# Accelerating Repetitive Construction Projects
With Uncertainty and Contractors’ Judgement

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Accelerating Repetitive Construction Projects

With Uncertainty and Contractors’ Judgement

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Keywords: Schedule acceleration, Fuzzy Set Theory, Repetitive projects, Linear scheduling.

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Abstract

Project acceleration is a common yet complicated task performed by contractors in construction projects. In repetitive projects, contractors often face have to accelerate their projects using tools that are not suited for repetitive projects and that neglect many factors influencing acceleration plans. This paper presents a new method for schedule acceleration of repetitive construction projects. This method brings two main improvements; it captures uncertainty associated with the acceleration cost and allows accounting for contractors own perspective while creating acceleration plans. Activities are prioritized for acceleration based on cost slope and contractors’ judgment. Fuzzy set theory is utilized to model uncertainties associated with acceleration costs, while contractors’ judgement is utilized to account for other influential factors. The developed method provides contractors with a set of measures and indices to evaluate different generated schedule acceleration plans. A case study was analyzed to demonstrate the method’s capabilities and its suitability for repetitive projects.
1. Introduction

In the construction industry, multiple parties are involved in complex projects taking place in highly dynamic environments, surrounded by risks and uncertainties. Throughout projects’ courses, different involved parties often need to accelerate projects. Contractors accelerate projects to recover from delays experienced during the execution of the work, benefit from contractual bonus, avoid penalties, and/or avoid undesirable weather and site conditions. Owners, on the other hand, accelerate projects to take advantage of market opportunities and/or to meet fiscal and business requirements. Schedule acceleration of repetitive construction projects can be a complicated task. This complexity can be attributed to the need to (1) identify critical activities, which is not as simple as in the case of traditional non-repetitive projects, (2) comply with the crew work continuity constraint, and (3) account for uncertainties associated with the required additional cost for compressing durations of individual activities. Consequently, the method at hand aims at addressing these complexities. The presented method works over three sequential stages. The first stage comprises an algorithm that identifies critical activity segments for repetitive projects. The second stage models uncertainties in additional costs and incorporates contractors’ judgement while queuing activities for acceleration. Finally, the third stage follows an iterative approach in assigning acceleration resources and finds near optimum acceleration plans based on users’ preferences.

2. Background

Literature reveals that a wide range of techniques have been introduced to accelerate projects’ schedules at both, the strategic and tactical levels. These techniques can be grouped into five main categories: (1) heuristic procedures (Siemens 1971, Hazini et al. 2004).
2013); (2) mathematical programming (Henderickson 1989, Pagnoni 1990); (3) simulation (Wan, 1994); (4) integration of simulation with genetic algorithms (Wei Feng et al 2000, Ding 2010, Zheng et al 2004, Hazini et al. 2014), and (5) genetic algorithms and fuzzy set theory (Eshtehardian et al 2008 a and b).

Although heuristic-based methods were the first to be introduced, their performance is problem-dependent. They are capable of providing good solutions, however, optimum or near optimum solutions are not guaranteed (Wei Feng et al, 2000, Ammar, 2010). Mathematical programming finds better solutions than search heuristics. Its main limitation is the excessive computational effort once the number of options to complete an activity increases or the network becomes too complex. Such a problem is magnified when trying to accelerate repetitive projects, as the repetition in activities increases the problem size exponentially. Computer simulation based methods require dedicated simulation professionals (Hajjar and AbouRizk, 2002) and experts’ opinions in absence of sufficient numeric data (Chung 2007). Fuzzy set theory (FST) is an alternative approach to the deterministic and probabilistic approaches. FST offers a computationally simpler alternative in comparison to mathematical programming and simulation. FST is also less sensitive to moderate changes in the shapes of input distributions, and does not require the user to make assumptions pertinent to correlations among input parameters (Shaheen et al, 2007). These techniques mentioned above address crashing projects through several approaches, such as assigning more resource hours, replacing selected resources with more productive resources and/or overlapping activities. However, these techniques are all addressing traditional (non-repetitive) projects.

On the other hand, accelerating repetitive construction projects faces an additional
challenge, which is identifying the activities to accelerate. This identification is easier in traditional projects due to the existence of a critical path, accelerating any activity on this path would shorten a traditional project’s duration. On the contrary, there is no similar method for readily identifying the sequence of critical activities or parts of activities which control the total project duration and can be used for accelerating schedules (Arditi et al. 2002 and Hassanein and Moselhi 2005). This renders techniques developed for traditional projects unusable for repetitive projects. Significantly less efforts have been exerted towards accelerating repetitive construction projects, which is the main focus of this research. Only two algorithms have been proposed; both utilize relative alignment of successive activities to identify activities to accelerate in repetitive projects (Hassanein and Moselhi 2005, Bakry et al. 2013). Least aligned activities are activities progressing at a lower rate than their successor. Accelerating such activities would result in shortening their duration, advancing their successor’s start date, and eventually shortening the project’s total duration.

Hassanein and Moselhi (2005) identified the least aligned activity by calculating the difference in moment of the area trapped between successive activity lines around a virtual vertical line. When an activity has a lower rate than its successor the area trapped between itself and its successor will result in a bigger moment of area, and vice versa. They calculated the alignment for each activity, and used the degree of misalignment as a criteria for prioritizing activities for acceleration. Later, Bakry et al. (2013) utilized a similar approach. They calculated the alignment of successive activities at each unit instead of addressing the activity as a whole. This necessitated more calculations, but identified activities to accelerate for each unit, thus enabling a more focused and efficient assignment of additional acceleration resources. Furthermore, Bakry et al. (2013) used the
degree of alignment to identify activities to accelerate, but they prioritized the identified activities for acceleration based on the cost slope, which enables finding the least cost plan to accelerate a project. Although Bakry et al.’s (2013) algorithm forms a more practical solution for accelerating repetitive projects than Hassanein and Moselhi’s (2005), yet they both shared the limitations of not accounting for any form of uncertainty, and limiting their queuing criteria for prioritizing activities to the cost slope.

Looking at criteria used to prioritize activities for acceleration, a recent study established that other criteria in addition to cost slope is utilized in industry for prioritizing and queuing activities for acceleration. Through their survey, Moselhi and Roofigari-Esfahan (2011) identified other factors commonly taken into consideration by contractors while prioritizing activities for acceleration. These factors include resource availability, risk involved, complexity and logistics, sub-contractor related concerns, number of successors, cash flow constraints, weather and others. Such factors have an impact on contractors’ decisions while making schedule acceleration plans. Addressing such factors in addition to the cost slope criteria is bound to generate more realistic acceleration plans.

This paper presents a method for generating and evaluating different acceleration plans for repetitive construction projects while accounting for (1) uncertainties associated with the acceleration cost and (2) contractors’ experience and judgment. The main focus of the method is on identifying which activity segments to accelerate and on prioritizing them for acceleration. This method is to be used when the need arises to expedite a project’s delivery, which means a contract has been signed, and approaches such as selecting a different delivery system (e.g. Fast Track) are not a viable option. The proposed method is designed to be flexible and to allow users to generate scenarios based on the relative
weights assigned to each of the two criteria stated above.

3. Proposed method

Unlike existing tools and techniques, the proposed method integrates contractors’ judgement and uncertainty in acceleration cost in queuing activities for accelerating repetitive projects. Contractors’ judgement accounts for their experience and how a contractor evaluates different influential factors, while uncertainty in acceleration cost models the risk associated with the additional direct cost needed to accelerate critical activities. This method works in an iterative approach towards achieving one of two main objectives, these are meeting a target project duration or a target project total cost.

Identifying Activities to Accelerate

Activities in a schedule are divided into segments, where each activity at each unit is a separate segment. Activities are divided as such to allow accommodating typical and non-typical activities. Typical activities have the same quantity for each unit and progress with the same rate, consequently they are represented in the schedule by straight lines. While non-typical activities, which constitute the general case in construction projects, have different quantities for different units and/or are performed by crews with varying productivities, consequently they are represented by broken lines. Although dividing activities into segments and studying the alignment of and accelerating each segment separately implies performing more calculations, yet it allows more focused assignment of additional acceleration resources. The algorithm presented by Bakry et al. (2013) is utilized to identify activities to accelerate that lead to project schedule compression. The least aligned segment is identified by calculating the difference in moment of the area trapped between successive activity lines around a virtual vertical line. The difference
between a segment’s moment of area and its predecessor’s moment of area is given the symbol Ω. Ω is calculated as shown in Equation 1 (Bakry et al. 2013):

\[ \Omega(i) = \text{Area}(i) \times e(i) - \text{Area}(i+1) \times e(i+1) \]  

(1)

Where \(\Omega(i)\) is the value reflecting the degree of misalignment of segment \(i\), \(\text{Area}(i)\) is the shaded area between segment \(i\) and \((i - 1)\), \(e(i)\) is the eccentricity of the center of gravity to the center line of area \(i\) as shown in Figure 1. Higher values of \(\Omega\) indicate less alignment of activities with their successors and vice versa.

**FIG. 1: Calculating \(\Omega\) for Successive Segments**

Segments with positive values of \(\Omega\) are nominated for acceleration, while segments with negative values of \(\Omega\) are called converging activities, those will not reduce project duration if accelerated. Converging activities are defined as activities progressing at a higher rate than their successor and their predecessor. Consequently these activities are likely to prolong project duration if accelerated as their start date is advanced and hence their successor’s start date. These converging activities can shorten total project duration if they are slowed down (relaxed). Figure 2 illustrates the effect of relaxing converging activities.

**FIG. 2: Effect of Relaxing Converging Activities**

A specially developed MS-Excel application is used to carry out the required calculations of \(\Omega\). The application’s function here is to carry out the schedule calculations and plot the results to save time and effort. The input to the application is the detailed schedule, and the output is the value of \(\Omega\) calculated for each segment as per Equation (1) and the cost and duration of each acceleration plan. As acceleration resources are assigned, as will be explained later on, the application automatically regenerates the schedule and recalculates the new
values of $\Omega$.

**Uncertainty in Acceleration Cost**

Project acceleration is performed by employing additional resources to decrease the duration required to complete the project. Accordingly, the main challenge is to identify the acceleration strategy that would require the least amount of additional cost (Moselhi and Alshibani, 2011). Project acceleration is usually performed as the need arises, without sufficient prior planning during the planning stage. Moreover, project documentation focuses on the original schedule and the final as built schedule, while project acceleration strategy and how it was reached is commonly left out. Hence, contractors do not usually have sufficient historical data to use while planning project acceleration. In view of these constraints and unique conditions associated with accelerating projects, it was deemed appropriate to account for risk and uncertainties in performing the compression process.

The next step after segments with a positive value for $\Omega$ had been identified is to input the acceleration data for each of the acceleration strategies. This data consists of the acceleration cost and impact on duration for each strategy for each activity. Several acceleration strategies were extracted from literature and included in the proposed method. These are (1) working overtime; (2) working double shifts; (3) working weekends and (4) employing more productive crews, while for converging activities strategies for relaxation are (5) using less productive resources or (6) introducing intentional work breaks (Hassanein and Moselhi 2005). Such strategies necessitate enduring an additional cost to enable completing an activity in a shorter duration. To model the risk associated with these additional costs trapezoidal fuzzy numbers are used. This gives users the flexibility to model additional costs without having to narrow down their estimate to a
deterministic number and overlook associated uncertainty. Trapezoidal fuzzy numbers are used to model uncertainties in the context of this method due to several reasons. Fuzzy modelling of uncertainty does not depend on availability of relevant historical data, also the use of trapezoidal membership is not only simpler and requires less computations in comparison to other functions, but also facilitates the process of input data for users in the construction industry. For each segment, a trapezoidal fuzzy number is utilized to express the additional cost required to reduce the duration by 1 unit of time. Trapezoidal fuzzy numbers model a number through 4 values a, b, c and d. Values a and d represent the least and most possible values that number can have, while b and c represent the boundaries of the most possible. For example if a user is uncertain about the exact additional cost for an activity, yet he knows through his experience that the additional cost ranges between $100 and $120 and most possibly between $108 and $115, then he can represent the additional cost using the fuzzy number (100, 108, 115, 120). This number is later defuzzified. Defuzzifying means generating a deterministic value to represent a fuzzy number. This deterministic value is called the Expected Value (EV) of the fuzzy number. The centre of area (COA) method is used for defuzzification, because COA generates an (EV) that matches the probabilistic mean of a normalized fuzzy number. The EV of a general trapezoidal fuzzy number can be expressed by Equation (2) (Shaheen et al., 2007).

\[
\text{EV Trapezoidal} = a + \frac{2(c-b)(b-a)+(b-c)^2+(c-b)(d-a)+(d-a)^2}{3(c-b+d-a)}
\] (2)

The EV value is generated for each fuzzy acceleration cost, and utilized as the cost slope for the corresponding segment. A priority ranking based on cost slope (PCS_i) is assigned for each segment based on their respective cost slope. The segment with the least cost slope is assigned high priority of 1, the segment with the highest cost slope is assigned the
least priority of 5, and the remaining segments are assigned values by interpolation.

**Contractors’ Judgement**

Establishing the cost slope as the only criteria when queuing activities for acceleration results in the least cost acceleration plan, yet overlooks many other influential factors. This method considers contractors’ judgement as an additional criteria when queuing activities for acceleration. This criteria allows users to account for significant parameters affecting the acceleration plan other than cost slope, like resource availability and involved risk. For simplicity and to avoid the need for extensive input data from users, the developed method collates these factors in a single criterion named contractor’s judgment. This criteria allows contractors to indicate their favouring or disfavouring of an activity for queuing in view of factors they see relevant.

Contractors employ their experience by assigning a priority ranking \((PCJ_i)\) to each segment also on a scale of 1 to 5. A score of 1 is assigned to a segment to express the contractors favouring for this segment to be accelerated, a score of 5 reflects the contractors disfavouring, while a score of 3 reflects the neutral case. Scores of 2 and 4 represent intermediate values. Understanding the involved influential factors and quantifying their impact to come up with a priority ranking for the contractor’s judgment, although in a subjective approach, is more comprehensive and realistic than prioritizing activities solely based on cost slope.

Now for the activities nominated for acceleration, each segment has two separate priority rankings, one representing cost slope priority \((PCS_i)\) and one representing contractors’ judgement priority \((PCJ_i)\). Both are merged together to produce a joint priority that will be used to queue activities for acceleration. Relative weights are used to set the comparative
importance of the two ranking criteria, cost slope and contractors’ judgement. These relative weights are used to allow the user to customize the prioritization process according to his specific needs. A bigger weight for the cost slope criteria will make the produced joint priority for an activity more dependent on its cost slope priority and vice versa. For example if a user wishes to build his acceleration plan based equally on the cost slope and the contractor judgment, he would assign both the weight of 0.5. While if he wishes his decision to be more relying on cost than contractor judgment he would assign a weigh of 0.6 for cost slope and a weight of 0.4 for contractor judgment. A weight of 1 for the cost slope criteria and 0 for contractor judgment would generate the least cost acceleration plan. As the user gains experience with this technique he will settle on the weights that better suit his needs. Consequently the joint priority is calculated as per Equation (3) below:

\[ P_i = (PCS_i \times WCS) + (PCJ_i \times WCJ) \]  

Where \( P_i \) is the joint priority for the \( i^{th} \) segment, \( PCS_i \) is the priority assigned to segment (i) based on cost slope, \( PCJ_i \) is the priority assigned to segment (i) based on contractors’ judgment. \( WCS \) and \( WCJ \) are the relative weights assigned to cost slope and contractor judgment, respectively.

**Acceleration**

After joint priorities have been calculated, now the actual acceleration starts. It is performed through incrementally assigning acceleration resources to the segment with the highest joint priority. Acceleration resources are added while taking into consideration each resource’s maximum availability. The segment’s duration is reduced to the new accelerated duration and the rest of the schedule durations and project costs are
regenerated accordingly. The developed method is applicable during the execution phase of the project, i.e. after contract signing and commencement of construction on jobsite. As such, normal cost and normal duration of project activities are considered to have crisp values as would be stipulated in contract documents. The project’s fuzzy total cost is calculated using Equation (4) below:

\[
FTC = DC + IC + \sum_{i=1}^{n}[a, b, c, d]i
\]  

(4)

Where FTC is the project’s fuzzy total cost, DC is project’s direct cost, IC is project’s indirect cost, a, b, c and d are the four values representing the fuzzy acceleration cost of segment (i), and n is the total number of accelerated segments.

After each segment is accelerated, the spread sheet regenerates the schedule, and the new project total cost and duration are plotted. These recalculations include recalculating Ω, as activities relative alignment changes when they are accelerated. The above procedure is repeated in an iterative manner until the targeted cost or duration are achieved, or until no further acceleration is possible. Figure 3 shows the detailed flowchart of the presented method.

**FIG. 3: Flowchart of the Presented Method**

**4. Interpretation of the generated fuzzy output**

As FST was utilized to capture the uncertainty in additional acceleration resources costs and the new project’s total cost is calculated as a fuzzy number. A number of measures and indices are introduced to interpret the results obtained, and to allow comparing and choosing between different possible acceleration plans. These measures and indices aim
at evaluating two aspects of the generated acceleration plan. Firstly, what is the possibility of having the project total cost falling within a specific range, and secondly what is the amount of uncertainty in the proposed acceleration plan.

To evaluate the possibility of having the project total cost fall within a specific range, two values are used, the possibility measure (PM) and the agreement index (AI). The possibility measure (PM) evaluates the degree of belonging to the membership of a targeted fuzzy number (Zadeh 1978). It can also be used to evaluate the possibility of occurrence of different events (Kaufmann and Gupta 1985). The most possible variable in a fuzzy number is the one that has a possibility measure of 1.0; i.e. has a membership value of 1.0. In the current context PM can be applied to evaluate the possibility of achieving a certain targeted cost of the selected acceleration plan. It is also applied to evaluate the possibility of having the cost of an acceleration plan falling within a defined range or being at a given crisp value, as described later in the project example. The possibility measure pertinent to two events takes its value from the maximum membership function value resulting from the intersection area of the two events’ functions.

It should be noted that in applying the possibility measure, no consideration is given to the size of intersection area. The possibility measure in certain circumstance does not provide an insightful assessment of the compatibility between the tested and targeted fuzzy events (Lorterapong and Moselhi, 1996). To address this shortcoming, the Agreement Index (AI) is used to compliment the PM. AI measures the conformance of two events through calculating the ratio of the intersection area between the two fuzzy events against the area of the event being assessed (Kaufmann and Gupta 1985). For example, assuming that A and B are two events, the agreement index of A with respect to B; AI (A, B) is defined as
per Equation (5). The area of intersection can be determined using partial integration given the four numerical values of a trapezoidal fuzzy number \([a, b, c, d]\). The higher the AI the higher the conformance between the two fuzzy events, and vice versa. In the proposed methodology, AI can be used to determine the probability of finishing the project within a certain budget or before a certain date.

\[
AI(A, B) = \frac{\text{area } A \cap B}{\text{area } A}
\]  

(5)

On the other hand, to evaluate the amount of uncertainty plaguing the proposed acceleration plan a number of measures are utilized. These are fuzziness \((F(A))\) as a measure of vagueness and variance and standard deviation as measures of how far away can a number lie from the expected value. The fuzziness measure \((F(A))\) used in this research is based on that developed by Klir and Folger (1988), and it can be calculated using the following equation:

\[
F(A) = \int_{a}^{b} (1 - |2A(x) - 1|) \, dx = b - a - \int_{a}^{b} 2A(x) - 1 \, dx
\]  

(6)

For a crisp number and a fuzzy uniform number, the fuzziness measure is equal to zero because the lack of distinction between a fuzzy uniform number or a crisp number and their complements is zero. The variance values of trapezoidal fuzzy numbers is calculated as originally introduced by van Dorp and Kotz (2003):

\[
\text{Variance(Trapezoidal)} = \left( \frac{(b-a)}{2} + \frac{1}{3} (c-b)^3 \right)^{0.5}
\]

(7)
Finally, the standard deviation for trapezoidal fuzzy number \((a,b,c,d)\) can be calculated using Equation (8):

\[
\sigma(a, b, c, d) = \frac{2(d-a)+c-b}{4}
\] \hspace{1cm} (8)

In the context of the presented method the measures of fuzziness, variance and standard deviation can be used to evaluate the produced acceleration plan. For example they can raise a flag in case too much fuzziness is noticed in a total cost. They could also be utilized to identify the acceleration plan with less uncertainty.

5. Case Study

The developed method was applied to a case study drawn from literature to verify and demonstrate its basic features. The case study, which was originally presented in El-Rayes (1997), consists of a 15 Km three-lane highway project, each Km consists of 5 sequential activities. These activities, in their order of precedence, are: (1) cut and chip trees; (2) grub and remove stumps; (3) excavation; (4) base; and (5) paving. All precedence relations are finish to start, with no lag time. Each activity is divided into 15 segments of equal lengths, each is 1km. This project includes typical and non-typical activities, as activities quantities vary from one segment to another. It also includes sequential and non-sequential activities, as the earthmoving activity starts at unit 4, then proceeds backwards till unit 1, then resumes again at unit 5 till 15. The five activities are executed by 15 crews, each working continuously without interruptions, this shows that trying to manually identify a critical path to accelerate is not feasible. Basic project schedule data can be found elsewhere (El-Rayes 1997). Only 1 acceleration strategy is considered in this example, which is adding overtime hours, with a maximum of 4 hours per activity per day. This is because the focus
of this method is on identifying and prioritizing segment for acceleration. In the case that multiple acceleration strategies are available for an activity, each strategies cost slope and contractor’s judgement rankings are calculated separately and the one with the highest joint priority would be chosen. Project’s indirect cost is 4,000 $/day. Overtime cost is 300$/Hr for “cut and chip trees” crews, 600$/Hr for “grub and remove stumps” crews, 700$/Hr for “excavation” crews, 400$/Hr for “base” crews, and finally 450$/Hr for “paving” crews. The initial schedule had a normal duration of 83 days and a total cost of $1,878,300. Table 1 shows activities’ durations, direct costs and acceleration costs, while Figure 4 shows the original project schedule. The acceleration costs shown in table are the total costs of the number of overtime hours needed to reduce the project’s duration by 1 day.

Table 1: Activities Durations, Direct Costs and Acceleration Costs

FIG. 4: Original Schedule

Four different scenarios are studied to demonstrate the capabilities of the developed method. These scenarios represent different targets a contractor can have during a project. These scenarios are:

1. The first is the base case scenario in which the acceleration is performed based only on cost slope, without considering uncertainties. The aim is to find the least possible project total cost to provide bases for comparison.

2. The second scenario similarly aims to find the least possible project total cost but takes into consideration contractor’s judgement as an additional queuing criteria.
3. The third scenario targets applying the developed method taking into consideration contractor's judgement and uncertainties in estimating acceleration costs to find the least project total cost.

4. The fourth scenario applies the developed method to predict the least cost acceleration plan that meets a target schedule of 78 days, under the same conditions of scenario 3.

**Scenarios analysis**

**Scenario 1**

In this scenario, the acceleration cost of each segment is taken as a crisp number, as in Table 1. The spreadsheet calculates the values of $\Omega$ for each segment. Then the segment with the least cost slope is given the highest priority of 1, and the segment with the largest cost slope is given a priority of 5. The rest of the segments are given a ranking between 1 and 5; proportional to the values of their respective cost slope. As contractor's judgement is not considered in this scenario, cost slope is the only ranking criteria for activities. In an iterative manner, overtime hours are assigned to the segment with the highest priority. After each overtime hour is assigned the new duration for accelerated segment is calculated, and the schedule's duration, values of $\Omega$ and project cost are updated accordingly. Also the total project duration and total project cost are plotted. After drawing the set of possible acceleration plans (Figure 6), the developed method locates the least project total cost to be $1,878,000, and the corresponding duration is 79 days.

**Scenario 2**

In this scenario, the developed method is used to find the least cost acceleration plan while considering the cost slope and contractor's judgment, however, the uncertainties
associated with the acceleration cost are not considered. The cost is set to be more important than contractor’s judgement and their importance, expressed by their relative weights, is set to 0.6 and 0.4, respectively. The cost slope ranking is based on deterministic costs same as in the previous scenario and contractor’s judgement has been added. For simplicity, each activity is given the same rank throughout all of its segments. Contractor’s judgement is set to rank 3 for activity “Cut and Chip”, set to 1 for the activity “Grub Stumps”, set to 5 for the activity “Earthmoving”, set to 2 for the activity “Base”, and finally is set to 4 for the activity “Pave”. Values of $\Omega$ are calculated, and overtime hours are assigned to the segments with positive value for $\Omega$ and the highest joint priority ($P_i$). The method finds the least project total cost to be $1,892,600, and the matching duration is 79 days.

Scenario 3

In this scenario the ranking assigned to contractor’s judgement is kept the same as that in the second scenario, but the additional cost needed for project acceleration is assigned in the form of trapezoidal fuzzy numbers. That additional cost is expressed in 4 values $(a,b,c,d)$, which are used as input to Equation (2) to determine the expected value (EV) for each fuzzy number. These calculated EV values are used to determine the cost slope ranking for different activities. The relative weights of each of the two rankings are left at 0.6 for cost slope and 0.4 for contractor’s judgment. Those relative weights are used to combine cost slope priorities and contractors’ judgement priorities to produce joint priorities ($P_i$). The results of running this scenario are used to perform risk analysis for the resulting acceleration plan. Table 2 below shows the fuzzy cost of overtime hours for different activities and the calculated expected value.
Table 2: Crews’ Fuzzy Overtime Cost

In this scenario, the method identifies the least project fuzzy total cost to be \( \{1,887,075, 1,887,250, 1,888,150, 1,889,820\} \) dollars and the corresponding duration is 81 days. The EV value of the fuzzy total cost is $1,888,137. The project’s fuzzy total cost is plotted in Figure 5. It can be seen from that Figure that the most possible and plausible total cost is between $1,887,250 and $1,888,150, as this is the range of project total cost having a membership value (\( \mu \)) of 1. To further demonstrate different interpretations that could be driven from the generated fuzzy total project cost, the possibility measure is applied to evaluate the possibility of different events. The following three events were examined:

- What is the possibility of accelerated project cost being between $1,888,900 and $1,889,400?
- What is the possibility of the accelerated project cost being exactly $1,887,700?
- What is the possibility of the accelerated project cost being less than $1,887,700?

**FIG. 5: Fuzzy total project cost for least cost acceleration plan (scenario 3)**

To examine the above listed possibilities against the trapezoidal fuzzy total project cost, all studied possibilities have to be expressed as trapezoidal fuzzy numbers as well. To examine the first possibility, the targeted cost is expressed as \( \{1,888,900, 1,888,900, 1,889,400, 1,889,400\} \). These values have corresponding degrees of membership equal to (0.55, 0.55, 0.25, 0.25) respectively. Accordingly, the possibility that the project compression cost falls between $1,888,900 and $1,889,400 is 0.55. As for the second possibility which sets the cost of the acceleration plan to exactly $1,887,700, the cost is also expressed as a trapezoidal fuzzy number \( \{1887700, 1887700, 1887700, 1887700\} \). The elements forming this number have corresponding degrees of membership of (1.00,
As the possibility measure pertinent to two events takes its value from the maximum membership function resulting from the intersection area of the two, the possibility of having the cost of the project acceleration plan equal to $1,887,700 is 1.0.

Similarly, for the third event which examines the possibility of having the total project cost less than $1,887,700, that cost is expressed \{1887700, 1887700, 1887700, 1887700\}, with its elements having corresponding degrees of membership of (1.00, 1.00, 1.00, 1.00). Therefore the possibility of having the cost of the project acceleration plan less than $1,887,700 is also 1.0.

As can be seen from the last 2 cases, although different possibilities were being evaluated, they both had a possibility measure equal to 1.00. This is why agreement index (AI) is utilized to augment the evaluation, through depending on the size of the intersection area. The area of intersection of the target cost being exactly $1,887,700 is less than the area of intersection of the target cost being less than $1,887,700. As per Equation 4, the agreement index is 0.0 for the first case and 0.3 for the second case.

Scenario 4

In this scenario, the developed method is tested to predict the cost of accelerating project schedule to a targeted duration of 78 days. The method predicts the project total to be $1,893,918. Applying the possibility measure reveals that the most possible and plausible compression project cost is between $1,892,270 and $1,894,870.

Table 3 show a comparison between the outputs of the four scenarios. It can be seen from the results that the developed method offers contractors a tool to evaluate the possibility of achieving a certain targeted plan; which is not possible to determine using other existing
project acceleration techniques. In addition, possibility measure, agreement index, expected value, fuzziness measure, and variances measures were applied to help describe the degree and characteristics of the uncertainty associated with the cost of the selected accelerating plan. Figure 6 portrays the comparison of the results generated for the first three scenarios and the original schedule’s duration and total cost.

Table 3: Comparing Output of 4 Scenarios

C = total project cost of acceleration plan

FIG. 6: Comparison of the results

An overview of the acceleration plans generated for the 4 scenarios detailed above reveals a number of facts. The first scenario that overlooked contractor’s judgement and addressed the cost slope in a deterministic approach located the least project’s total cost among the 4 scenarios. In the second scenario, the prioritization of segments for acceleration differed than the first scenario as the contractor’s judgement was taken into consideration, thus shifting the selection of segments to accelerate away from the least costly segments. Accordingly the identified least cost was more than that identified in the first scenario. Furthermore, when uncertainty was also considered, the acceleration plan changed accordingly, and the identified least total cost was still more than the first cost based scenario and at a different duration too. The fourth scenario had a specific target which was to reach a duration of 78 days only, which is shorter than the least cost duration identified in the 3 previous scenarios. The identified plan achieved that duration at a cost higher than all 3 previous plans. These results show that the selection of the acceleration plan differs when uncertainties in additional cost and/or contractor’s judgement are taken into consideration. The above scenarios were analyzed using the developed spread sheet
application. The application is designed using Microsoft Excel® 2010 Macro-Enabled Worksheet. The computer used has a Core (TM) i5-2400 CPU at 3.1 GHz processor and 8.00 GB of installed memory. The running time for each of the four scenarios was below 2 minutes.

6. Summary and concluding remarks

This research presents a new method for acceleration of repetitive construction projects. The developed method fulfilled the purpose of the research through bringing to contractors and project managers a number of improved features: (1) it considers contractors’ judgement in selecting which activities and which repetitive units to be accelerated; (2) it accounts for uncertainties associated with the activities’ acceleration costs; (3) it allows the user to perform risk analysis based on generation and evaluation of different scenarios. In addition to these main features, the presented method had a number of characteristics that make it practical and appealing to use. The contractor’s judgment criteria lets managers incorporate factors they see influential in addition to the cost slope when planning their acceleration. Allowing managers to account for uncertainty associated with acceleration cost paves the way for providing closer to reality estimates as the manager doesn’t have to narrow down his estimate to a single deterministic value. While the suggested risk analysis parameters facilitate deeper evaluation of different scenarios. These incorporated features form an addition to existing tools and techniques available for accelerating repetitive construction projects. The presented method has a number of limitations. As the relative alignment for successive activities is evaluated for each unit separately rather than once for the whole activity, a lot of calculations have to be performed, which could reduce the applicability of the method to larger and more complex projects. Such a limitation could be
even more pressing if a contractor has many available acceleration strategies to choose from. As results revealed that accounting for contractor judgment generates different acceleration plans, it is recommended to try account for contractor judgment in a more objective approach. It is also recommended to account for uncertainty in variables additional to the cost slope, such as the productivity of additional acceleration resources.

The developed method can accommodate typical and non-typical activities, and sequential and non-sequential activities. The presented method selects from available alternatives for project acceleration while maintaining crew work continuity. A highway construction project drawn from the literature was analyzed to demonstrate the use of the developed method and to illustrate its capabilities. Different scenarios were run to fully evaluate the presented method. The results of these scenarios illustrate how the acceleration plan differed when the uncertainty in additional costs and contractor’s judgement was included as an additional queuing criteria. Although the cost based plan found a less total project cost but it didn’t include other influential factors. Also when the uncertainty was taken into consideration, further analysis was available to shed more light on different possibilities of different completion plans. The results show that (1) the developed method can produce more practical schedule acceleration plans that meet the level of possibility measure set by the user, and (2) FST based methods can be used effectively for schedule acceleration of repetitive projects, accounting for uncertainties without needing relevant historical data and fitting probability distribution curves compared to probabilistic based methods. The developed automated spreadsheet application facilitates the use of the developed method and allows users to fine tune it to suit their respective project conditions.
References


• Moselhi, O., and Alshibani, A., 2011. Cost and Experience Based Method for Project Acceleration. In proceedings of The Sixth International Structural Engineering and Construction Conference (ISEC-6) Zürich, Switzerland, 21-26 June.


Table 1: Activities Durations, Direct Costs and Acceleration Costs

<table>
<thead>
<tr>
<th>Unit</th>
<th>Cut and chip trees</th>
<th>Grub &amp; remove stumps</th>
<th>Excavation</th>
<th>Base</th>
<th>Paving</th>
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<tbody>
<tr>
<td>1</td>
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<td>4</td>
<td>900</td>
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### Table 2: Crews’ Fuzzy Overtime Cost

<table>
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<tr>
<th>Activity</th>
<th>Fuzzy Overtime Cost $/hr.</th>
<th>Expected Value</th>
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<td>B</td>
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<td>Cut and Chip</td>
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<td>290</td>
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<td>Grub Stumps</td>
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<td>580</td>
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<td>Earthmoving</td>
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<tr>
<td>Pave</td>
<td>400</td>
<td>430</td>
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### Table 3: Comparing Output of 4 Scenarios

<table>
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<tr>
<th>Method</th>
<th>Input distribution</th>
<th>Output distribution</th>
<th>Total cost ($)</th>
<th>EV($)</th>
<th>Duration (days)</th>
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<tbody>
<tr>
<td>Scenario 1</td>
<td>Crisp</td>
<td>Crisp</td>
<td>1,878,000</td>
<td>1,878,000</td>
<td>79</td>
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<tr>
<td>Scenario 2</td>
<td>Crisp</td>
<td>Crisp</td>
<td>1,892,600</td>
<td>1,892,600</td>
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<tr>
<td>Scenario 3</td>
<td>Trapezoidal</td>
<td>Trapezoidal</td>
<td>(1887075,1887250,1888150,1889820)</td>
<td>$1,888,137</td>
<td>81</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Trapezoidal</td>
<td>Trapezoidal</td>
<td>(1890895,1892270,1894870,1897460)</td>
<td>1,893,918</td>
<td>78</td>
</tr>
</tbody>
</table>
Figures Captions List

FIG. 1: Calculating $\Omega$ for Successive Segments

FIG. 2: Effect of Relaxing Converging Activities

FIG. 3: Flowchart of the Presented Method

FIG. 4: Original Schedule

FIG. 5: Fuzzy total project cost for least cost acceleration plan (scenario 3)

FIG. 6: Comparison of the results
Start

Divide schedule into segments

Input repetitive schedule data

Input acceleration data: available resources and fuzzy costs

Calculate $\Omega$ for each activity segment

For segments with +ve value for $\Omega$, calculate the cost slope for different acceleration strategies

Assign priorities based on cost slope (CS) on a scale of 1-5

Assign priorities based on contractor's judgment (CJ) on a scale of 1-5

Assign weights for CJ and CS, and generate combined priorities on a scale of 1-5

Accelerate segment with highest combined priority

Update schedule

New project cost = Direct $ + Crashing $ + Indirect $

Results interpretation

Satisfying results?

Yes

Report accelerated schedule and new cost

End

No

Do all segments have least possible duration?

Yes

Achieved desired duration?

No

Yes

End

No

Input repetitive schedule data

Input acceleration data: available resources and fuzzy costs

Calculate $\Omega$ for each activity segment

For segments with +ve value for $\Omega$, calculate the cost slope for different acceleration strategies

Assign priorities based on cost slope (CS) on a scale of 1-5

Assign priorities based on contractor's judgment (CJ) on a scale of 1-5

Assign weights for CJ and CS, and generate combined priorities on a scale of 1-5

Accelerate segment with highest combined priority

Update schedule

New project cost = Direct $ + Crashing $ + Indirect $
Original duration
83 days

Cut and chip
trees

Remove stumps

Earthwork

Base

Pave