability allocation from the Owner's perspective

One could also observe that the Civil and Structures Contractor liability changes from 5 days in the scenario where the Systems Contractors is the claimant to 1 day in the scenario where the Owner is the claimant. This is due to the acceleration credit the storage facility construction that has shared reposibilities between the Owner and Civil and Structures Contractor. However, if the Civil Contractor was claiming a time extension, a time extension equal to the concurrency period would have been granted. Likewise, the excusable delay also changed from 30 days to 22 days mainly due to the accleration credit given to the Owner. It is important to note that ForSIM supports shared liability for concurrent delays. Unlike other delay analysis methods, ForSIM enables the analysis of such scenarios, which would usually take a long time and be undertaken by an expensive team of analysts, to be completed in very short time: depending on the schedule size and project duration, this simulation process may only take a few minutes.

One significant observation is that Change Orders (CO) involving scope increases or changes typically necessitate changes to the project schedule by adding new activities to the schedule, along with logic modification. More importantly, if these activities were added to a schedule retrospectively, it would require subjective interaction with the schedule. Moreover, COs usually specify a time extension for the project as a whole, which is not an accurate result, as the criticality of events may change as the project progresses. In such a situation, the time extension granted should be invalid, however, this invalidity is usually not realized. On the contrary, ForSIM allows a time extension to be granted at the activities level without schedule modification or the interaction of the analyst(s) with the schedule, thus, this process ensures more accurate analysis. This benefit was observed on this case study, as the expansion of the storage facility is modelled as an event impacting the 100% design submission for both the Systems and Civil scopes of work. Overall, this approach minimizes the need for modifying the project schedule or issuing updated schedules to reflect changes to the project.

6.3.2. Results Verification and Validation

To validate ForSIM analysis results, events tracability feature that is associated with simulation models is used. Figure 6-11 shows the simulation log of the trial run which traces the calculated changes in the project duration, extension of time or acceleration award and liability allocation incrementally at every time step.



```
Simulation log - Notepad
File  Edit  Format  View  Help
===============================================
Day : 1
         Previous Duration          : 360
         Current  Duration          : 363
         Time Extension/Acceleration: 3
         Responsible Partities      : Owner,Systems Contractor,Civil
                                      and Structures Contractor,Weather
         Liability Alocation        : 1,0,0,0
===============================================
Day : 2
         Previous Duration          : 363
         Current  Duration          : 365
         Time Extension/Acceleration: 5
         Responsible Partities      : Owner,Systems Contractor,Civil
                                      and Structures Contractor,Weather
         Liability Alocation        : 3,0,0,0
===============================================
Day : 3
         Previous Duration          : 365
         Current  Duration          : 366
         Time Extension/Acceleration: 6
         Responsible Partities      : Owner,Systems Contractor,Civil
                                      and Structures Contractor,Weather
         Liability Alocation        : 4,0,0,0
===============================================
Day : 4
         Previous Duration          : 366
         Current  Duration          : 366
         Time Extension/Acceleration: 6
         Responsible Partities      : Owner,Systems Contractor,Civil
                                      and Structures Contractor,Weather
         Liability Alocation        : 4,0,0,0
===============================================
Windows (CRLF)   Ln 31, Col 39   100%
```

Figure 6-11: Snapshot of ForSIM's simulation log

As it can be noticed, the owner's delay in issuing the notice to proceed on the first day of the project has resulted in delay of 3 calendar days to the overall completion of the project. As the simulation advanced, the results of every time step was used as basis for measuring changes in the following time step while cumulatively tracking time extension or acceleration and liability of project participants. These changes could aslo be cross-referenced with the events impact (Figure 6-7) as well as the simulated activities information (e.g. total float, duration, etc.).

6.4. Discussion

The proposed framework shares similarities with daily window analysis methods; however, it is expected to have more capabilities. Table **6-2** shows a comparison of capabilities for the two methods in resolving complicated delay situations. Both methods provide real-time critical path analysis and are capable of analyzing concurrent delays. However, the daily window analysis method is mainly designed for prospective delay analysis, and the nature of its required inputs (daily progress percentage at the activities level) makes it nearly impossible to apply to retrospective analysis. Under daily window analysis, liability allocation is quantified at a very high level (owner, contractor or neither), while the proposed framework allocates liability according to every unique responsible entity listed in the SoE by taking advantage of the traceability feature in the simulation. Moreover, daily window analysis is limited when modelling partial delay situations, as they can only be represented using a low progress percentage or a rounded full day work stoppage. On the contrary, the proposed framework could be implemented in very small time steps (e.g. minutes, hours, etc.) if needed, which would enable more accurate representation of partial delay situations. Another advantage of the proposed framework is the possibility of modelling the uncertainty associated with the impact of events on scheduled activities using probability distributions.

Table 6-2: Capability comparison of ForSIM and daily window analysis method

Capability	Daily window delay analysis	ForSIM
Real-time critical path analysis	✓	✓
Concurrent delay	✓	✓
Prospective analysis	✓	✓
Retrospective analysis	-	✓
Liability allocation at micro level	-	✓
Modelling impact uncertainty	-	✓
Modelling partial delay	-	✓
Integrated delay analysis process (identification, quantification and analysis	-	✓

It also important to note that identifying delay events is not an easy task, as it requires considerable experience as well as a thorough understanding of the project and schedule. The proposed framework eliminates such a requirement, because its algorithm is designed to analyze events regardless of their impact and criticality. Consequently, there is a significant cost savings that would usually be spent on acquiring external experts to perform the delay analysis. Lastly, the proposed framework automatically integrates delays into the schedule, which eliminates the interaction of analysts with the schedules being analyzed. This is vital in retrospective delay analysis, as it allows the analysis to be completed without the schedule modification that is usually associated with implementation of other delay analysis techniques.

6.4.1. Analytical Procedure Comparison

Generally, all types of windows delay analysis techniques share a similar analysis procedure. The key difference exists in the analysis time frame. Daily window analysis method uses a daily window, while other methods either choose analysis time frames randomly or based on significant events that took place during the project. Although ForSIM framework is flexible in determining the window time frame, which enables analyst to examine the sensitivity of the selected time frame on the results at no cost, previous research has indicated that the smaller the window size, the more accurate the results will be. A key distinction of ForSIM is that it has an additional layer to quantify the impact of events as part of the delay analysis.

6.4.2. Accuracy Comparison

As discussed previously, windows delay analysis methods generally produce more accurate delay analysis results than other techniques, with daily window analysis being the most accurate technique. However, the proposed framework is expected to have even more accurate analysis results as demonstrated in his section.

One significant inaccuracy of the daily window analysis is the negligence of potential activity acceleration. To illustrate this inaccuracy, a hypothetical case study, as shown in Figure 6-12, has been developed.

		Duration in days									
Activities	**Predecessors**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Activity A		50%	50%								
		50%	50%								
Activity B	Activity A			33%	33%	33%					
				C	C	33%	67%				
Activity C	Activity A			50%	50%						
				O	O	O	O	50%	50%		
Activity D	Activities B & C						50%	50%			
										50%	50%

Planned Actual

Figure 6-12: Illustrative case study for inaccuracy of daily window analysis

Figure 6-12 shows the as-planned versus the as-built schedules for a simple four-activity project. The plan was to complete these activities in seven days, however, the as-built shows that it took ten days to complete these activities. To analyze the delay liability using daily window analysis, a total of 10 windows are analyzed, as shown in Figure 6-13. The critical path of the planned schedule was A-B-D. In the first two days, the project advanced as planned, without any change in the total project duration. In the third window (Figure 6-13[a]), both Activities B and C encountered delays, leading to one day delay to the project completion. As Activity B was critical at the end of the third window, the Contractor (C) becomes liable for this one day delay. Continuing to the fourth window, the critical path is subject to another one day delay that is also attributable to the contractor, leading to a total delay of two days to the project. In the window of the fifth day [Figure 6-13(c)], Activity C continued to contribute delays attributable to the owner (O), leading to the creation of parallel critical path to the project (A-B-D and A-C-D), but the project duration remained nine days. If delay analysis was conducted prospectively prior to the completion of Activity B, daily window analysis would proactively allocate this delay to the contractor, which would deny him the opportunity to accelerate Activity A and finish it as planned. This inaccuracy also demonstrates the unsuitability of using the conventional CPM method for prospective delay analysis. The implication of this inaccuracy is illustrated in the analysis of the remaining windows.

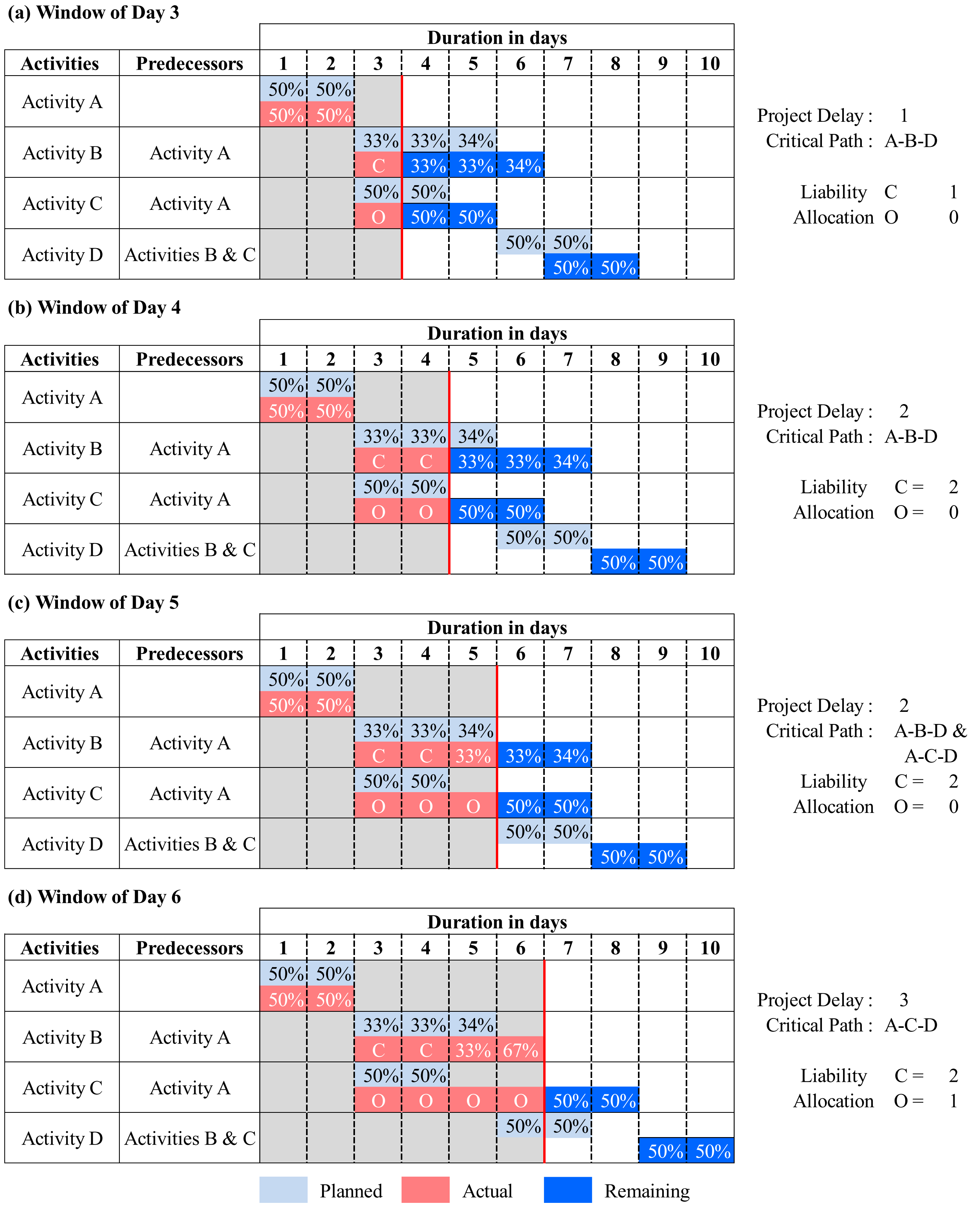


Figure 6-13: Daily window analysis method

In the window of Day 6 [Figure 6-13(d)], while the contractor accelerated Activity B, Activity C continued to encounter owner-attributable delays, leading to one critical path (A-C-D). However, due to the change in the critical path, the owner becomes liable for one day of delay while the contractor remains responsible for two days of delay, despite the fact that the completion of Activity B was only delayed by one day. The main reason for this inaccuracy is that rather than proactively assigning delays to activities, delays should only be considered when activity durations exceed the planned duration. It is important to note that contractors usually control the means and methods for projects execution and such inaccuracy denies them the opportunity to recover from schedule delays.

Although this is a hypothetical case, the magnitude of such an inaccuracy could be costly in a real-life scenario. To avoid this inaccuracy, the ForSIM framework allows the analyst to assign delay liabilities only after the delay occurs.

6.4.3. Impact of Disruption on Delay Analysis

One critical limitation in daily window analysis is the lack of consideration of disruptions when analyzing the impact to the schedule. To articulate this limitation, it is important to highlight the difference between a delay and disruption. Delay refers to the critical effect of events on activity progress, meaning that the activity will not be completed as planned or on time, while disruption refers to the occurrence of events that cause inefficient activity progress. To better demonstrate the implications of this limitation, a simple hypothetical case study, as shown in Figure 6-14, has been developed.

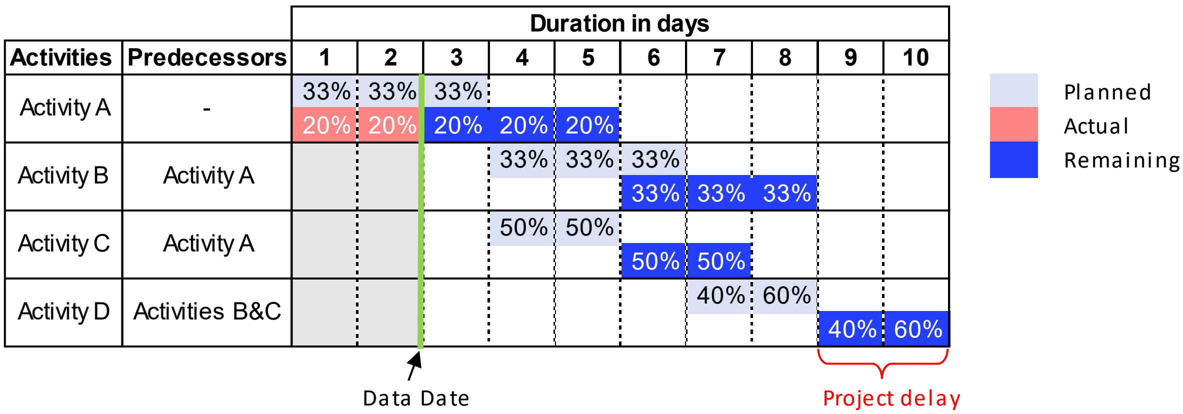


Figure 6-14: Illustrative case study of the impact of disruption on delay analysis

As can be noted from the figure, Activity A was to be completed in three days with 33% production every day: however, due to a slow start, only 40% production was achieved by the end of the second day. The daily window analysis method calculates the remaining duration based on either the planned or actual production, resulting in a forecasted duration of five days for Activity A, and, consequently, resulting in a two-day delay to the project. It also relies on IBC that requires the recording of the responsible party on the bar chart as either "O" for owner liability, "C" for contractor liability, "N" for delays that not liable to owner or contractor, or a combination of any of these three letters to represent shared responsibilities. Therefore, in such scenario where there is disruption in activities progress (slow progress), the daily window analysis method is limited to two options, either ignore the disruption impact or consider it as a full day of delay, which lead to inaccurate analysis results.

6.4.4. Analysis Times

The implementation of any windows-based delay analysis techniques is costly and time consuming. Although the daily window analysis technique saves considerable time on the analysis aspect, it requires additional resources to be deployed to estimate daily progress percentage. On the contrary, the ForSIM framework only requires project information, which is typically captured in different forms, such as daily reports, logs, letters, etc., to be organized in a specific format to facilitate the analysis at negligible cost. Additionally, the use of simulation enables the analysis of different scenarios easily and efficiently.

6.4.5. Events Categorization

Typically, construction projects generate large amount of documentation. In claims situations, analysts invest numerous time and cost to review this documentation to identify route causes of problems, i.e. demonstrate causation. This lengthy and costly process is not considered by any of the current claims analysis methods. Unlike other analysis methods, ForSIM considers the issue and offers a mechanism for reducing the number of documents under consideration through its event categorization process and structure of the SoE.

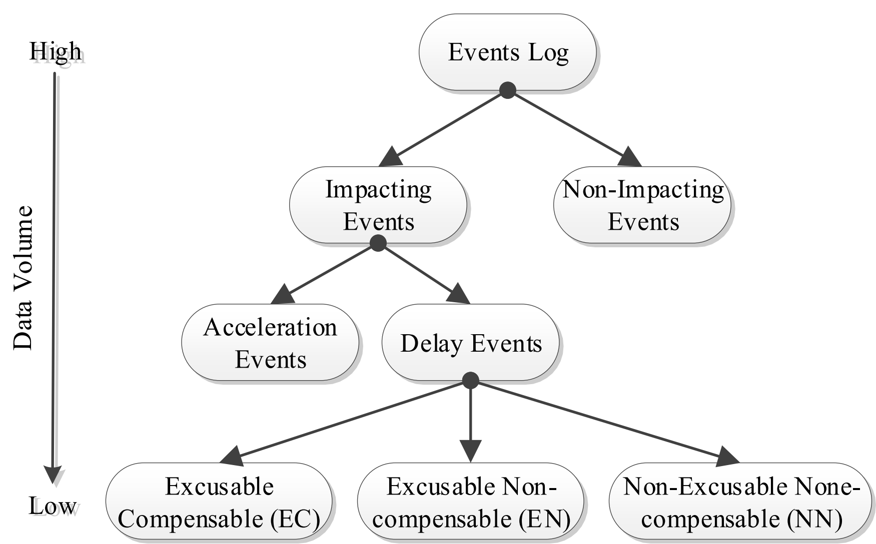


Figure 6-15: Events categorization hierarchy

Although, events captured in the SoE of a project impact project activities, they might not impact the overall project duration. Reviewing documentation of events that do not impact the project schedule in time claims situations becomes unnecessary. However, the overall categorization process, as shown in Figure 6-15, helps in filtering and reducing project data to identify causes of delay and their impact (causation) on the construction schedule. The framework uses traceability feature to filter those events with no critical impact and track those events which have actually impacted the project critical path as well as their impact label (delay or acceleration). Once these events are identified, analysts can review their documentation by referring to the associated reference field in the SoE that captures source of documentation. Therefore, the author argues that ForSIM finds hidden relationships between events and schedule timelines, which allows focused analysis and concentrates efforts on the relevant points in dispute negotiation and settlement.

6.5. Summary and Conclusions

This chapter contained the analysis and results of two trials implementation of ForSIM, together with discussion on simple hypothetical case studies. Based on the findings of these trial runs, ForSIM was found to be capable of successful development of as-built schedules and analysis of a live time claim situation typical in nature and complexity to many of today's construction projects. This chapter also describes the procedure and methodology undertaken to verify and validate the results of the impplementatio. The advantages and features that ForSIM brings to the industry practice were also highlighted.

Chapter 7. Conclusions and Recommendation for Future Research

7.1. Chapter Introduction

This thesis is organized into seven chapters, Chapters one introduces the research problem, Chapters two and three cover literature review on topics relate to the study and analyzing deficiencies in the industry practice and the remaining chapters covering reports of further research activity completed concerning the findings of chapters two and three. This chapter outlines a number of academic and industry contributions and finally list further research areas worth investigating in future studies.

To ensure a logical progression of research, a number of research objectives were set as follows:

1. Establish a standardized data structure to facilitate automated retrieval of project information and analysis of time claims
2. Develop Forensic Schedule Information Modeling (ForSIM) framework for the analysis of time claims.
3. To develop, test and evaluate ForSIM prototype through a number of case studies and to identify its limitations and advantages.

Later in this chapter, the findings of the study and contributions will be matched, or linked, to the research objectives to prove that they are all well accomplished.

7.2. Conclusions

7.2.1. Theoretical and Practical Review

The literature review was conducted to explore state-of-the-art information and practices related to the research topic and form the theoretical basis of the research problem. This exercise revealed that despite considerable resources invested in the planning of construction projects, changes to planned project timelines are inevitable. Previous research has focused on aspects of claims analysis with an emphasis on resolving some technical issues for methods used in delay analysis. Less emphasis has been placed on achieving an efficient administrative process in the approach to time claims assessment, and even less on exploring alternative means of time claims analysis. The literature also showed that, despite the considerable effort expended on identifying and quantifying factors impacting productivity, these studies are not integrated with the time claims management perspective.

Following the literature review exercise, and preliminary findings, critical problematic issues were observed in connection with the administrative process in which time claims are assessed, including inefficient documentation and organization of contemporaneous records, the need of a specific set of skills for delay identification and analysis, as well as the disintegrated management process, all of which can result in a lengthy and costly resolution process. Also, other problematic areas in connection with the technical analysis of time claims were identified regardless of previous research efforts, including inadequate testing of alternative means for claims analysis, inefficient and inaccurate development of as-built schedules and analysis of time claims, subjective interaction with project schedules, impractical solutions, inability to account for partial delays, failure to allocate liability at micro levels (subcontractors, suppliers, consultants, etc.) and restricted form of analysis.

7.2.2. Evaluation of Findings

When the findings of the theoretical and practical review were contrasted, it was observed that the limitations identified as being critical were found to have theoretical basis. This, in turn, resulted in drawing the following conclusion:

> **The industry practice to administrate a dispute process and analyze contemporaneous records in the format of time claims assessment suggests that there is a need for a new approach to analyze construction schedules and quantify time impacts in a more realistic, accurate and efficient manner.**

The failings and shortcomings of the overall management, analyses, and assessment of time claims, as well as the need for improvements, are formulated as a problem with a simulation-assisted framework proposed as the solution.

The new approach takes the form of a **Forensic Schedule Information Modeling** framework for time claims analysis, abbreviated as **ForSIM.**

7.2.3. ForSIM – Proposed New Framework for Time Claims Assessment

The key differences between the proposed framework and existing delay analysis methods is that the proposed framework places considerable emphasis on integrating the four main components of existing time claims assessment processes, namely identification, impact quantification, analysis and evaluation, in a single simulation-assisted system.

From the technical perspective, ForSIM addresses the critical interface between the documentation and organization of contemporaneous project data and simulation assisted assessment of time claims, which is a significant departure from the current practice. It is particularly important to organize information (upon which the analysis and assessment are based) in a standardized format that can facilitate an automated analysis process, along with providing accurate and efficient conclusions. In addition, ForSIM addresses the matter of allocating liability among all parties involved, and at the same time limits the interaction of the analyst with schedules for claim analysis purposes which eliminates some of the subjectivity associated with the analysis of delay claims using other methods. A detailed specification of ForSIM, including conceptual and detailed architectures, was included in Chapters 4 and 5. The conceptual architecture provided the skeleton upon which the functionality of ForSIM is built, while detailed design provided specialized algorithms for the application of ForSIM.

Assessment and testing of ForSIM was completed in two stages. The first stage involved testing the prototype model on a segment of real tunnelling project to develop an as-built schedule. The observed benefits of the application of ForSIM in the first stage of testing were fully discussed in Chapter 5. The second stage was comprised of a trail run on a an abstract claim situation based on a scenario encountered in an actual project. The capabilities of ForSIM in analyzing and assessing time claims in comparison to other methods were discussed in Chapter 6. The overall conclusion from these findings was that ForSIM has the potential to significantly improve current practice and help achieve a more efficient and accurate assessment of time claims in construction projects.

If a contract specifies that ForSIM is to be used for claim submission and assessment, contracted parties would have a standard basis for ensuring that claims are made transparently and with appropriate disclosure and assessment.

7.3. Research Contribution

Considering the importance of time claims in the construction industry, as well as the degree of financial implications, improving industry practice related to delay claims is beneficial to all practitioners. This research presented a simulation assisted framework that is relevant to both academic researchers and industry practitioners. The summary of contributions to the body of knowledge are summarized as follows:

- *Development of a systematic simulation-assisted framework for the analysis of time claims*: ForSIM overcomes many deficiencies of methods for claims analysis and provides enhancements to the practice of time claims analysis through computational speed and accuracy, and subsequently contributes to considerable cost savings in dispute resolution processes. The framework will enable analysts to assist clients to resolve complex issues rather than being observers and decoders of project schedules complexities. Since it is based on simulation technologies, the system has a wide array of proven benefits that are essential to both conducting a robust forensic construction schedule analysis and overcoming the shortcomings of existing techniques, including:
    - *Simplifying complex claims*: ForSIM has the ability to digest a large amount of information that may not easily be understood by the parties involved in claims analysis situations.
    - *Traceability of events and activity progress*: Existing scheduling tools only reflect the latest status of activities, which limits the analysis process. On the contrary, ForSIM provides a history of events that took place during the execution of activities, along with a simulation log of calculations and outputs which can be used

to demonstrate mitigation and/or acceleration measures that were taken during the activity execution phase. This guarantees transparency, liability, and full functionality disclosure. Also, ForSIM quantifies, traces, and categorizes impacts of events discretely based on their criticality to the project, which enables liability allocation at the micro level, including subcontractors, suppliers, consultants, etc.

- *Modeling uncertainty of project data*: As discussed in this research, contemporaneous project records are subject to inaccuracies and inconsistencies due to many factors, specifically on events timelines that are critical to claims analysis. Unlike traditional methods, ForSIM enables the modeling of these uncertainties using probability distributions.
- *Facilitating integrated claim management process*: ForSIM integrates all the main components of time claims management, including delay identification, impact quantification, analysis without the need of special skill set and assessment of liability for changes or deviations from the original project schedule. As a centralized and practical claims analysis system, ForSIM offers an integrated time claims analysis system that is much more viable for claims assessment than other methods that were available previously, thus considerably minimizing the expense of dispute resolution. ForSIM is also a comprehensive framework that is based on existing delay analysis techniques and principles, and its implementation can be based on commonly used tools, such as Microsoft Excel and MS project, all of which incentivizes acceptance and adoption by industry practitioners.
- *Simplicity and Expandability*: The proposed simulation model architecture is easy to understand and expand. Obviously, the underlying principles and techniques for

analyzing time claims take time to understand, but developers should be able to understand the workflow of the system and then fill in details as necessary. The proposed data structure of the event schedule is simple, logical, and allows the delay analyst to set different scenarios easily and efficiently. The cost of organizing the project data into the proposed event schedule format is negligible when compared to the cost of involving external parties. Moreover, the overall model architecture enables easy expansion of the framework by either adding new attributes to the entity information model or expanding the functionality to analyze other aspects of project management.

- *Development of a standardized comprehensive format for documenting project data.* ForSIM promotes organization of project data through the schedule of events, which can also be used for other project controls aspects: The event schedule format is simple and since it is aligned with automated time claims analysis, the value of data organization can finally be realized.
- *Automated development of as-built schedules which are multifunctional and rich in information*: ForSIM could serve as a one-step repository of all project schedule information, including the sequence of work execution, schedule logic changes, performance analysis, project event documentation, impact quantifications, causation and liability allocation. It also eliminates the tedious and labor-intensive process of as-built schedule development and claims analysis processes. Moreover, ForSIM supports prospective or retrospective development of as-built schedules. This means that more time can be spent on iterative improvements to prepare better-quality time related claim submissions, and most likely, comply with any restricted timelines prescribed by

contractual provisions. This also eliminates the need for scheduling skills that are usually required for the development of as-built schedules and the need for balancing between the purpose of the analysis and the cost of as-built schedule preparation.

- *Separating the analysis of events from schedule impact, i.e., independent events analysis*: Claims reflect the claimants' perspective and they are usually met by disagreement and counterarguments from recipients. These disagreements unfortunately are reflected in the analysis of claims which limits the ruling to one of the following: accept the outcome of the analysis as is, request reanalysis of claims based on a reallocated liability, or make a judgmental conclusion. ForSIM mechanism for causation identification can be used to identify points of difference or dispute quickly and easily, so the modelling inputs can be iterated efficiently and reanalyzed to understand their implications. Therefore, by separating events from the schedule analysis, ForSIM enables liability allocation assessment irrespective of the schedule analysis and facilitates comparison of different scenarios, all of which helps in focusing disagreements on facts rather than subjectivity. This also eliminates the need for analyst interaction with project schedules, resolving problems associated with the subjectivity and potential manipulation of the process.

7.4. Research Limitations and Recommendation for Future Research and Development

The broad focus of this research was on problems arising with claims analysis. Research eventually addressed the administrative and technical problems related to time assessment claims. Although the primary aims of this study were achieved, it has a number of limitations. These limitations and recommendations for future research to further advance the body of knowledge are as follows:

- The construction industry is ambivalent towards the application of simulation in claims analysis. While simulation models might eliminate the need of understanding the behavior of complex interactions, litigation processes usually require an accurate and transparent quantification process. This might hinder achieving transparent quantification and foster distrust in the model in the audience in a litigation environment, since tracking a complex simulation model would be time consuming due to the size and detail of data required in a litigation process. This limitation could be addressed by investing on transferring a ForSIM prototype into a commercial model to be made available for industry practitioners use. This would allow researchers to prove its capability and achieve industry wide acceptance.
- The focus of this research was limited to analysis of schedule changes and quantification of time awards. The limitation of the developed ForSIM prototype were presented in Section 5.3. The functionality of the ForSIM framework for time claims analysis can also be expanded to include the following:
    - Integration with other information repositories such as Building Information Models (BIM) and weather condition forecasting tools. This would help in automating the data capturing process for the development of event schedules, removing the requirement to rely on human interpretation of project documentation.
    - Integration with a dynamic system model to model and capture the impact of soft human elements such as poor management, experience, guesswork, etc.
- The demonstration of entitlement and claims presentation through the application of machine learning to time claims informatics is currently a significant academic research

area. This work should involve examine theories of legal decision making such as the impact of models of argumentation on claims representation and reasoning.

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