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SIMULATION-BASED FRAMEWORK FOR CONSTRUCTION DELAY ANALYSIS

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Abstract: The most common types of construction disputes relate to schedule impacts, or delay claims. They are caused by 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. Various schedule delay analysis methods have been developed and used. Among them, window-based delay analysis methods have been recognized as the most credible methods, however, they still have functional limitations and use prerequisites. This study discusses some of the outstanding drawbacks, identifies new issues and demonstrates inaccuracies in some of the proposed methods. To improve delay analysis practices, a new framework for forensic delay analysis is introduced. The framework takes full advantage of a time-step simulation approach to model project data, analyze delay claims, and quantify both acceleration and time extension award. Details of the simulation-based framework are introduced along with demonstration of its merit over existing delay analysis methods. The proposed framework is applicable for both prospective and retrospective delay analysis situations.

1 INTRODUCTION

Construction projects frequently experience inevitable changes to their execution plan due variety of reasons, which might result in disputes among the contracted parties. Time related claims are the most common type of disputes because they are associated with damages and financial impacts for all the contracted parties (Keane and Caletka 2015). Thus, most standard forms of contracts include provisions which 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 agreed contracts duration (Keane and Caletka 2015). Disagreement in any of the instances leads to a claim. Therefore, delay analysis plays a vital role in resolving and settling these disputes.

Analysis of delay claims is often a study in the relationship of cause and effect which could 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 uncomputerized processes and they do not consider concurrent delays situations, critical path changes (Yang and Tsai 2011), quantify liabilities at subcontractors' level, partial delays (Hegazy and Zhang 2005), uncertainty of events' impact and most importantly relies on the experience and subjectivity of the analyst. These limitations result in time consuming processes, errors and inaccuracies in the analysis results. Although new analysis techniques have addressed some of these limitations separately, 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 construction industry has been using simulation for designing, planning and analyzing construction operations (AbouRizk 2010). Over the past three decades, various types of simulation methods have been developed to cope with different systems behaviors, including Monte Carlo simulation, Discrete Event Simulation (DES), System Dynamics (SD). These methods are being widely used to study and model construction operations, such as tunneling operations (Rahm, et al. 2013, Ebrahimy, et al. 2011), scheduling problems (Araúzo, et al. 2009, Tang, Mukherjee and Onder 2013) and earthmoving operations (Marzouk and Moselhi 2004, Zhang 2008, Hsiao, et al. 2011, Mohamed and Ali 2013).

Despite the wide usage of simulation in construction operations, its application in claims analysis is very limited. The tendency of using DES focused on modeling different scenarios under different conditions to analyze and evaluate changes in systems behaviour (AbouRizk and Dozzi 1993, Al Malah, et al. 2013). SD models have also been used in claims analysis process because the use of concepts and arrows in qualitative models provide clear argument routs and makes it easier to understand than the quantitative models (Howick 2003, Williams, Ackermann and Eden 2003).

To improve the construction delay analysis practices, advancements in simulation can be explored and tested. This study aims at exploring how the analysis of time related claims could be improved by taking full advantage of time-step simulation concept. It will introduce a framework that integrates various schedule-related factors under one environment using simulation to analyze construction delays and allow analysts to make well-informed judgements. Simultaneously, quantifying the time extension and/or acceleration award and providing feedback for the delay analyst in graphical and statistical fashion.

2 BACKGROUND

Delay claims have been classified into two main situations; simple and complicated situations (Kao and Yang 2009). 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. Complications arise when changes to the critical path(s) occur; when non-critical activities become critical. Other complications arise in situations of concurrent delays, missing activity from as-planned to as-built schedules, pacing delays, float ownership and losing productivity disputes. In such cases, traditional delay analysis methods become inaccurate in assessing damages and time extensions (Arditi and Pattanalitchamroon 2006).

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 and Al-Gahtani 2005). Most of these methods have the capability to solve simple delay situations, but some are inadequate for solving complicated delay problems. Previous research also noted that different techniques give different results (Stumpf 2000), and selecting the most appropriate methodology depends on accessibility to the project control documentation, time and available resources (Bubshait and Cunningham 1998). Detailed description of these methods as well as their limitations are extensively discussed in the literature (Stumpf 2000, Mohan and Al-Gahtani 2005, Kim, Kim and Shin 2005).

Among these techniques, the windows analysis methods have been recognized as the most creditable methods (Gothand 2003, Kim, Kim and Shin 2005). Its key difference from other techniques is that it divides the project duration, as given by as-planned schedule, into digestible time periods (windows). It then identifies and analyzes successively the delays that arisen in each window and examine their effects as being liable to either the project owner or the contractor (Hegazy and Zhang 2005). Also, it enables the assessment of the effect of different rates of progress in different phases of the project. The length of the analysis window is usually based on either major project milestones or times when a major delay(s) occurs. Starting from the planned schedule, each window is analyzed separately by introducing contemporaneous site information on the schedule, including activities' actual start, actual finish, and delays. Delays are usually introduced as new activities that are linked to impacted activities. This forms as-built events stretch until the end of the current window. The residual part of the schedule, till end of the project, remains unmodified (without delays). If the project duration is changed, the critical activities are analyzed to allocated liability. Also, if there are concurrent delays, both parties share responsibility and no damages can be covered. This process continues until all the windows are analyzed. At the end of the analysis, the total project delay is the summary of delays on all the windows (AACE International 2011).

A modified windows analysis method was later introduced by Gothand (2003). The key difference is that the modified method explicitly determines delay liabilities to the project participants prior to the analysis through a meaningful negotiation that distribute responsibility of delay values. To overcome the inadequacy of concurrent delay and acceleration, Kim, Kim and Shin (2005) proposed a delay analysis method using delay section. 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. These techniques still require 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 the schedules can be manipulated by constraints and logic changes. In a series of studies, Hegazy and Zhang (2005) and Menesi (2007) addressed the critical path fluctuation flaw by proving that smaller window spans would result in more accurate delay analysis. Furthermore, one study proposed a daily window delay analysis technique using an intelligent bar chart (IBC) that is made of spreadsheet cells in which activities durations are represented as group of cells rather than bars (Hegazy & Zhang, 2005). Each cell is then used to store daily percentage complete of activities, delays, responsible party and other delay related data.

The proposed practice is designed for prospective delay analysis. The researchers acknowledged that the proposed IBC does not substitute the traditions means of site data collection. Thus. regardless of the subjectivity and potential inaccuracy in estimating percent complete 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 it were to be used for retrospective analysis, reconstruction of the project schedule with daily records would be resource-intensive and costly process. Therefore, a simpler solution that can maximize the utilization of the currently available tools and practices would be invaluable and contributive. Further problems in connection, the researchers acknowledged that the proposed method needs refinements as it still falls short in addressing some major delay issues including, but not limited to, considering partial daily delay, owner-requested versus contractor-own acceleration and apportioning delays at subcontractor level (Hegazy & Zhang, 2005). The study also acknowledged that the reliance on spreadsheet makes it only suitable for small and medium-size projects and that large and complex projects would need a more powerful implementation.

3 FRAMEWORK ARCHETICTURE

The framework models the dynamics of schedule changes by integrating the impact of delay events with Critical Path Method (CPM) computation. It is based on time-step analysis concept where the analysis result of a time-step forms the basis for the successor time-step. A High-level architecture of the framework is illustrated in Figure 1. Detailed descriptions of shown components are discussed in the following sections.

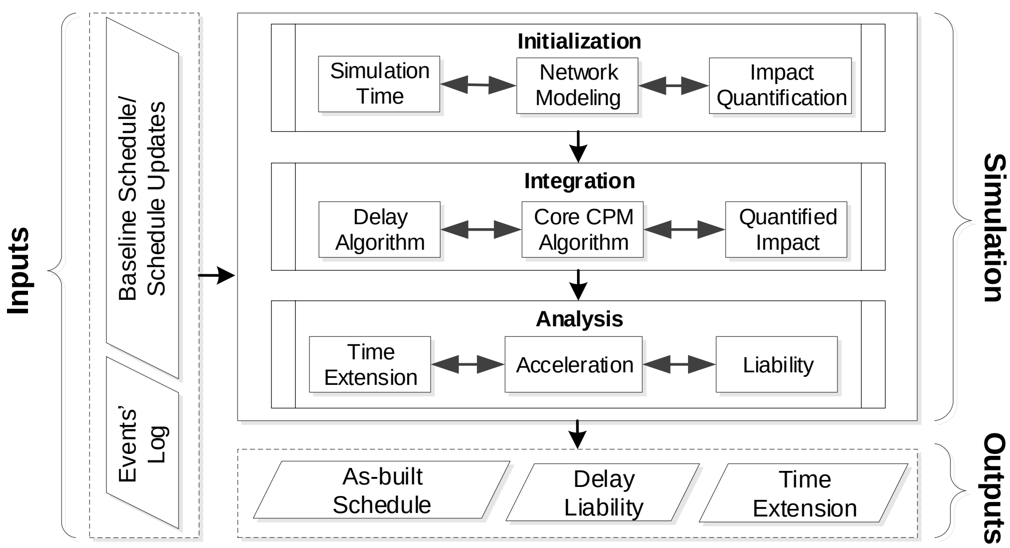

Figure 1: High-level Architecture of the Proposed Framework

3.1 Inputs

The proposed framework relies on data from three sources, which serve as input to the framework: the baseline schedule, schedule updates and the schedule of events (event's log). The framework utilizes the baseline schedule as initial reference to model the schedule network, and accordingly, setting the benchmark for measuring time extension and/or acceleration. The baseline sets the planned timelines, the sequence of execution and the constrains imposed on the schedule. The framework also considers schedule updates when they are available to reflect inevitable schedule changes. As schedule updates become available, they are used to set new benchmarks for activities duration, constraints and execution logic.

The framework proposes a well-structured events' log that is mainly designed to capture information required to analyze construction schedules. The events log lists all events that might impact the project schedule including, but not limited to, approved time extensions, unsettled time extensions requests, weather conditions, etc. Those events are sorted in a chronological order by reference to the date of occurrence, duration, impacted activity, and reliable parties for the delay. The proposed framework requires certain attributes of an event to be captured in a firm format for it to be considered as an event. Detailed descriptions of these attributes as follows:

Table 1: Events' Log Attributes

Attribute	Description
ID	Each event is assigned a unique ID once it is entered into the Events Log to be used as identifier to the event.
Description	A detailed account of events that describes their circumstances.
Cause	A concise description of the event in a few words; brief but comprehensive.
Start Date	This refers to the starting time of an event
Quantification type	The framework support three types of impact quantification as follows: ***Fixed**:* The time impact assumed to be certainly known; ***Probability:*** The time impact is assumed to be uncertain ***Formula:*** A specific equation that expresses the impact of an event.
Parameters	Considering the three quantification types supported by the framework, the parameters filed are used as follows: ***Fixed:*** the parameter reflects the duration of the event in days. ***Probability:*** the parameters reflects the inputs required for the selected distribution by the analyst. ***Formula:*** the parameter(s) should reflect the inputs variables that specified by the analyst when setting up the formula.
Responsible Parties	The entity or entities that are responsible or liable for event's occurrence.
Impact Type	The framework supports the following two types of impact: ***Global Impact:*** this refers to the event that impact the whole project. ***Task-specific:*** this refers to the event that impact certain activities. The predefined activities are captured by listing their IDs in the filed under Impacted Activities column.
References	This refers to source documents supporting the occurrence of events.
Issue Date	This refers to the date in which supporting documents of events are issued.

The Events log could be implemented in variety of ways; however, it must be in a computer interpreted format such as database, ontology, Excel sheet, etc. As it can be noticed, the events' log is mainly concerned with delay information, however, it could also be extended to include other type of attributes such as cost, resources and potential mitigation measures.

3.2 Simulation

The simulation-based approach is employed to effectively model and quantify impact of events on project schedules. Since construction schedules are subject to changes as the project progress, it is reasonable to model time as the simulation entity, which could represent hours, days, weeks, etc. The system work flow is shown in Figure *2*. The simulation components are discussed separately in the following sections.

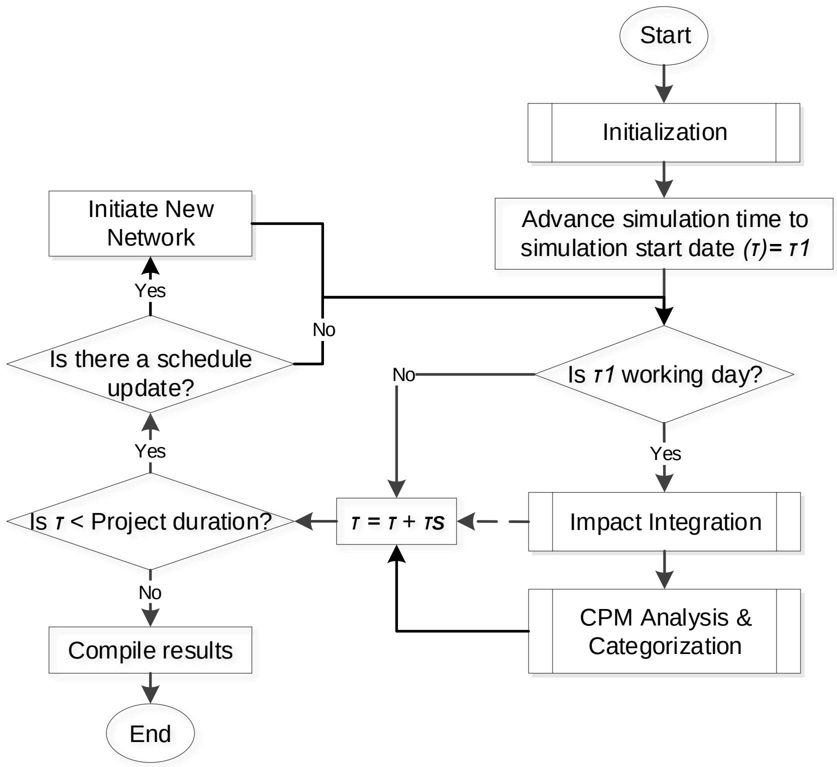

Figure 2: System Work Flow

3.2.1 Initialization

The initialization process starts by interpreting and processing the framework inputs. All the information stored in the baseline schedule and the events' log will be stored and manipulated using programing languages such as .Net or Java. The initialization, as shown in Figure 3, includes quantifying the impact of events, defining the network structure and setting up the time-step simulation.

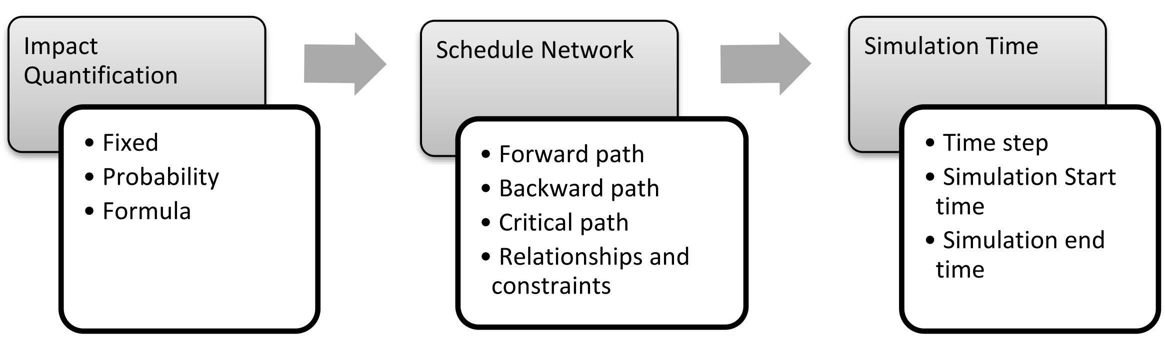

Figure 3: Initiation Process

As it has been mentioned, the framework supports three ways of quantifying events impact that are fixed, formula and probability. Events with fixed impact does not require impact quantification as the impact is assumed to be known. Events with probability impact are those that have uncertain impact durations, accordingly, the framework support using probability distributions such as uniform, triangle or beta distribution to capture uncertainty of the event impact. Methods like Monte Carlo simulation or Inverse transformation method can be used to quantify these events. While events with impact that can only be expressed in formula, the framework enables the analyst to define the quantification model and then computes the events impact. At the end of the initialization the calculated impacts of events are used to calculate the end dates of events. At time zero (τ0=0), the starting simulation date and time is initiated as the smallest early start time in the project schedule. Then, the simulated time will be incremented by a predefined time step (TS) throughout the simulation of the entire schedule. As it has been noted in previous researches, using large time steps results in fast but inaccurate/unstable simulations while small time steps lead to more precise simulations but will take more time.

The CPM is the foundation of this framework and for most of the other delay analysis techniques. Initial values of activities attributes (e.g. ID, name, duration, etc.) that are embedded at compile time (τ0) are used to model the network of the project. The framework relies on the basic CPM principles which include modeling precedence relationships, leads and lags, calendars as well as both forward and backward passes computation through the schedule network. Modelling the aforementioned principles could be done programmatically in variety of ways, and it primarily depends on the modeller preference. The framework mainly concerns with having a full functional CPM calculation of the project attributes regardless of the modeling approach. The modelled CPM is executed at the initiation stage to set up the delay measurements which include identifying the critical path activities and accordingly the planned project duration.

3.2.2 Impact Integration

The integration process starts by advancing the simulation time from zero (τ0) into the starting simulation time (τ1). The simulation explores the Events Log to see if any active events, occurring events at τ1 under simulation, taking 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 TS span. For events with global impact type, durations of all active activities, ongoing activities at τ1, are updated according to the quantified impact. Also, for events with task-specific impact type, only the impacted activities associated with the event are treated as active activities and 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 duration of impacted activities is updated accordingly. It is important to note that activities duration is only updated to the maximum of the TS span per a time step and the update could either by positive or negative.

3.2.3 Network Analysis

Once the impacts of all active events at the time interval are applied, the CPM is executed to analyze the overall impact on the schedule. Changes in activities duration may result in either extension or compression (acceleration) to the project schedule or formulation of a new critical path(s), therefore, the simulation re-identifies the critical path of the schedule and the overall project duration. If the CPM execution resulted in no changes in the critical path, active events would be labelled as non-impacting events and the simulation would advances time to the next time step. However, when changes to the critical path exist, active events are labeled as impacting events and responsibility (liability) counters are initiated for every unique responsible party that is associated with active events during the run time interval. Also, when there is extension to the critical path, active events are labeled as delay events; however, when there is compression to the critical path, active events are labelled as acceleration events.

The integration process, then, continues by incrementing the simulation time by a fixed time interval (τS) as well as repeating the impact integration, criticality analysis and event categorization processes at every time interval. When schedule updates are available, the network model is reinitialized as per the new project schedule. Finally, the simulation is terminated when the simulated date is beyond the end of the last impacting event.

3.3 Outputs

As it can be noticed, the framework imitates the dynamic of project schedule without committing real resources, and subsequently, extracts no obvious but useful information from large project information and documentation. The outputs of the framework include as-built schedule, quantified time extension and/or acceleration and liability allocation. The as-built schedule is a result of incorporating the impact of all the impacting events into the durations of base schedule's activities. Then, a comparison of the as-built schedule and the baseline schedule is presented in a graphical and statistical fashion. Also, time extension or acceleration is quantified by comparing the simulated project duration of a time interval to the previous time interval. Each delay event would have one or more responsible parties which 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.

4 DISCUSSIONS

There are many differences between the proposed framework and the existing delay analysis approaches. In the proposed framework high emphasis is placed on integrating the various components of delay management process, including delay identification, impact quantification, analysis and evaluation into a simulation-based system, which is a significant departure from the traditional methods. Also, from the technical perspective the proposed framework addresses the critical interface between the documentation and organization of contemporaneous data process and the delay management process. Detailed discussion of the expected capabilities of the proposed framework in comparison to the other analysis techniques is presented in the following sections. Illustrate

4.1 Capability Comparison

The proposed framework shares some similarities with the daily window analysis, however, it is expected to have more capabilities. Table 1 shows capabilities comparison between the two methods in resolving complicated delay situations. Both methods provide real-time critical path analysis and 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 activities level) makes it nearly impossible for retrospective analysis. Liability allocation under daily window analysis is quantified at a very high level (owner, contractor or neither) while the proposed framework allocates liability as per every unique responsible entity listed in the events log by taking advantage of the traceability feature in simulation. Moreover, the daily window analysis is limited when modelling partial delay situations as they can only be represented with 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.) which would enable more accurate partial delay representation. Another advantage of the proposed framework is modelling uncertainty associated with the impact of events on the schedule activities using Monte Caro simulation.

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

Table 2: Capabilities comparison of the proposed framework and daily window analysis method

Capability	*Daily window delay analysis*	*Proposed framework*
Real-time critical path analysis	✓	✓
Concurrent delay	✓	✓
Prospective analysis	✓	✓
Retrospective analysis	X	✓
Liability allocation at micro level	X	✓
Modelling impact uncertainty	X	✓
Integrated delay analysis	X	✓
Modelling partial delay	X	✓
Automated delay integration	X	✓

4.2 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. The daily window analysis method uses a daily window while other methods choose time frame randomly or based on significant events that took place during the project. Although, the proposed 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 approved that the smaller the window size, the more accurate the results would be. More importantly, the proposed framework has an additional layer to quantify impact of events prior to the delay analysis.

4.3 Accuracy Comparison

As discussed previously, windows delay analysis method generally produce more accurate delay analysis than other techniques with the daily window analysis being the most accurate technique, however, the proposed framework is expected to have more accurate analysis results. One significant inaccuracy of the daily window analysis is the negligence of potential contractor acceleration. To better articulate the inaccuracy, a hypothetical simple case study, as shown in Figure 4, is developed.

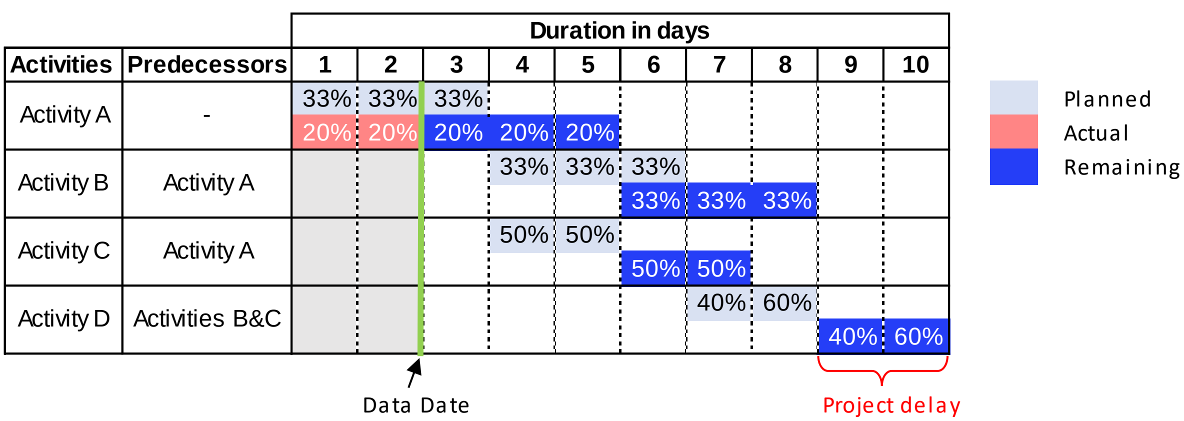

Figure 4: Simple Case Study

As it can be noticed, Activity A was planned to be completed in three days with 33% production every day, however, due to a slow start, only 40% production was completed by the end of the second day. The daily window analysis method calculates the remaining duration based on either the planned or actual production which results in a forecasted five days duration for Activity A to be completed, consequently, resulting in two days delay to the project. In this case, by the end of window two, the daily window analysis proactively allocates this delay to the contractor which denies him the opportunity to accelerate the activity and finish it as planned. Although this is hypothetical case, the magnitude of such inaccuracy could be costly in a real-life scenario. To avoid this inaccuracy, the proposed framework assigns delays liability only after they occur.

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 analysis time, it requires additional resources to be deployed to estimate daily progress percentage. On the contrary, the proposed framework only requires project information, which is typically captured in different forms such as daily reports, logs, letters, etc., to be organized in a firm format to facilitate the analysis at negligible cost. Additionally, the use of simulation enables the analysis of different scenarios very easily and efficiently.

5 CONCLUSION

This paper proposed a comprehensive framework for construction schedules analysis. The proposed framework uses simulation algorithms to address delay analysis problems including information overload, accuracy of delay and/or acceleration quantification and time required to analyse construction schedules. Many of the proposed framework components are similar in principle to the window-based analysis approaches in terms of analysis and evaluation, however, it has distinguish features that are expected to significantly improve the analysis process and accuracy of its results. The proposed structure of the events' log helps in standardising and organizing project information that is usually required to complete delay analysis exercises, and it could be expanded to serve other project management functions. Through the use of simulation, the framework automatically integrates impacting events into the project schedule and analyzes their impact on the overall project duration without any interaction with the project schedules. It also has the capability to model uncertainty of events' impact and partial delays. If delays and/or accelerations are encountered, time quantification, causation, classification of events and liability allocation at micro levels are assessed automatically. The framework also eliminates the need for scheduling and analysis skills as well as the experience that is usually required in claims, thus reducing the time and cost of analysis process.

Further details and elaboration of the framework components will be presented in a series of publications. Presently, the framework is being implemented and tested under different scheduling and claim scenarios. By reducing or eliminating inherent failings and shortcomings of current delay analysis practices, the findings of the study are expected to enhance the industry practices in analyzing time-related claims.

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