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Journal of Architectural Environment & Structural Engineering Research
https://ojs.bilpublishing.com/index.php/jaeser

ARTICLE

Assessing the Impact of the Lead/Lag Times on the Project Duration Estimates in Highway Construction

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ARTICLE INFO

Article history
Received: 21 June 2021
Accepted: 5 August 2021
Published Online: 10 August 2021

Keywords:
Scheduling
Highway projects
Lead
Lag
Time sensitivity measures

ABSTRACT

The literature mentions multiple factors that can affect the accuracy of estimating the project duration in highway construction, such as weather, location, and soil conditions. However, there are other factors that have not been explored, yet they can have significant impact on the accuracy of the project time estimate. Recently, TxDOT raised a concern regarding the importance of the proper estimating of the lead/lag times in project schedules. These lead/lag times are often determined based on the engineer's experience. However, inaccurate estimates of the lead/lag time can result in unrealistic project durations. In order to investigate this claim, the study utilizes four time sensitivity measures (TSM), namely the Criticality Index (CI), Significance Index (SI), Cruciality Index (CRI), and the Schedule Sensitivity Index (SSI) to statistically analyze and draw conclusions regarding the impact of the lead/lag time estimates on the total duration in highway projects. An Excel-based scheduling software was developed with Monte Carlo simulation capabilities to calculate these TSM. The results from this paper show that the variability of some lead/lag times can significantly impact the accuracy of the estimated total project duration. It was concluded that the current practices used for estimating the lead/lag times are insufficient. As such, it is recommended to utilize more robust methods, such as the time sensitivity measures, to accurately estimate the lead/lad times in the projects scheduled.

1. Introduction

Developing an accurate work schedule requires high precision estimates of both work quantities and production rates. These estimates are used to determine the activity duration and calculate the total project duration. However, there are many unforeseen factors, such as weather, traffic, and soil type that can cause changes to the estimated quantities and production rates resulting in inaccurate estimated durations. Many of these factors have been identified and addressed in the literature and discussed thoroughly as documented by the Federal Highway Administration (FHWA) [1].

One critical factor that is usually underweighted but can negatively impact the project duration is the estimated lead or lag time between activities [2]. The Texas Department of Transportation (TxDOT) considers it as a risk when developing their contract time estimates. It is

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DOI: https://doi.org/10.30564/jaeser.v4i3.3383

theorized that additional information on the impact of the lead/lag time can improve the contract time determination system performance [2]. The Project Management Body of Knowledge (PMBOK) guide describes the lead time as "an acceleration of the successor activity," while the lag is described as "a delay in the successor activity [3]." The lead/lag time does not occur due to external factors such as weather or material delay; instead, it occurs as a result of the nature that the activities have in relation to each other.

Traditionally, the lead/lag time (referred to as lag time from this point forward) is expressed as a number of days that needs to be accounted for before starting or ending the succeeding activity. However, expressing the lag time as a percentage of the predecessor activity duration is a common practice in highway projects [2]. For example, a given activity, "A", may have a duration of 10 days and a Start-to-Start relationship with another activity, "B". If they had a lag of 50%, activity "B" would not be able to start until 5 days after activity "A" had begun.

The literature reviewed show that several studies have addressed various factors that can affect the duration of construction projects. However, none of these previous studies addressed the impact of the effect of lag time on the project total duration. Usually, planners estimate the lag time using their personal experience [2]. However, inaccurate estimation of the lag times can lead to unrealistic project durations [2]. Hence, it is essential to investigate the impact of the estimated lag times on the project duration. This study presents a thorough analysis of the effect of the inaccuracy in estimating the lag times on the estimated project duration in highway construction.

2. Literature Review

The literature reviewed was organized into four different categories. The first category focuses on the most common factors that affect the production rates of activities in highway projects. The second category discusses different scheduling methods that are used by various state Departments of Transportation (DOTs). The third one discusses the four time sensitivity measures (TSM) that have been utilized for the analysis performed in this study. Lastly, the fourth section presents a brief review of the Monte Carlo simulation since it is essential for calculating the TSM.

2.1 Factors Affecting the Production Rates of Highway Projects

The literature includes several studies that addressed factors that can impact construction productivity and, subsequently, the total project duration. The factors reviewed included weather conditions, location, traffic, equipment, and soil type.

Weather is one of the major factors that can have a major influence on construction operations. Several studied focused on the effect of different weather attributes, such as temperature, rain, wind speed etc.., on the production rates in construction sites [4-10]. For instance, a study by Koehn and Brown showed that the maximum productivity can be achieved in a temperature range of 50°F to 80°F [4]. This finding was supported by other studies that reported a similar range for temperature comfort [5,6]. Other research focused on the impacts of rainfall; one study showed that rainfall can affect construction operations for days after it stops due to the water absorbed by the materials stored on site [7]. Due to the correlation between the impacts of different weather conditions on production rates, other studies focused on the development of comprehensive models for assessing the impacts of different weather attributes collectively including rain, temperature, windspeed, and snow on different construction operations [8-10].

The type of soil can have a significant impact on the project duration as production rates tend to vary based on the soil types encountered in the project. For instance, the duration of earthmoving activities using the same crew and equipment can differ based on the soil capability to absorb or drain water after rainfall events [7]. Also, one study found that drilling closer to a riverbank can take longer than drilling in a dry soil [11].

Previous studies have also shown that the project location can affect the duration of construction projects. A study showed that urban projects in developing countries take less time than rural projects because of the availability of skilled workers and equipment [12]. However, developed countries like the U.S. have lower productivity in urban areas due to the higher annual average daily traffic (AADT). Generally, urban areas experience more congestion, which delays activities and prolongs the project duration [13].

In reality, location and traffic often correlate with each other, since AADT rates vary based on location. Specifically, greater traffic flow causes longer activity durations in asphalt construction when material is delivered [14]. Some studies have discussed and presented tools, such as simulation models and manuals, that can be used to assess the impact of traffic on production rates [15].

Contractors also consider labor and equipment as a significant source of delays in projects [16]. One study assessed the impact of the equipment on earthmoving activities in construction projects [17]. Other studies have discussed the technological advances of equipment for different construction activities over time [18,19]. Also, some

DOI: https://doi.org/10.30564/jaeser.v4i3.3383

studies focused on calculating the production rates for specific equipment. For example, Ok and Sinha presented a model that estimates the productivity of dozers [20]. The consensus in all these studies is that advancement in equipment technology has led to an increase in productivity and, hence, shorter durations.

Other factors that impact the project time have also been briefly discussed in different studies. Some studies have reported that the productivity rates decrease in larger crew sizes [21,22]. Sanders and Thomas confirm this finding as they have indicated that crews composed of small number of workers are more efficient [23]. Another study showed that higher work quantities resulted in higher productivity due to the recurrence of the activity [21]. Additionally, Riley et al. found that material delivery schedules can lead to lower production rates, which result in longer activity durations [24]. Lastly, nighttime operations can negatively impact the production rate due to the low visibility and fatigued labor [25].

2.2 Scheduling Highway Projects

Construction projects, including highway projects, require special consideration of the various uncertainties that can impact the activity durations and the difficulty in formulating the project schedule given the limitations on resources [26]. To facilitate project scheduling, many techniques have been adopted by professionals in the industry. These techniques include deterministic and probabilistic methods.

The most common scheduling technique used in the construction industry is the Critical Path Method (CPM) [26]. The CPM is easy to use and implement since it only requires one estimate for each activity duration; that makes it very convenient for projects with many activities [27]. The CPM uses only deterministic durations and focuses on identifying the longest (critical) path in the project schedule network. However, scheduling construction project with CPM is unrealistic and often results in inaccurate project schedules given that the nature of the construction activities is probabilistic.

Although probabilistic scheduling techniques provide a more feasible alternative for estimating accurate durations in highway projects, they are rarely implemented by DOTs. This is because obtaining the data needed to establish probability distributions for the project activities, as the case is in the Program Evaluation and Review Technique (PERT), is a laborious and time-consuming job [28-31]. Therefore, some studies have suggested to utilize only two time estimates instead of three in the case of PERT [30,32,33]. Other probabilistic techniques, such as Monte Carlo (MC) Simulation, can be very time consuming and require high computational skills.

To facilitate and standardize the process of estimating the activities durations and scheduling highway projects, many state DOTs have developed contract time determination systems (CTDS), such as Texas, Louisiana, Kentucky, and Oklahoma [34-38]. Other states have also developed tools for determining the production rates based on statistical analysis [39,40]. Furthermore, surveys have showed that some states, including Florida, Wyoming, and New Jersey, still determine the contract time using Gantt charts and the CPM [41-43].

2.3 Time Sensitivity Measures

Time sensitivity measures provide further insights about the uncertainty of a given project duration by deploying four steps, which are: 1) creating the base project schedule, 2) modeling the activity durations as probability distributions, 3) scheduling the project using Monte Carlo simulation, and 4) computing the values of the TSM using the simulation outputs [44]. The calculations of the TSM are based on some of the characteristics of the project activities, such as the frequency of their existence on the critical path, the amount of float available for each activity, and the variability of the activity duration to reflect the impact of a given activity on the total project duration, as will be discussed in the following sections [44-46].

The Criticality Index (CI) was first introduced as the probability of a given activity being on the project critical path [44-46]. Further studies utilized different approaches to determine the criticality of an activity [47-49]. However, it has been stated that the CI is insufficient for measuring the project risk since activities with a high CI may not always have a significant impact on the project duration. This is due to the fact that such activities -with high CI- may have a low duration so that their impact on the project duration is insignificant [46].

Williams identified problems with the CI; thus, he introduced the Significance Index (SI) to consider the criticality of the activity along with the activity duration and available slack (float) [50]. The SI reflects “the relative importance between the activities.” However, the SI did not properly evaluate activities in some examples [51]. A case was shown where two activities were on the same critical path and had the same SI and CI values, but one of them should have been more significant due to its longer duration [51].

The Cruciality Index (CRI) was also introduced by Williams as a more advanced method to assess the relative importance of an activity; it measures the correlation between the activity duration and the projects duration [50]. The index can use different correlation methods, such as Pearson’s

DOI: https://doi.org/10.30564/jaeser.v4i3.3383

product-moment, Spearman's rank, or Kendall's tau rank correlation [44,52]. However, Williams found the CRI to be counter-intuitive since it measures the risk of the activity in the project [50]. For example, if an activity is always critical with no uncertainty in its duration, its CRI value will be 0.

The Schedule Sensitivity Index (SSI) was proposed by the PMBOK to measure the relative importance of an activity [3]. The measure uses the CI and standard deviations of the activity and the project durations [44,46]. Similar to the shortcoming of the CRI, Elshaer noted that the SSI will be 0 if the activity duration is constant even though the activity is always critical [52].

2.4 Monte Carlo Simulation

Monte Carlo (M.C.) simulation is often used in project management to determine possible project outcomes with respect to a designated objective, such as time or cost, using a given probability distribution [53]. In construction projects, M.C. simulation can be deployed using three-point estimates to represent the pessimistic, most likely, and optimistic durations of a given activity as a triangular distribution [54]. A triangular distribution is commonly used in construction project since the activity durations follow a beta distribution which can be approximated to a triangular distribution [55].

The probability distribution is used to randomly select a duration for each activity to schedule the project and calculate the total duration. This procedure is repeated multiples times based on the target precision and the allowed computational time. M.C. simulation is considered a valuable technique because of its capability to simulate multiple possible scenarios [56]. This process may cause a change in the critical path which also changes the total project duration [57]. Because of this capability, it has been commonly used for risk assessment in project management [58-71]. The complete process of deploying M.C. simulation to calculate the four time sensitivity indexes is discussed in the following sections.

3. Problem

The effect of the lag time is usually underestimated; however, it can be critical and lead to unrealistic estimated project durations. To demonstrate this point, Figure 1-a shows a schedule where all activities are critical. Normally, crashing the duration of an activity that is on the critical path should shorten the total project duration. This concept does not always apply when there is an illogically estimated lag time in the schedule, as shown in this example (Figure 1-a). The normal total project duration is 22 days. When activity "B" is crashed to 12 days instead of 15, the total duration stays the same due to the effect of the unjustified lag time between "B" and "C". However, when the lag time is excluded, the total project duration decreases when activity B is crashed to 12 days (Figure 1-b).

4. Methodology

A review of the literature was initially conducted to gather information regarding the scheduling methods used for highway projects. Part of the review also focused on TSM and their application to assess the impact of different types project activities on the estimated total project duration. To be able to utilize these sensitivity measures, a modification was introduced in scheduling any project, where the lag times were modeled as individual dummy activities. These dummy activities have durations equal to the lag time and maintain the same relationship between its original predecessor and successor activities, as shown in Figure 2.

Additionally, the calculations of the TSM require the use of Monte Carlo (M.C.) simulations, so an Excel-based scheduling software was developed to run the simulations needed to calculate the TSM for the different project activities. The user inputs the project schedule with the three-point duration estimates and the software simulates it depending on the number of runs desired. The program facilitates importing and exporting information between the data collection sheets. Ultimately, the four time sensitivity measures are output based on the information from the M.C. simulation.

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A sample of projects were collected from the Texas Department of Transportation (TxDOT). A sample of the most frequent lag activities were chosen for the application and analysis. A set of at least 30 data points were collected for each of the lag activities for statistical justification. Statistical analysis was deployed to draw conclusions about the effect of the lag time on the project estimated duration based on the four sensitivity measures previously discussed. The complete methodology process is illustrated in Figure 3.

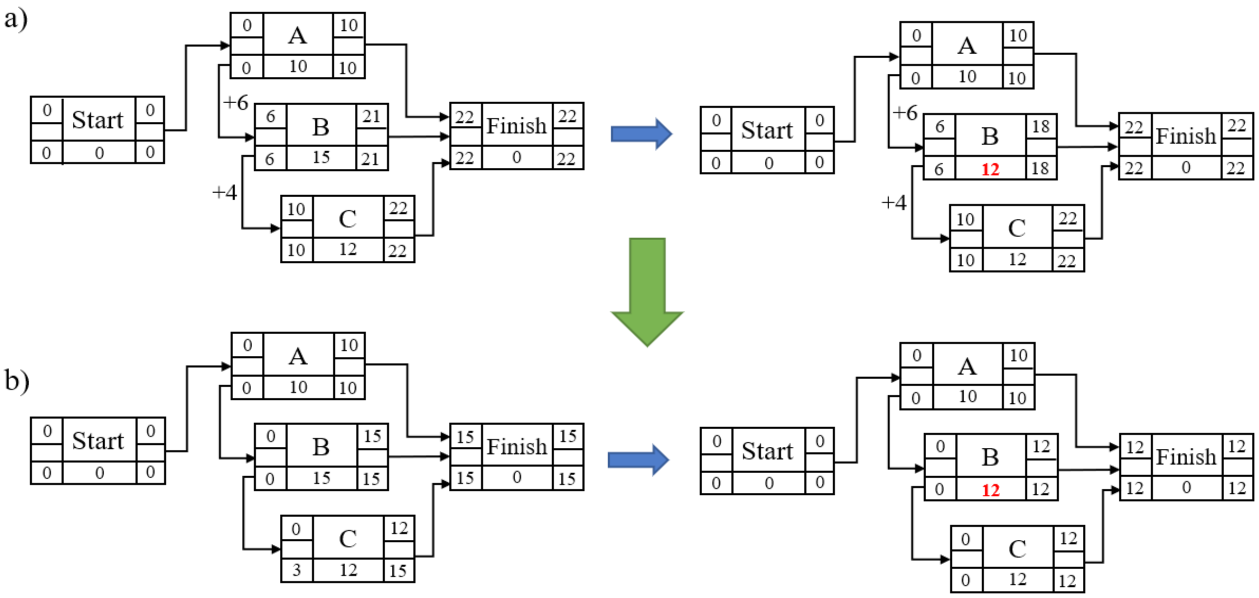


Figure 1. Crashing of activity B when a) there is lag and b) there is no lag.

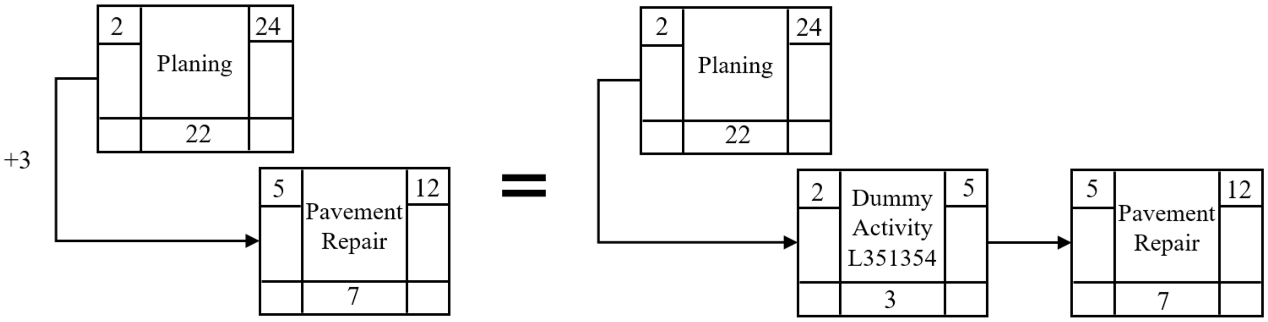
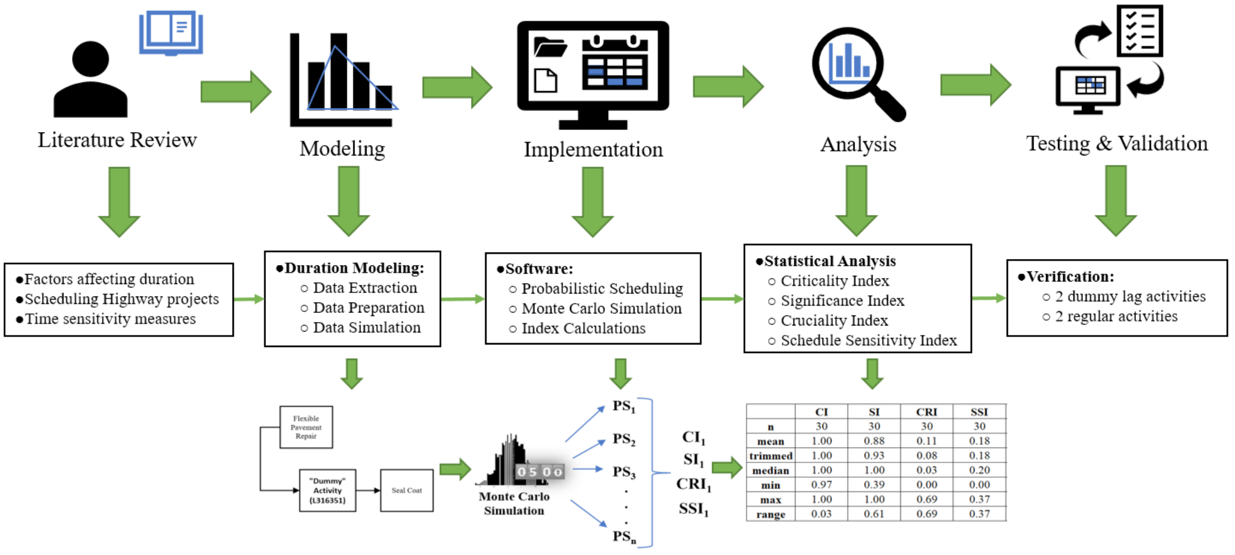


Figure 2. Modeling 2 activities from a schedule.



	CI	SI	CRI	SSI
n	30	30	30	30
mean	1.00	0.88	0.11	0.18
trimmed	1.00	0.93	0.08	0.18
median	1.00	1.00	0.03	0.20
min	0.97	0.39	0.00	0.00
max	1.00	1.00	0.69	0.37
range	0.03	0.61	0.69	0.37

Figure 3. Methodology process.

DOI: https://doi.org/10.30564/jaeser.v4i3.3383

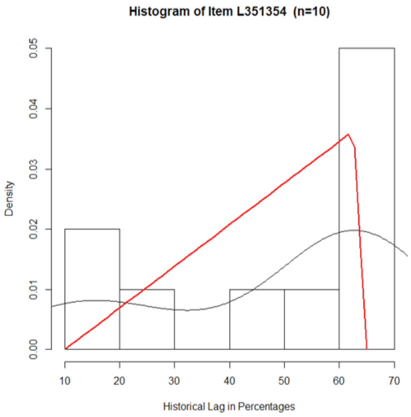
5. Model Development

The model developed to assess the impact of the lag time on the project duration is comprised of three main steps, which are 1) lag time and project activity duration modeling, 2) software development to run M.C. simulation, and 3) time sensitivity measures calculation.

5.1 Duration Modeling

To assess the impact of the lag time properly, a sample of overlay highway project schedules were collected. Overlay projects involve the leveling up or surfacing of a road using hot-mix asphalt. After identifying the lag time throughout the selected projects, they were modeled as dummy lag activities, as shown previously in Figure 2. Identical lags between the same successor and predecessor were traced throughout the projects to gather data points for modeling the dummy lag activity durations as probability distributions. A triangular distribution was created for each dummy lag activity using different duration values collected throughout the sample projects using the R statistics software, as shown in Figure 4.

Dummy Name	Item	Predecessor	Lag (%)
L351354	Flexible Pavement Structure Repair	Planing and Texturing Pavement	50, 10, 12, 65, 65, 65, 65, 65, 50, 25



Dummy Name	Item	Predecessor	Pessimistic (%)	Most Likely (%)	Optimistic (%)
L351354	Flexible Pavement Structure Repair	Planing and Texturing Pavement	65	61.83	10

Figure 4. Creating the triangular distribution for the dummy lag activity.

The project schedules were modified by replacing the normal lag time with the dummy lag activities. Additionally, the durations of all project activities, including the dummy activities, were represented by probability distributions created using historical data collected from the selected overlay projects. Activities that had deterministic values (same values) across all the projects reviewed were modeled probabilistically by calculating the pessimistic and optimistic values as ±0.001 the original duration.

5.2 Software Development

The deployment of the time sensitivity measures to assess the effect of the lag times on the project duration necessitated the development of a software that can schedule the selected projects and simulate them using the Monte Carlo technique. The outputs of the simulation, such as activity duration, activity slack, and project duration, are used to calculate the time sensitivity indexes for the project duration using a predefined set of equations. The software was created using Visual Basic Application (VBA) through Microsoft Excel. The main screen for the scheduling software is shown in Figure 5.

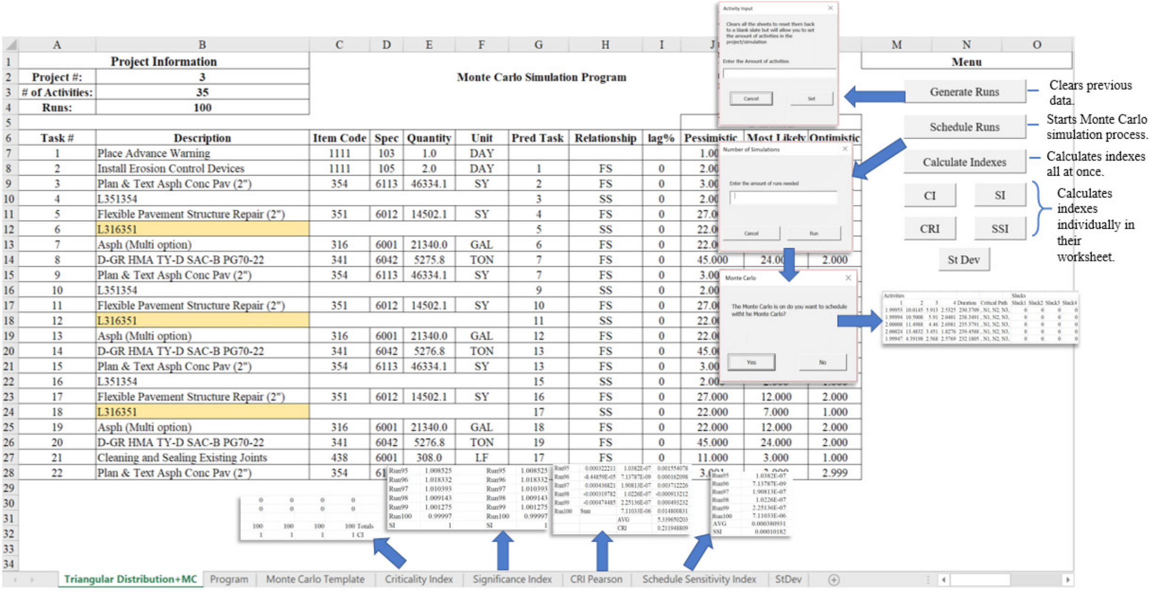
The user first inputs the information needed to schedule the project, such as the list of activities, their three durations, and the relationships between activities. Once the information is set, the user may select the "Generate Runs" button where they specify the number of simulations desired. Next, the M.C. simulation begins, and the project is scheduled up to the number of simulations set. The software outputs and organizes information regarding activity duration, slack, and project duration in the designated sheets. Lastly, the TCM are then calculated using the formulas retrieved from the literature, as will be discussed in the following section.

5.3 Modeling the Time Sensitivity Measures

The Criticality Index (CI) is calculated by counting the number of times an activity occurs on the critical path during the different simulation runs, as shown in Equation 1; the A_S stands for activity slack and n is the number of runs. The CI has a value from 0 to 1; a value closer to 1 shows that the activity is frequently critical [44-49].

$$CI = \frac{number\ of\ times\ A_S\ is\ equal\ to\ "0"}{n} \tag{1}$$

The Significance Index (SI) is calculated using the formula shown on Equation 2; the A_D stands for activity duration, P_D is the project duration, and $AvgP_D$ is the average project duration for all runs. The SI is calculated for each simulation run and the average is used to determine the final SI for the activity. The SI ranges from 0 to 1, where 0 indicates that the activity is not important when compared to other activities and vice versa. This measure is based on the amount of the slack an activity has [50 -51].



	A	B	C	D	E	F	G	H	I	J	K	L
1	**Project Information**											
2	**Project #:**	**3**				**Monte Carlo Simulation Program**						
3	**# of Activities:**	**35**										
4	**Runs:**	**100**										
5												
6	**Task #**	**Description**	**Item Code**	**Spec**	**Quantity**	**Unit**	**Pred Task**	**Relationship**	**lag%**	**Pessimistic**	**Most Likely**	**Optimistic**
7	1	Place Advance Warning	1111	103	1.0	DAY				1.00		
8	2	Install Erosion Control Devices	1111	105	2.0	DAY	1	FS	0	2.00		
9	3	Plan & Text Asph Conc Pav (2")	354	6113	46334.1	SY	2	FS	0	3.00		
10	4	L351354					3	SS	0	2.00		
11	5	Flexible Pavement Structure Repair (2")	351	6012	14502.1	SY	4	FS	0	27.0		
12	6	L316351					5	SS	0	22.0		
13	7	Asph (Multi option)	316	6001	21340.0	GAL	6	FS	0	22.0		
14	8	D-GR HMA TY-D SAC-B PG70-22	341	6042	5275.8	TON	7	FS	0	45.000	24.0	2.000
15	9	Plan & Text Asph Conc Pav (2")	354	6113	46334.1	SY	7	FS	0	3.00		
16	10	L351354					9	SS	0	2.00		
17	11	Flexible Pavement Structure Repair (2")	351	6012	14502.1	SY	10	FS	0	27.0		
18	12	L316351					11	SS	0	22.0		
19	13	Asph (Multi option)	316	6001	21340.0	GAL	12	FS	0	22.0		
20	14	D-GR HMA TY-D SAC-B PG70-22	341	6042	5276.8	TON	13	FS	0	45.0		
21	15	Plan & Text Asph Conc Pav (2")	354	6113	46334.1	SY	13	FS	0	3.00		
22	16	L351354					15	SS	0	2.00		
23	17	Flexible Pavement Structure Repair (2")	351	6012	14502.1	SY	16	FS	0	27.000	12.000	2.000
24	18	L316351					17	SS	0	22.000	7.000	1.000
25	19	Asph (Multi option)	316	6001	21340.0	GAL	18	FS	0	22.000	12.000	2.000
26	20	D-GR HMA TY-D SAC-B PG70-22	341	6042	5276.8	TON	19	FS	0	45.000	24.000	2.000
27	21	Cleaning and Sealing Existing Joints	438	6001	308.0	LF	17	FS	0	11.000	3.000	1.000
28	22	Plan & Text Asph Conc Pav (2")	354	61						3.0		2.999

Activity Input

Clears all the sheets to reset them back to a blank slate but will allow you to set the amount of activities in the project/simulation

Enter the Amount of activities

Number of Simulations

Enter the amount of runs needed

Monte Carlo

The Monte Carlo is on do you want to schedule witht he Monte Carlo?

Generate Runs – Clears previous data.

Schedule Runs – Starts Monte Carlo simulation process.

Calculate Indexes – Calculates indexes all at once.

CI, SI, CRI, SSI – Calculates indexes individually in their worksheet.

Figure 5. The different functions of the Excel-based software.

$$SI = \frac{(A_D * P_D)}{(A_D + A_S) * (AvgP_D)} \tag{2}$$

The Cruciality Index (CRI) is based on the Pearson's product-moment correlation and can be calculated using Equation 3. The $AvgA_D$ is the average activity duration for all runs. Similar to the SI, the CRI is also calculated at each simulation to get the average. Since the correlation between two items can be on the negative side - indicating an inversely proportional relationship- the absolute value of the average is used to bound the CRI in a range from 0 to 1. A value of "0" indicates that there is no correlation between the activity duration and the project duration, and vice versa [44,50,52].

$$CRI = \left| \frac{\sum((A_D - AvgA_D) * (P_D - AvgP_D))}{\sqrt{\sum(A_D - AvgA_D)^2 * \sum(P_D - AvgP_D)^2}} \right| \tag{3}$$

The Schedule Sensitivity Index (SSI) is calculated using Equation 4. In this formula, the standard deviation of the activity durations and project durations are used with the CI previously calculated for the activity. The SSI has a range of 0 to 1, where a value of closer to 1 signifies the larger impact that an activity has on the total project duration, and vice versa [44,46,52].

$$SSI = \frac{\sigma A_D * CI}{\sigma P_D} = \frac{\sqrt{\sum((A_D - AvgA_D)^2)/(n-1)} * CI}{\sqrt{\sum((P_D - AvgP_D)^2)/(n-1)}} \tag{4}$$

6. Application and Results

After modeling the project schedules to incorporate the lag times as separate activities, the M.C. software developed was deployed to schedule the projects and compute the TSM for all the project activities, as shown in Figure 6. There were 98 highway projects rescheduled for application of analysis. All projects were of the same type (overlay projects) to unify the basis of analysis and avoid the impact of any variability due to the nature of the project. Ten lag times were identified and selected for analysis based on the frequency of their occurrence throughout the projects; Table 1 lists the selected lag activities.

Table 1. The dummy lag activities used for analysis.

Dummy Activities	a) Predecessor/ b) Successor	Relationship	Frequency
L351354	a) Planning and Texturing Pavement/ b) Flexible Pavement Structure Repair	SS	9
L316354	a) Planning and Texturing Pavement/ b) Seal Coat	SS	11
L540341	a) Dense-Graded Hot-Mix Asphalt/ b) Metal Beam Guard Fence (MBGF)	SS	2
L666540	a) Metal Beam Guard Fence (MBGF)/ b) Pavement Markings	SS	2
L533134	a) Backfilling Pavement Edges/ b) Shoulder Texturing	SS	3
L354508	a) Constructing Detours/ b) Planning and Texturing Pavement	SS	4
L341316	a) Seal Coat/ b) Dense-Graded Hot-Mix Asphalt	SS	8
L316351	a) Flexible Pavement Structure Repair/ b) Seal Coat	SS	7
L247112	a) Subgrade Widening/ b) Flexible Base	SS	4
L134341	a) Dense-Graded Hot-Mix Asphalt/ b) Backfilling Pavement Edges	SS	3

DOI: https://doi.org/10.30564/jaeser.v4i3.3383

7. Analysis

Statistical analysis was conducted for each index calculated for the ten lag activities using the R statistics software. First, descriptive statistical analysis was conducted to obtain information about the mean, minimum, and maximum values of the indexes. The empirical cumulative distribution function (eCDF) was also constructed to estimate the probabilities of obtaining different values indexes. Lastly, confidence intervals were established for each of the dummy lag activities to determine a range of values that are likely to cover the true values of the indexes.

7.1 Assessment of a Lag Time

Lag activity L13434, which defines the wait time between the dense grading of hot-mix asphalt and the backfilling of the pavement edges activities, was selected to demonstrate how the assessment of the impact of lag times on the project duration was performed. As shown in Table 1, activity L13434 was listed three times in the sample projects collected from TxDOT. Since at least 30 data points are required for a valid statistical analysis, the projects in which the selected lag activity (L13434) occurred were replicated. This was done by changing the quantities for all the activities in the schedule based on a random factor between 0.5 and 1.5. This created schedules that followed the same logic with relationships and predecessors, but with varying durations. Once all projects were ready, they were scheduled using the Excel-based M.C. simulation software.

The software generated the CI, SI, CRI, and SSI values for each activity in the projects, which provided the data points needed to statistically analyze each measure. The TSM values were analyzed using statistical analysis software "R"; the obtained results for activity L134341 are shown in Table 2.

The descriptive statistics show that the means of the CI and SI are very high for lag activity L134341; the mean values are greater than 0.8. Additionally, the eCDF indicated that there is a very low probability that the values of the CI and SI can be less than the mean. The reported probabilities were less than 33.33% and 36.66% for the CI or SI, respectively as shown in Table 2. This indicates that the activity was highly critical in most projects. However, the confidence interval for the CI for L134341 could not be determined since all CI results had a value of 1, which indicates that the lag activity is always on the critical path.

However, the mean CRI had a value of 0, which showed that this activity did not have a high correlation to the total project duration. This was true for all the projects simulated since the maximum CRI value was 0.03. On the other hand, the SSI had a mean value of 0.37 with a maximum value of 0.71. Although this dummy activity did not impact the total project duration in most projects, it had some significant impacts on the total duration in few projects. As such, it is suggested to monitor this lag activity closely during its execution and until its completion. All the results of the selected lag activities are shown in Table 2.

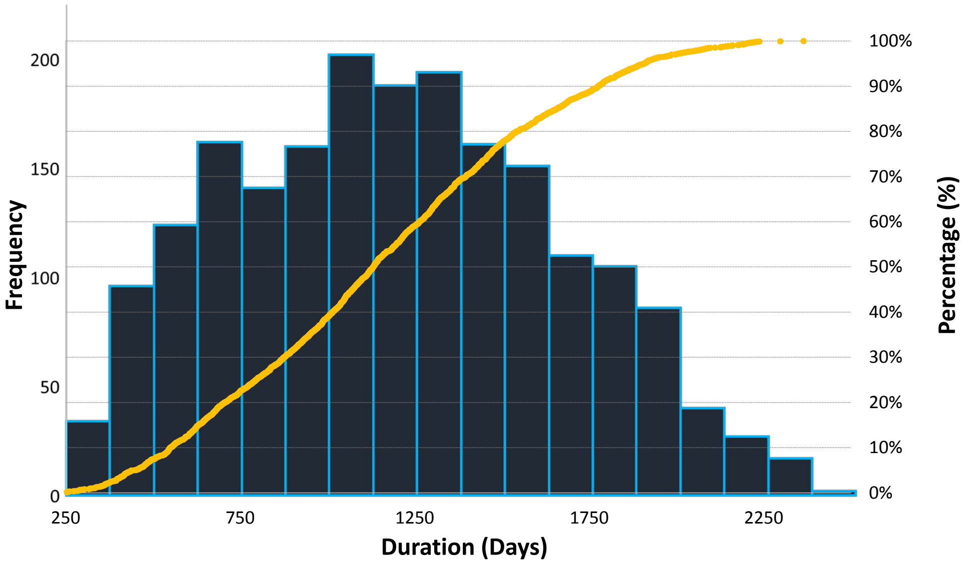


Figure 6. Project durations and CDF obtained by M.C. simulation using the Excel-based software developed.

DOI: https://doi.org/10.30564/jaeser.v4i3.3383

Table 2. Analysis on the TSM for the different lag activities selected.

	TSM Descriptive Summary							eCDF	Conf. Interval	
Lag	**TSM**	**n**	**mean**	**median**	**min**	**max**	**range**	**Prob. TSM ≤ mean**	**Lower**	**Upper**
L351354	CI	40	0.85	1.00	0.00	1.00	1.00	32.50%	N/A	
	SI	40	0.89	1.00	0.08	1.00	0.92	20.00%	0.91	1.00
	CRI	40	0.07	0.04	0.00	0.99	0.99	77.50%	0.02	0.07
	SSI	40	0.06	0.05	0.00	0.46	0.46	77.50%	0.02	0.07
L316354	CI	39	0.67	1.00	0.00	1.00	1.00	38.46%	N/A	
	SI	39	0.68	1.00	0.02	1.00	0.98	38.46%	0.10	1.00
	CRI	39	0.11	0.07	0.00	0.88	0.88	76.92%	0.04	0.12
	SSI	39	0.09	0.00	0.00	0.94	0.94	76.92%^	0.00	0.04
L540341	CI	45	0.57	0.57	0.43	0.68	0.25	48.88%	0.55	0.57
	SI	45	0.72	0.72	0.62	0.83	0.20	51.11%	0.69	0.72
	CRI	45	0.38	0.48	0.00	0.80	0.80	33.33%	0.43	0.53
	SSI	45	0.49	0.49	0.02	0.73	0.71	48.88%	0.45	0.51
L666540	CI	30	0.51	0.55	0.25	0.66	0.41	33.33%	0.49	0.56
	SI	30	0.55	0.55	0.46	0.65	0.19	63.33%	0.54	0.57
	CRI	30	0.10	0.11	0.01	0.35	0.34	53.33%	0.06	0.14
	SSI	30	0.50	0.50	0.40	0.71	0.31	53.33%	0.44	0.53
L533134	CI	40	0.79	1.00	0.27	1.00	0.73	37.50%	N/A	
	SI	40	0.85	1.00	0.47	1.00	0.53	37.50%	0.64	1.00
	CRI	40	0.01	0.02	0.00	0.03	0.03	37.50%	0.00	0.02
	SSI	40	0.06	0.06	0.00	0.20	0.20	60.00%	0.03	0.08
L354508	CI	30	1.00	1.00	1.00	1.00	0.00	0.00%*	N/A	
	SI	30	1.00	1.00	1.00	1.00	0.00	0.00% *	N/A	
	CRI	30	0.01	0.00	0.00	0.12	0.12	76.67%	0.00	0.00
	SSI	30	0.02	0.02	0.01	0.03	0.02	63.33%	0.02	0.02
L341316	CI	40	1.00	1.00	0.91	1.00	0.09	10.00%*	N/A	
	SI	40	1.00	1.00	0.98	1.00	0.02	0.08% *	N/A	
	CRI	40	0.12	0.12	0.00	0.36	0.36	52.50%	0.05	0.17
	SSI	40	0.05	0.04	0.00	0.41	0.40	77.50%	0.02	0.06
L316351	CI	30	1.00	1.00	0.97	1.00	0.03	6.70%*	N/A	
	SI	30	0.93	1.00	0.39	1.00	0.61	23.33%	N/A	
	CRI	30	0.08	0.03	0.00	0.69	0.69	66.67%	0.02	0.10
	SSI	30	0.18	0.20	0.00	0.37	0.37	87.50%	0.15	0.24
L247112	CI	30	1.00	1.00	1.00	1.00	0.00	0.00%*	N/A$^{\Delta}$	
	SI	30	0.95	1.00	0.64	1.00	0.36	30.00%	N/A$^{\Delta}$	
	CRI	30	0.08	0.08	0.01	0.18	0.18	53.33%	0.04	0.10
	SSI	30	0.00	0.00	0.00	0.01	0.01	96.66% ^	0.00	0.01
L134341	CI	30	0.83	1.00	0.32	1.00	0.68	33.33%	N/A	
	SI	30	0.90	0.96	0.68	1.00	0.32	36.66%	0.85	0.99
	CRI	30	0.00	0.00	0.00	0.03	0.03	66.67%	0.00	0.01
	SSI	30	0.37	0.41	0.06	0.71	0.65	46.67%	0.21	0.45

*: Activities where eCDF probability was tested at 0.99 instead of their mean of 1.00

^: Activities where eCDF probability was tested at 0.01 instead of their mean of 0.00

7.2 Statistical Analysis of the Indexes

The statistical analysis of the CI of all the lag activities shows a mean CI above 0.5, which indicates that the lag activities have appeared on the critical path more than half the time throughout the simulations. Out of the test sample (10 lag activities), 40% of them had a minimum CI above 0.5. Since many dummy activities had a maximum CI of 1, the eCDF probability for them was computed at 0.99, as noted in Table 2. Additionally, the confidence intervals displayed meaningful values for only two activities. For the rest of activities, the CI could not be determined – indicated by N/A in Table 2 - for two main reasons data. First, for the smaller part of the lag activities investigated, there were large ranges of CI data. This indicates that these activities had significant differing criticality values in the various projects examined, as the example shows in Figure 7 (a). The second reason is that the majority of the lag activities investigated had a CI value of 1. This indicated that almost all the activities are always on the critical path, as the example shows in Figure 7 (b). The summary of the descriptive statistics of the CI of all dummy lag activities is shown in Table 2.

All the lag activities had a mean SI greater than 0.5, which means that most of them had no slack throughout most of the simulation runs. Fifty percent of the lag activities had a minimum SI above 0.5. Since the SI also measures the criticality of activities, the results were in conformance with the CI results discussed above and encountered similar errors in the eCDF and confidence intervals. From the available intervals, there is one activity, L666540, that had the narrowest confidence interval and the highest percentage of values smaller than the mean. This signifies that the median value for this dummy activity could be low compared to other activities. The summary for the SI of the dummy lag activities is also shown in Table 2.

The results show that all the dummy lag activities had a mean CRI below 0.5, which means their activity duration did not have a high correlation with the total project duration. Although 40% of the lag activities that had a maximum CRI value above 0.5, the medians were very small value except for one activity. The percentages computed using the eCDF further showed that most of the CRI values of many activities were low. Furthermore, the confidence intervals displayed only one activity with an upper bound greater than 0.5; this activity was the only one with a high CRI in many projects. The descriptive statistics summary for the CRI of the dummy lag activities is shown in Table 2.

The results show that all activities had a mean SSI less than 0.5. Out of the 10 activities, 40% had a maximum SSI value above 0.5. The eCDF computations showed that many dummy activities had low SSI, similar to the CRI. Additionally, the confidence intervals showed that two activities impacted the project duration more than others; their lower bound was much higher than others and the upper bound was greater than 0.5. The descriptive statistics summary for the SSI is also shown in Table 2.

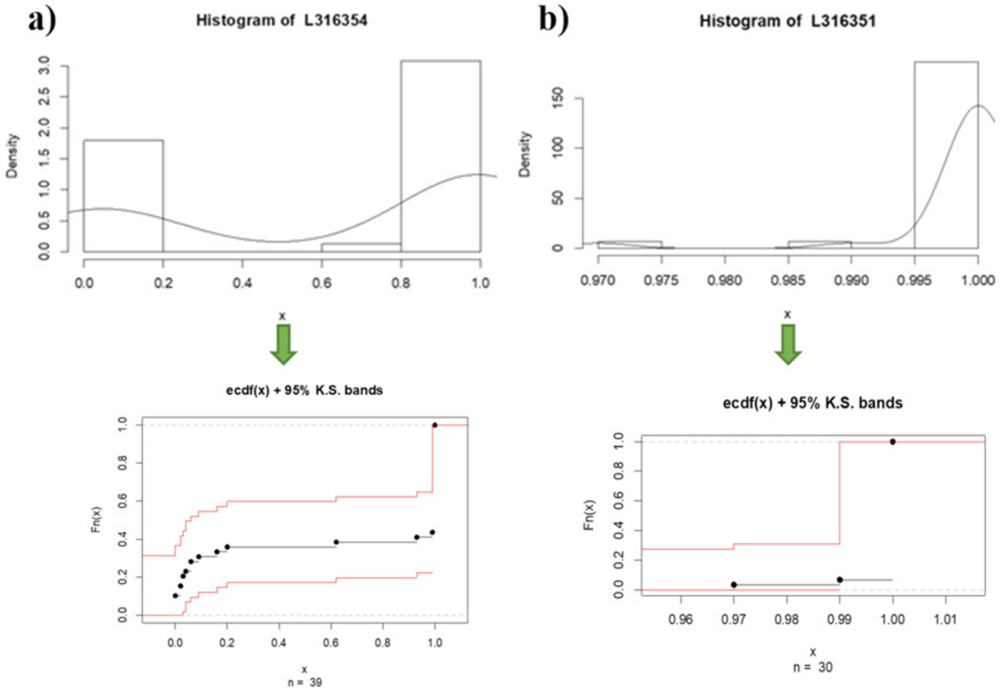


Figure 7. Histograms and eCDF graphs of the CI data for two of the dummy lag activities.

DOI: https://doi.org/10.30564/jaeser.v4i3.3383

8. Validation of Results

The aforementioned results indicate a high criticality of the lag activities evaluated based on the high values of the CI and SI obtained. Additionally, higher CRI and SSI values indicate a larger impact on the total project duration, while a low CRI and SSI signify a lower impact on the project duration. The results obtained from the TSM were validated by conducting a one-way sensitivity analysis on a sample of lead and regular activities. Since all the activities evaluated had high CI and SI, the activities selected for the sensitivity analysis came from two different groups. The first one is characterized by high CI and SI, as well as high CRI and SSI, while the second group is characterized by high CI and SI, but low CRI and SSI. Additionally, the activities were selected based on their frequent occurrences throughout the projects. Two lag activities, L540341 and L341316, and two regular activities, Seal Coat and Flexible Pavement Structure Repair, were selected to undergo the sensitivity analysis.

To conduct the one-way sensitivity analysis, all project activities durations were set to deterministic values except for the duration of the activity under investigation; its duration was modeled using a triangular distribution, as previously explained. The selected projects in which the activities occurred were then simulated using M.C. simulation. Since the activity investigated is the only probabilistic duration in the project, it was feasible to measure its direct impact on the total project duration by calculating the standard deviation (SD) of the project time.

In a one-way sensitivity analysis, the SD show how much the total project duration varies when the duration of a particular activity changes. Hence, the straightforward pattern of the SD values was obtained from the simulation runs of the one-way sensitivity analysis and was used to validate the results of the time-sensitivity indexes. The results obtained using the activities selected for the sensitivity analysis are shown in Table 3.

The first dummy lag activity, L540341, was characterized by high CI, SI, CRI, and SSI. A one-way sensitivity analysis confirmed its high impact on the project duration (CRI and SSI) with a standard deviation of 75 days; the original project duration was 239 days, as shown in Table 3. This indicates that the aforementioned activity (L540341) alone can cause a variation in the project duration of ±31%, which can shift the project duration in the range 164 and 314 days. Similarly, the Seal Coat activity had high CI, SI, CRI, and SSI. This was also confirmed by its high SD of 150 days; the project original duration was 720 days. This means that this activity can vary the project duration in the range ±20%.

Alternatively, the other two activities, lag activity L341316 and Pavement Structure Repair, had a high CI and SI but a low CRI and SSI. This was reflected by the relatively low SD of 4 days out of the original project duration of 401 days caused by activity L341316. Similarly, Flexible Pavement Structure Repair had a low impact on the project duration reflected by a SD of 1.58 days, as shown in Table 3.

The one-way sensitivity analysis was further carried out to assess and compare the impact of 4 additional lag activities (L351354, L666540, L341316, and L316351) on the same project duration. The project deterministic total duration – based on CPM- was 149 days. Information about the CI, SI, CRI, and SSI of the selected lag activities are given in Table 2. Although the selected lag activities are characterized by high CI and SI but a low CRI and SSI, their impact on the project total duration can be significant, as shown in the Tornado chart in Figure 8.

Table 3. The results for the validation.

CI & SI	CRI & SSI	Activity	SD	CI	SI	CRI	SSI
High	High	L540341	74.75	0.64	0.81	0.71	0.61
High	High	Seal Coat	150.80	1.00	1.00	0.71	0.70
High	Low	L341316	3.56	1.00	1.00	0.02	0.02
High	Low	Pave. Struct. Repair	1.58	1.00	1.00	0.05	0.01

9. Discussion

The analysis of the CI and SI results showed that most lag times are highly critical in the projects analyzed. The SI measures the significance of an activity compared to other project activities based on the activity duration and the amount of slack that might be available if the activity falls off the critical path and becomes non-critical during a given scenario. Generally, activities that possess higher slack in the non-critical status are less significant as they can be delayed for a longer time without them impacting the total project duration. In other words, the SI is a more comprehensive measure than the CI since it measures the relative importance between the project activities based on their criticality, as well as the amount of slack available.

However, the CI and SI do not measure the impact of an activity on the total project duration. For example, some activities may always remain on the critical path, but they might have a very limited impact on the project duration because of their very short duration. This is when the CRI and SSI fill in the gap since they assess the importance of the activities based on not only the previous measures, but also their overall impact on the project duration.

The CRI assesses the impact an activity has on the project duration by measuring the correlation between the changes that occur in the activity duration and the corresponding changes in the total project duration. The project duration might not change, change slightly, change moderately, or change significantly. Accordingly, the following classification reflects strengths in the correlation in the range of: none or very weak (0.0-0.1), weak (0.1-0.3), moderate (0.3-0.5), or strong (0.5-1.0). Similarly, the SSI relates the changes in the activity duration to the changes in the total project duration using a value representing the activity's impact. In general, activities with a higher duration variability (standard deviation) have a higher SSI.

There are four cases that can occur when comparing the four TSM: 1) high criticality and high variability, 2) low criticality and low variability, 3) high criticality and low variability, and 4) low criticality and high variability. The criticality depends on the existence of the activity on the critical path and the available slack, which is reflected by the CI and SI. Alternatively, the variability is determined based on the activity duration range, which is captured by the SSI and CRI. As such, the dummy lag activities investigated were classified according to these four cases using the mean of the TSM, as shown in Table 4. It should be noted that none of the lag activities investigated could be classified as case 2.

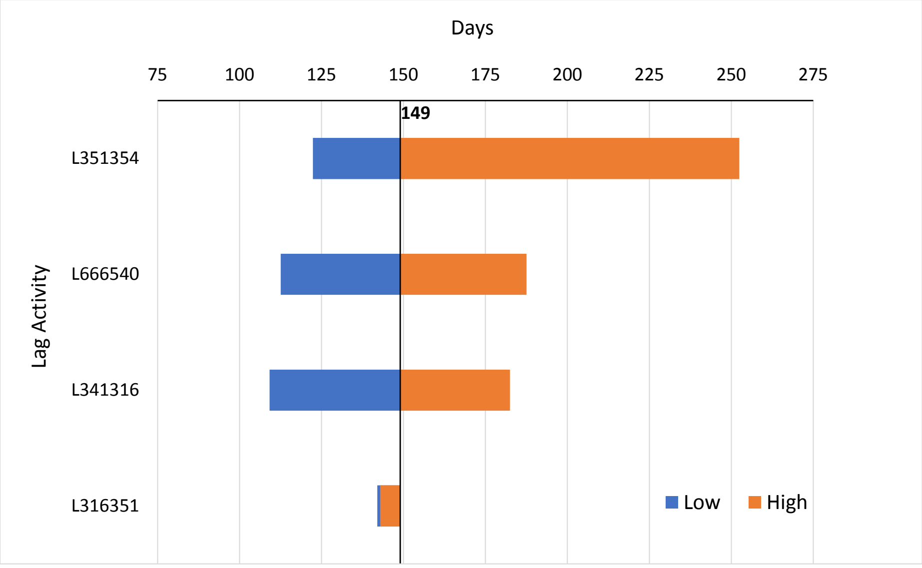


Figure 8. Impact of different lag activities on the project total duration.

Table 4. Comparison of the means for all measures.

Case #	Lag	Predecessor	Successor	mean (CI)	mean (SI)	mean (CRI)	mean (SSI)	mean (SD)	mean (duration)
1	**L134341**	Dense-Grad. Hot-Mix Asph.	Backfilling Pav. Edges	0.83	0.90	0.00	0.37	40.44	80.00
3	**L351354**	Planning & Texturing Pav.	Flex. Pav. Structure Repair	0.85	0.89	0.07	0.06	21.99	20.93
	L316354	Planning & Texturing Pav.	Seal Coat	0.67	0.68	0.11	0.09	28.71	35.00
	L533134	Backfilling Pavement Edges	Shoulder Texturing	0.79	0.85	0.01	0.06	4.10	12.44
	L354508	Constructing Detours	Planning and Texturing Pav.	1.00	1.00	0.01	0.02	2.40	6.00
	L341316	Seal Coat	Dense-Grad. Hot-Mix Asph.	1.00	1.00	0.12	0.05	10.12	26.04
	L316351	Flex. Pav. Struct. Repair	Seal Coat	1.00	0.93	0.08	0.18	6.23	14.05
	L247112	Subgrade Widening	Flexible Base	1.00	0.95	0.08	0.00	0.95	3.67
4	**L540341**	Dense-Graded Hot-Mix Asph.	Metal Beam Guard Fence	0.57	0.72	0.38	0.49	237.98	362.33
	L666540	Metal Beam Guard Fence	Pavement Markings	0.51	0.55	0.10	0.50	5.17	9.83

DOI: https://doi.org/10.30564/jaeser.v4i3.3383

The first case (high criticality and high variability) as well as the second case (low criticality and low variability) provides a definitive assessment of the overall importance of a given activity. However, the third (high criticality and low variability) and fourth cases (low criticality and high variability) are quite inconclusive regarding the overall importance of the activity. Although the four indexes provide relatively accurate insightful information about the criticality of the project activities and their impacts, they should be assessed carefully since the calculations depend on the accuracy of the project modeling and the availability of the data. An inaccurate representation of the data range can result in incorrect conclusions about the activities. For instance, calculating the SSI can be tricky since it depends on multiple variables that need to be selected carefully for an accurate computation.

The inaccuracies in estimating the lag time may be caused by different factors. One important factor is the lack of experience of the engineer who is estimating the lag time in the project schedule [72]. Another factor is that lag time may be added by contractors when none is necessary just to manipulate the schedule and show activities more critical than they truly are [72]. Also, lag time may just be added to allow time for procuring materials before an activity starts [73]. Equipment technology has also changed throughout the years which has improved the productivity and expedited the construction operations of highway projects. In turn, this has altered the relationships between the activities, including the lag time estimates, depending on the equipment and technology used [74]. As such, the estimation of the lag time should be conducted with the due diligence.

The impact of the lag time on the project duration can be significant. In this study, for example, the total lag time accounted for 31% of the total project duration in the projects obtained on average. The highest lag duration in a single project was 63% of the total duration, while the lowest one was 0%. To further demonstrate the impact of lag times on the highway projects durations, a project was simulated using M.C. technique. At first, the durations of all the project activities were simulated, see Figure 9(a), then the simulation was repeated after the exclusion of the lag activities to eliminate their impacts on the total project duration. The results show that number of projects with total durations less than 500 days tend to increase after excluding the impact of the lag times, as shown in Figure 9(b).

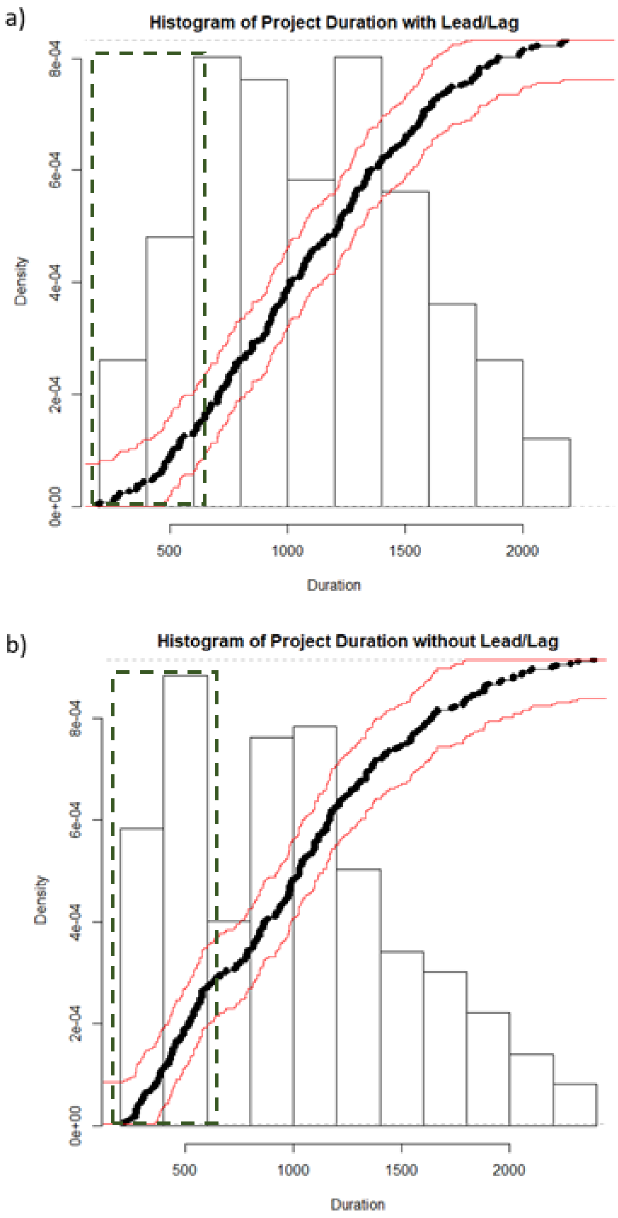


Figure 9. Histograms and eCDF comparison of the project duration with and without lag time.

10. Conclusions

The results showed that most of the lag times investigated in this study are highly critical. Also, the data showed that some of the lag activities can have a significant impact on the total duration in some of the projects. This was reflected by the results from the descriptive statistics that showed high maximum values for the CI and SI for all lag activities, as well as relatively high CRI and SSI values for some of the lag activities investigated. As such, it is important for project managers to have a proper and a comprehensive established method when developing their schedules for highway construction projects. An established method will ensure consistency, reduce the inaccuracies in the project durations estimates caused by the lag time, and improve the accuracy of the overall project schedule.

Since the analysis in this research was limited to overlay projects, there may be other highway project activities that require the use of lag times to maintain the schedule logic but may not have been included in this study. As such, it is recommended to conduct further investigation on the lag times using a larger pool of data from different work activities in different project types. Lastly, the development of a new overall index may be essential to reflect the importance of each activity. This can be achieved by combining the information available from the four TSM and aggregating it into a single index.

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DOI: https://doi.org/10.30564/jaeser.v4i3.3383