Better Construction Project Management through Better Scheduling

Final Report

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This project investigated the effect of using Critical Path Method (CPM) schedules on South Carolina transportation projects. The analysis used 2,097 projects let after February 2007 and substantially completed by August 2015. Among these projects, 55.22% had CPM schedules. Among the projects without CPM schedules, 47.49% were delayed beyond the original contract completion date, and 16.08% were delayed beyond the date adjusted by change orders; the average delay beyond the original contract completion date was 28.5 days, and the average delay beyond the adjusted completion date was –14.6 days (i.e., they were completed 14.6 days before the adjusted completion date). Among the projects with CPM schedules, 54.32% were delayed beyond the original contract completion date, and 14.50% were delayed beyond adjusted completion date; the average delay beyond the original contract completion date was 54.8 days, and the average delay beyond the adjusted completion date was –9.8 days. Chi-square test results indicated that projects with larger bid amounts and longer durations were more likely to have a CPM schedule. The t-test results indicated that the Bridge, General, and Hot-mix Asphalt Paving projects with CPM schedules had a statistically significant longer average delay beyond the original contract completion date than projects without CPM schedules. Conversely, the t-test results indicated that the short duration (less than six months) projects without CPM schedules had longer average delay beyond the adjusted completion date than projects with CPM schedules. It should be noted that for the SCDOT, projects with CPM schedules are those with a significant amount of risk and complex scope whereas projects without CPM schedules are those with low risk and limited scope. A binary logistic regression model was developed to predict project delay and this model indicated that the variable "total bid amount" was statistically significant at the 95% confidence level. A neural network model was also developed using change order remarks and texts from daily work reports as inputs. This model correctly predicted a project will be delayed 53.7% of the time. Best-fit distributions were developed for delayed and early completion projects. Using these distributions and the Total Law of Probability, the probability that a project will be delayed can be estimated. Based on the literature view and SCDOT current practice, it is recommended that the SCDOT considers using a more methodical approach that examines multiple criteria for identifying those projects that need CPM schedules. Additionally, the SCDOT may consider incorporating the probabilistic information about project delay in the schedules, such as providing a range for the activity duration in the CPM schedule instead of simply using the expected duration. Lastly, it is recommended that the SCDOT consider including a provision in future contracts to ensure that all personnel (SCDOT and contractors) are using the same schedule for project management.</td></tr>
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- Ms. Wei Johnson (Co-Chair)
- Mr. Olson Benjamin
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- Ms. Meredith Heaps

EXECUTIVE SUMMARY

This project sought to 1) determine the state-of-the-practice on the use of Critical Path Method (CPM) for project management, 2) determine whether a South Carolina Department of Transportation (SCDOT) project is delivered on time and budget when CPM is used for project management by the Resident Construction Engineer (RCE), and 3) identify the factors that influence project delay.

Online Survey and Telephone Interviews

A total of 23 state DOTs, 51 Resident Construction Engineers (RCEs) from 16 different states, and 45 contractors from 16 different states responded to the survey. The CPM scheduling method was the most widely used technique. Nearly 96% of the responding state DOTs use CPM for project management, and almost one-third of the contractors use only CPM for scheduling. The state DOTs use CPM in conjunction with two other techniques: Gantt charts and Milestone charts. The two most common reasons stated by the responding state DOTs and RCEs for using CPM scheduling for a project are its complexity and risks. Additionally, one-fourth of the responding state DOTs indicated that a project's estimated project cost was also used as an indicator for selecting CPM scheduling. Most of the state DOTs (86.4%) require CPM schedules for their projects, and more than 90% of the contractors indicated that they are required to provide CPM schedules as part of their contract.

Most state DOTs incorporate either resource (22.7%) or cost (9.1%) or both (27.3%) in their CPM schedules. The most commonly used software for scheduling among state agencies is Primavera products (50% use Primavera P6). All of the state DOTs indicated that CPM schedules are also used for assessing claims. Some state agencies have a framework for selecting CPM for projects (e.g., Caltrans), but most agencies implement CPM schedules based on perceived project risks and complexity. TxDOT personnel indicated via the phone interview that the district construction engineer has the discretion to decide whether to use or waive a certain scheduling technique for projects.

Slightly more than half (55%) of the RCEs indicated that the time between Notice to Proceed and first work date consumes a significant portion of the total project duration. About two-thirds (68%) of the RCEs indicated that a significant number of change orders are made in the last third portion of the project. According to the RCEs, the top three reasons for project extension are contract modifications, weather, and change orders by the owner. In evaluating the contractors' performance on projects, 70% of the RCEs indicated that the contractors strive to follow CPM schedules; however, 60% of the RCEs indicated that CPM schedules do not appear to reduce the number of change orders. Most of the RCEs (80%) indicated that CPM schedules are used for making decisions on a project and for assessing claims (80%).

About two-thirds of the contractors indicated that they prepare CPM schedules whether or not they are required by the contract. Three-fourths of the contractors indicated that they maintain a separate schedule for work than the contractual schedule (provided to the RCE). This response suggests that the state DOTs and RCEs might not have the actual construction schedule for the project. More than half of responding contractors (55.6%) use in-house personnel for scheduling and less than 30% of the contractors use a dedicated person for scheduling. About 36% of the

contractors indicated that they understand the importance of CPM scheduling and see it as a valuable tool for project success.

Effectiveness of CPM Scheduling

The analysis used two sets of data, *before* 2007 and *after* 2007; in 2007, the SCDOT required CPM schedules for those projects that have high risks. The *before* 2007 dataset consists of 1,856 projects let after February 2000 and substantially completed by March 2013. The *after* 2007 dataset consists of 2,097 projects let after February 2007 and substantially completed by August 2015.

In the *before* 2007 dataset, 22.20% of the projects had CPM schedules. Among the projects without CPM schedules, 58.66% were delayed beyond the original contract completion date, and 25.76% were delayed beyond the adjusted completion date; the average delay beyond the original contract completion date was 124.7 days, and the average delay beyond the adjusted completion date was 75.1 days. Among the projects with CPM schedules, 47.82% were delayed beyond the original contract completion date, and 16.26% were delayed beyond adjusted completion date; the average delay beyond the original contract completion date was 130.5 days, and the average delay beyond the adjusted completion date was 34.9 days. Among the projects with CPM schedules, 56.79% were completed within the original budget.

In the *after* 2007 dataset, 55.22% of projects had CPM schedules. Among the projects without CPM schedules, 47.49% were delayed beyond the original contract completion date, and 16.08% were delayed beyond the adjusted completion date; the average delay beyond the original contract completion date was 28.5 days, and the average delay beyond the adjusted completion date was –14.6 days (i.e., they were completed 14.6 days before the adjusted completion date). Among the projects with CPM schedules, 54.32% were delayed beyond the original contract completion date, and 14.50% were delayed beyond adjusted completion date; the average delay beyond the original contract completion date was 54.8 days, and the average delay beyond the adjusted completion date was –9.8 days. Among the projects with CPM schedules, 55.87% were completed within the original budget.

Chi-square tests were used to examine the relationship between projects with CPM schedules and delayed projects, and t-tests were used to compare the average delay (in days) between projects with and without CPM schedules. In the *before* 2007 dataset, it was found that projects with larger bid amounts and medium durations were more likely to have a CPM schedule. The t-test results indicated that the "General" projects without CPM schedules and medium-duration projects had statistically significant longer average delay beyond the original contract completion date than projects with CPM schedules. Also, it was found that projects without CPM schedules in SCDOT District 2 had statistically significant longer average delay beyond the adjusted completion date than projects with CPM schedules.

In the *after* 2007 dataset, it was found that projects with larger bid amounts and longer durations were more likely to have a CPM schedule. The t-test results indicated that Bridge, General, and Hot-mix Asphalt Paving projects with CPM schedules had statistically significant longer average delay beyond the original contract completion date than projects without CPM schedules. Also, it was found that the short duration (less than six months) projects without CPM schedules had longer average delay beyond the adjusted completion date than projects with CPM schedules.

Factors Affecting Project Delay

A number of project delay factors were examined. These include project type, project location, project size, and project duration. Several methods were used to determine the influence of these factors on project delay. The correlation analysis showed that the projects' delay (in days) did not vary linearly with any of the considered factors. For this reason, a binary logistic regression model was developed instead of a linear regression model. One binary logistic regression model was developed for predicting whether a project will be delayed and another for predicting whether a project will be completed within budget. The best-fit delay model indicated that the variable "total bid amount" was statistically significant (at the 95% confidence level). On the other hand, the best-fit budget model indicated that the variables, "project duration", "SCDOT District", and "whether CPM was used" were statistically significant (at 95% confidence level).

Models to Predict Project Delay

The developed binary logistic model mentioned above can be used to predict whether a project will be delayed. Additionally, this study developed a methodology that uses a combination of text-mining and neural network to predict delay. It was found that for change order remarks made by the RCEs, the three most frequently used single words were: "days", "contract", and "date." The top three two-word phases were: "completion date", "contract completion", and "change order." Sentiment analysis on the single words from the change order remarks revealed that the most positive sentiment word was "work" and most negative sentiment word was "delay." The neural network model correctly predicted a project will be delayed 53.7% of the time.

Another method developed in this project to predict delay is via the use of probability density functions (PDFs) and the Law of Total Probability. The PDFs were constructed separately for projects that completed after the original contract completion date (delayed projects) and those that completed before the original completion date (early completion projects) using the *after* 2007 dataset. The Pearson 6 (4 Parameter) distribution was found to be the best fit for the delayed projects, and the Johnson SB distribution was found to be the best fit for the early completion projects. Using these best fit distributions, it was found that the probability that the duration of a SCDOT project is extended beyond the average delay (36.57% past the original duration) is 0.24; in other words, approximately 1 in 4 SCDOT projects will be delayed longer than the average delay.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Timely completion of transportation projects is one of the most critical problems facing state agencies. Several studies have assessed the efficiency of projects managed by States Department of Transportation (DOTs) and the results showed that only about half of the projects met their projected budget and schedule. According to the study by Crossett and Hines (2007), the average on-budget project delivery was 46% over a five-year period (2001 – 2005), and in a follow-up study by Crossett and Schneweis (2011), the average was 47% over a ten-year period (2001 – 2010). The on-time performance is only slightly better at 53% (Crossett and Hines, 2007) over the five-year period and 55% over the ten-year period (Crossett and Schneweis, 2011). The delay in a construction project may affect the overall project due to its adverse effects, such as cost escalation, poor quality of products, late completion of work, disruption of work, and termination of contracts (Kaliba et al., 2009; Aibinu and Jagboro, 2002). In addition, delay affects all parties involved in the construction project, such as owners, contractors, consultants, nearby communities, and the traveling public (Hugh, H., 2003).

Modern project management techniques date back to the work of Harry Gantt who developed a graphical method for tracking projects with multiple tasks (Gantt, 1910). The shortcoming of a Gantt chart is that it does not show the interrelationships between the activities within a work sequence. In the 1950s, DuPont developed the Critical Path Method (CPM) to address the interrelationships of separate activities within a project schedule. Thus, CPM is a project management tool aimed to improve the efficiency of a project. CPM breaks down the complex activities of a project into a network of tasks that can be associated with costs and resources. Galway (2004) defined CPM as a network representation of activities with deterministic task durations. His approach facilitated the computation of critical paths (i.e., set of tasks that determines the project length). CPM encourages project efficiency by allowing a scheduler to evaluate various sequences of tasks, and therefore, optimize the schedule.

The use of CPM has grown over the years since its inception as a commercial software in the 1950s. Three separate surveys have been conducted to examine how Engineering News Record's (ENR) top 400 companies used CPM. The first survey was conducted in 1974 by Edward Davis, the second in 1990 by Tavakoli and Riachi, and the third in 2003 by Kelleher. The first survey revealed that 90% of the ENR companies used CPM in 1974. This percentage increased to 92.6% by 1990, and it further increased to 98.5% in 2003. The increase in usage of CPM schedules for project management is due to the advances in computer technologies in the mid-1980s (Kelleher, 2004; Liberatore et al., 2001). The popularity of CPM scheduling grew so much that scheduling in the construction industry and the use of CPM scheduling became synonymous (Yates, 1993).

The SCDOT first introduced the CPM requirement in 2005 for those projects that have a budget of 5 million dollars or more. Then in 2007, the SCDOT changed the requirement such that CPM schedules are only needed for specific projects; that is, those that are deemed high risks. In the SCDOT supplemental specification document (dated March 1, 2007), it is stated that the contractor should provide and update construction schedule to the SCDOT, which will be used as a quantitative basis for:

- Monitoring and evaluating the contractor's progress in completing contracted work;
- Evaluating requests for additional contract time;

- Budgeting for construction estimate payments; and
- Managing SCDOT engineering and inspection personnel.

The supplemental specification indicated that the contractor's construction schedule needs to encompass the entire contract period and be developed consistent with the contract milestones and the contract maintenance of traffic plan. It also indicated that the critical path activities need to be identified for the duration of the work and that the schedule needs to reflect the utility relocations noted in the contract documents.

Within the SCDOT, there may be a perception that CPM schedules are only used by contractors and RCEs to quantify or justify time-extensions rather than as a project management tool to aid project delivery. For this reason, the SCDOT would like to know how well those projects with CPM schedules performed in terms of on-time completion and budget compared to those without CPM schedules.

The objectives of this study are:

1) determine the state-of-the-practice on the use of CPM for project management,
2) determine whether a SCDOT project is delivered on time and budget when CPM is used, and,
3) identify the factors that influence project delay and budget.

The next chapter (Chapter 2) presents a literature review of related work. Chapter 3 describes the methodology used to synthesize the data for analysis and the statistical methods used to perform hypothesis tests. Chapter 4 presents the findings from the survey and statistical analyses. Lastly, Chapter 5 presents this study's conclusions and recommendations.

2 LITERATURE REVIEW

2.1 Factors Affecting Project Delay

Numerous studies have examined factors that contribute to project delay. For example, delay factors have been examined for general construction projects (Chan and Kumaraswamy, 1996; Sambasivan and Soon, 2007), building projects (Assaf et al., 1995; Ogunlana et al., 1996), road construction projects (Kaliba et al., 2009; Mahamid et al., 2012), and large-scale projects (Assaf and Al-Hejji, 2005). Delay factors have also been examined for different economic conditions and countries (Al-Kharashi and Skitmore, 2009; Arditi and Gunaydin, 1998; Assaf and Al-Hejji, 2005; Doloi et al., 2012; Kaliba et al., 2009; Mansfield et al., 1994; Sambasivan and Soon, 2007). According to these studies, the common causes of delay in transportation projects include financial difficulties in the owner's organization, poor contract management, shortages of material or equipment, change orders from the owner, poor site management, and awarding contracts to lower bidder (Kaliba et al., 2009; Mahamid et al., 2012; Mansfield et al., 1994; Park & Papadopoulou, 2012). A study by Bordat et al. (2004) using data from the Indiana DOT reported that the contributing factors for delay, cost overruns, and change orders were contract bid amount, difference between the winning bid and second bid, difference between the winning bid and the engineer's estimate, project type, and location. Aibinu and Jagboro (2002) grouped the effects of construction delay into six categories: time overrun, cost overrun, dispute, arbitration and litigation and total abandonment. Santoso and Soeng (2016) conducted a survey on the effect of delay and found that respondents have given a larger weight on on-time performance relative to cost and quality.

In all the previous studies on project delay, the effect of CPM schedules on project delay has not been evaluated.

2.2 Predicting Probability of Project Delay

The probability of a project being delayed can be determined from historical data and subsequent fitting of the data to a Probability Distribution Function (PDF) (Kim et al., 2009). In general, the PDFs of projects can be used to develop a confidence interval for the probable completion date (Isidore and Back, 2002) and quantify risks associated with project completion.

Gunduz et al. (2013) developed a delay assessment model based on fuzzy set theory by considering the well-known delay factors. Their developed fuzzy assessment model determined that the overall probability of a project being delayed is 52.5%. The authors provided recommendations for how to avoid delay in construction projects based on their literature review and review of the 83 factors affecting delay. Shi et al. (2001) developed a method for computing delay of various activities in a project and for assessing their contribution to the overall project delay. Their method consists of a set of linear equations that can be easily coded into a computer program. Their method can be used to evaluate the in-progress project delay at any point in time during the construction stage.

Ahmed et al., (2002) stated that delay can be minimized only when their causes are known. Therefore, in their study, the causes of delay in construction projects were identified through surveys. Their study showed that in 44% of the cases, the delay is caused by contractors.

Sambasivan and Soon (2007) examined construction delay causes and their impacts on project completion. The authors identified the top 10 causes and 6 effects of delay. They developed an empirical relationship between each cause and effect. The empirical relationship was developed using correlation analysis. The intent of the developed empirical relationships is to help practitioners understand how project management can be used to reduce the probability of delay. Love et al., (2013) developed best-fit distributions using data from 276 Australian construction projects, and they found that the Burr (4 Parameter) distribution has the best-fit for the time of delay in construction projects. It should be noted that the data used in the Love et al. study were collected through surveys of contractors, mechanical and electrical engineers, project managers, quantity surveyors and structural engineers.

Using the constructed PDFs as explained in the Love et al. study and the Law of Total Probability (LTP), this project developed a method to estimate the probability of delay for transportation construction projects.

2.3 State DOTs Scheduling Practice in the 1990's and 2010's

Rowings et al. (1993) conducted a survey of scheduling practices by state DOTs. Their survey received responses from 36 state DOTs. The following summarizes their findings:

- 40% used CPM scheduling and 35% used bar charts. Among those state DOTs that used CPM scheduling, 53% used it on selected projects (i.e., those with higher in contract bid amount and complexity).
- 47% indicated they used a software to do the scheduling. The software used for scheduling included Primavera and SureTrak. Half of the state DOTs required their contractors to use the same scheduling software.
- The contract duration was determined by personal experience/judgment, project size, type, and complexity (44%), standard production rates (30%), historical records (22%), and use of CPM (4%).
- In regard to schedule specifications, some state DOTs used different specifications for different projects (27%), some used just one specification for all projects (20%), some used "other" unspecified methods (7%) and some had no specific specifications (47%).

In a more recent study, Kallaf et al. (2016) conducted a similar survey as Rowings et al. A total of 31 state DOTs participated in the survey. The following summarizes their findings:

- Contractors do not always follow the specifications or submit updated schedules in a timely manner.
- State DOTs delay and withhold payments to force contractors to comply with the scheduling specifications.
- Both bar charts and CPM schedules are commonly used. The scheduling method is dependent on the type of project and magnitude of complexity.
- Contractors with employees trained in CPM are timelier with their schedule submittals, especially in regard to time impact analysis reports.
- The majority of the state DOTs do not conduct a review of contractors' resources to ensure availability. However, some state DOTs include a special provision for certain projects,

such as those that cost more than $20 million and those that require the submittal of a resource-loaded schedule.

As part of this project, a review of standard specifications and supplemental specifications of state DOTs was conducted. It was found that bar charts and CPM are the most commonly used scheduling methods by the state DOTs. Some state DOTs use both of these methods for all of their projects and some use one of the two depending on the project size, complexity and risk. The most widely used scheduling software is Primavera. Most of the payment for scheduling is incidental to the work item. Most of the state DOTs do not require a dedicated scheduler. Table 2.1 provides a detailed summary of the review. The symbols used in Table 2.1 are as follows:

⊘	Not required
◣	Required for some projects
■	Required for all projects
●	Require fulfilling one of the formats of scheduling
X	No information found on scheduling technique and other criteria

CPM	Critical Path Method
PSC	Progress Schedule Chart
TSLD	Time Scaled Logic Diagram
AC / ASC	Activity Chart/ Activity Schedule Chart
WN	Written Narration
ND	Network Diagram

Table 2.1 Summary of state DOTs scheduling practices

DOT	Scheduling technique required or preferred by state DOT: Bar Chart	CPM	PSC	TSLD	AC or ASC	WN	ND	Required software to use	Payment method	Designated Scheduler Required
ALABAMA	◣	◣	X	X	X	X	X	X	X	X
ARIZONA	●	●	X	X	X	X	X	X	X	X
ALASKA	X	■	X	X	X	X	X	X	X	X
ARKANSAS	X	X	X	X	X	X	X	X	X	X
CALIFORNIA	X	■	X	X	X	X	X	Primavera P6	Paid for CPM	X
COLORADO	◣	■	X	X	X	X	X	Primavera product; MS Project	Incidental to work item	X
DELAWARE	X	■	X	X	X	X	X	X	Incidental to work, item for PSC, Paid item for CPM	X
DISTRICT OF COLUMBIA	X	■	X	X	X	X	X	Primavera Product; Other, approved by engineer	X	X
FLORIDA	X	■	X	X	X	X	X	X	X	X

GEORGIA	X	■	X	X	X	X	X	Form prescribed by engineer	X	X
HAWAII	X	X	X	■	X	X	X	Primavera, SureTrak; Other, specified in the contract	X	X
ILLINOIS	X	●	●	X	X	X	X	Primavera SureTrak; MS Project	X	X
IDAHO	■	■	X	■	X	X	X	X	Incidental to work item	X
INDIANA	◣	X	X	X	X	X	X	X	Paid for the Item	X
IOWA	X	■	X	X	X	X	X	Computer developed schedule; Other, approved by engineer	Incidental to work item	X
KANSAS	X	X	■	X	X	X	◣	X	Incidental to work item	X
KENTUCKY	◣	◣	X	X	X	■	X	X	X	X
LOUISIANA	■	X	X	X	X	X	X	X	X	X
MAINE	X	■	X	X	X	X	X	X	Incidental to work item	X

MARYLAND	X	■	X	X	■	X	X	X	Incidental to work item for AC, Paid item for CPM	YES
MASSACHUSETTES	X	X	X	X	X	X	X	X	X	X
MICHIGAN	X	◣	■	X	X	X	X	Form (1130) prescribed by the Department	Incidental to work item	X
MINNESOTA	■	◣	X	X	X	X	X	Primavera P6	X	X
MISSISSIPI	X	■	X	X	X	X	X	Form prescribed by the Department	X	X
MISSOURI	X	X	X	X	X	X	X	X	X	X
MONTANA	X	◣	X	X	■	X	X	Primavera P6, Any Primavera Product	Paid for the Item	X
NEBRASKA	X	■	X	X	X	X	X	X	X	X
NEVADA	●	■	X	●	X	X	X	Any Primavera product	X	X
NEW HAMPSHIRE	◣	■	X	X	X	X	X	Primavera Product, MS Project	Incidental to work item	X
NEW JERSEY	X	X	X	X	X	X	X		Paid for the Item	X
NEW MEXICO	◣	■	X	X	X	X	X	Computer developed schedule; Other, directed by the Department	X	X
NEW YORK	X	◣	X	X	X	X	X	X	No payment (contractor's obligation)	X
NORTH CAROLINA	X	X	X	■	X	X	X	Form prescribed by the Department	X	X
NORTH DAKOTA	■	◣	X	X	X	X	X	MS Project	Paid for the Item	
OKLAHOMA	X	◣	X	X	■	X	X	X	X	X

X

OREGON	■	◣	X	X	X	X	X	Primavera P3/ SureTrak / other approved, MS Project	X	X
OHIO	■	X	X	X	X	X	X	X	Incidental to work item	X
PENNSYLVANIA	X	■	X	X	X	X	X	Asta Powerproject or compatible	Paid for the CPM	X
RHODE ISLAND	X	■	X	X	X	X	X	X	X	X
SOUTH DAKOTA										
TEXAS	■	■	X	X	X	X	X	X	Incidental to work item	YES

TENNESSEE	◣	◣	X	X	X	X	X	Computerized Schedule software for some projects	X	X
UTAH	X	■	X	X	X	X	X	Primavera P6	No payment (contractor's obligation)	X
VERMONT	X	■	X	X	X	X	X	X	X	X
VIRGINIA	◣	X	X	X	X	X	X	Primavera Product	Incidental to work item	X
WEST VIRGINIA	X	◣	X	X	◣	X	X	X	X	X
WISCONSIN	■	◣	X	X	X	X	X	Computer developed schedule; Other, directed by the Department	X	X
WASHINGTON	◣	◣	X	X	X	X	X	X	X	X
WYOMING	■	◣	X	X	X	X	X	Primavera P6	Incidental to work item for bar chart; Paid for CPM	X

2.4 State-of-the-Practice on CPM Scheduling

Three separate online surveys were developed as part of this study. One for state DOTs, one for RCEs, and one for contractors working with state DOTs. The surveys were made available between June 14, 2017 and July 23, 2017. The surveys focused on gathering information about selection criteria for CPM projects, preferred scheduling techniques and software, contract requirements for projects with CPM schedules, decision making on CPM schedules, delay factors associated with CPM scheduling, RCE evaluation of CPM schedules as used by the contractors, responsibilities of schedulers and value of CPM to their organization. A total of 23 state DOTs, 51 Resident Construction Engineers (RCEs) from 16 different states, and 45 contractors from 16 different states responded to the survey.

2.4.1 Summary of responses from State DOTs

The following summary will first list the question in *italic* followed by a summary of the responses.

1. *Do you use Critical Path Method (CPM) for project management?*

Table 2.2 State DOTs use of CPM scheduling

	Count	Percentage
Yes	22	95.6%
No	1	4.4%

As shown, nearly 96% of the responding state DOTs (22 out of 23) use CPM for project management.

2. *What scheduling technique do you use other than CPM? (select all that apply)*

Table 2.3 State DOTs use of alternatives to CPM scheduling

	Count	Percentage
CPM only	8	36.4%
Gantt charts	11	50.0%
Milestone charts	3	13.6%
Other: • Bar Charts (Excel) • TxDOT standard specs item 8.5 • Monitoring charts	3	13.6%
Total number of respondents	22	

As shown in Table 2.3, 8 state DOTs (36.4%) use only CPM schedules for project management. Other techniques used by state DOTs for scheduling include Gantt charts (50%) and milestone charts (13.6%). In the "Other" categories, some mentioned the use of bar charts (in Excel), customized scheduling forms, and monitoring charts. Note that for questions where respondents are asked to "select all that apply," the percentages do not add up to 100% because a survey respondent may select more than one answer choices.

3. *How do you select projects for CPM scheduling? (select all that apply)*

Table 2.4 State DOTs criteria for requiring CPM scheduling

	Count	Percentage
Based on the complexity of the project	16	72.3%
Based on the risk associated with the project	12	54.5%
Based on total bid amount of the project	6	27.3%
Following the rules and regulations of the agency	5	22.7%
Other: • Based on contract special provision • Incentive/ disincentive • CPM for all projects • Contractor option	6	27.3%
Total number of respondents	22	

As shown in Table 2.4, the top three reasons for selecting projects for CPM are scheduling: project complexity (16 out of 22 or 72.3%), project risk (54.5%), and total bid amount (27.3%). These reasons are consistent with the literature review findings and the SCDOT's practice.

4. *Do you require CPM specifications for each project? (i.e. ensures least interference with traffic, employ sufficient labor and equipment at all times, use of certain methods or equipment, etc.)*

Table 2.5 State DOTs requirement for CPM specifications

	Count	Percentage
Yes, for all projects	8	36.4%
Yes, for most of the projects	3	13.6%
Yes, for some of the projects	8	36.4%
No	3	13.6%
Total number of respondents	22	

As shown in Table 2.5, among the 22 state DOTs that use CPM schedules, only 13.6% do not require CPM specification for their projects.

5. *Are specifications for scheduling the same for all projects or customized for each project?*

Table 2.6 State DOTs use of customized specifications for scheduling

	Count	Percentage
Standard, for all projects	11	50.0%
Standard, for most of the projects (customized for some projects)	7	31.8%
Customized, for all projects	4	18.2%
Total number of respondents	22	

6. *What software does your agency currently use for scheduling? (select all that apply)*

Table 2.7 State DOTs software preferences for scheduling

	Count	Percentage
Primavera P6, version 15 or newer	6	27.3%
Primavera P6, version 8 (8.1, 8.2, 8.3, 8.4)	11	50%
Primavera P6, version 7 or older	4	18.2%
Primavera P3	2	9.1%
SureTrak	0	-
Microsoft Project 2010	3	13.6%
Microsoft Project 2013	1	4.6%
Microsoft Project 2016	3	13.6%
Other: • Asta Powerproject • Paper • Contractor preference	4	18.2%
Total number of respondents	22	

As shown in Table 2.7, the majority of state DOTs use Primavera, followed by Microsoft Project.

7. *What software is used for Gantt charts scheduling technique? (i.e. Excel, pen/paper)*
8. *What software is used for Milestone charts scheduling technique? (i.e. Excel, pen/paper)*
9. *What software is used for "other" scheduling technique? (i.e. Excel, pen/paper)*

Table 2.8 State DOTs identification of software for scheduling other than CPM

- MS Excel
- Asta powerproject
- MS Word
- Pen-paper
- DOT provide contractor the option to choose their desired software.
- DOT specific form is used for milestone charts

10. *What types of information are loaded with schedules?*

Table 2.9 State DOTs type of information included in schedules

	Count	Percentage
Resource	5	22.7%
Cost	2	9.1%
Both (resource and cost)	6	27.3%
None	5	22.7%
Other: • Activities • Project specific calendar • Conditional resource loading	4	18.2%

• Cost with all schedules or resources with contract amount greater than certain cut-off (e.g., contract amount > $7.5 million)	
Total number of respondents	22

11. Do you currently host your schedule database on the cloud?

Table 2.10 State DOTs on hosting schedule database on the cloud

	Count	Percentage
Yes	3	13.6%
No	19	86.4%
Total number of respondents	22	

12. Do you have plans to move your database to the cloud in the next five years?

Table 2.11 State DOTs future plan on cloud storage of scheduling database

	Count	Percentage
Yes	2	9.1%
No	7	31.8%
Maybe	10	45.5%
No response	3	13.6%
Total number of respondents	22	

It is interesting to note that a good number of state DOTs (2 indicated yes and 10 indicated maybe) are considering moving their schedule database to the cloud.

13. Do you allow contractors to access your schedule database?

Table 2.12 State DOTs on contractors' access to schedule database

	Count	Percentage
Yes	3	13.6%
No	17	77.3%
Depends on the contract	2	9.1%
Total number of respondents	22	

14. In what situations do you require a revised CPM schedule? (select all that apply)

Table 2.13 State DOTs requirement for revision to CPM schedule

	Count	Percentage
Critical path changes	21	95.5%
Change orders	14	63.6%
Resource unavailability	4	18.2%
Other: • Activity original duration changes	10	45.5%

• Monthly updates • Mandatory monthly updates • Contract time changes • Contractor deviates from current progress schedule • Project behind schedule greater than certain days (i.e. 10 days) • Time extension require for revised CPM	
Total number of respondents	22

15. Do you use CPM for assessing claims?

Table 2.14 State DOTs use of CPM scheduling for assessing claims

	Count	Percentage
Yes, for all claims	9	40.9%
Yes, for selected claims	13	59.2%
No	0	0.00%
Total number of respondents	22	

2.4.2 Summary of Responses from Resident Construction Engineers' (RCE)

A total of 51 resident construction engineers from sixteen (16) different states responded to the online survey. Most of the RCE respondents (33 out of 51, 64.7%) are SCDOT employees.

1. *If you have the authority, how would you select projects for CPM scheduling? (select all that apply)*

Table 2.15 RCEs on selection criteria for CPM scheduling

	Count	Percentage
Based on the complexity of the project	47	92.2%
Based on the risk associated with the project	31	60.8%
Based on the total duration of the project	27	52.9%
Based on total bid amount of the project	20	39.2%
Based on the previous experience with similar type of work/contractor	21	41.2%
Following the rules and regulations of the agency/client	7	13.7%
Other… • All projects require CPM • Anticipated conflicts • Time incentives	3	5.9%
Total number of respondents	51	

2. *How often do you refer to CPM (Critical Path Method) schedule for decision making on projects?*

Table 2.16 RCEs decision making based on CPM schedule

	Count	Percentage
Frequently	10	19.6%

Occasionally	34	66.7%
Never	7	13.7%
Total number of respondents	51	

3. *Do you find contractors strive to follow CPM schedule?*

Table 2.17 RCEs evaluation of contractor on following CPM schedules on projects

	Count	Percentage
Frequently	10	19.6%
Occasionally	34	66.7%
Never	7	13.7%
Total number of respondents	51	

4. *If not required by the contract, do contractors still use a CPM schedule?*

Table 2.18 RCEs on contractors use of CPM schedules

	Count	Percentage
Yes, all	0	0%-
Yes, most of the contractors	2	3.9%
Yes, some of the contractors	26	50.9%
No	23	45.1%
Total number of respondents	51	

More than half of the responding RCEs (28 out of 51, 54.9%) indicated that contractors prepare a CPM schedule whether it is required or not by the contract.

5. *Do you find the duration between the Notice to proceed (NTP) and start of work in construction projects consume a significant fraction of the total duration of the project?*

Table 2.19 RCEs evaluation of start delay of projects

	Count	Percentage
Yes, for all projects	1	1.96%
Yes, for most of the projects	6	11.76%
Yes, for some of the projects	22	43.14%
No	22	43.14%
Total number of respondents	51	

6. *Do you observe a significant fraction of the change orders from contractors in the last third of the project?*

Table 2.20 RCEs evaluation of number of change orders in last third of the project

	Count	Percentage
Yes, for all the projects	1	1.96%
Yes, for most of the projects	9	17.7%
Yes, for some of the projects	25	49.02%
No	16	31.4%

Total number of respondents	51

7. *What are the most common reasons for requesting project extension? (select all that apply)*

Table 2.21 RCEs reasons for project extension

	Count	Percentage
Weather	34	66.7%
Contract modifications	36	70.6%
Resource constraints	5	9.8%
Inadequate planning and scheduling	16	31.4%
Change orders by owner	29	56.9%
Delay in approving drawing and materials by owner	1	1.96%
Slowness in decision making process	9	17.7%
Other: • Inadequate planning and scheduling • by contractor but blames scope of work • Inadequate plans • Utilities/Utility conflicts/Utility Delays/ • Utility Relocations/Permitting	11	21.6%
Total number of respondents	51	

8. *From your observations, does the use of a CPM schedule reduce the number of change orders in projects?*

Table 2.22 RCEs use of CPM scheduling to reduce number of change order of projects

	Count	Percentage
Yes, for all projects	0	0%
Yes, for most of the projects	6	11.8%
Yes, for some of the projects	14	27.5%
No	31	60.8%
Total number of respondents	51	

9. *Do you use CPM for assessing claims?*

Table 2.23 RCEs use of CPM scheduling for assessing claims

	Count	Percentage
Yes, for all claims	16	31.4%
Yes, for selected claims	25	49%
No	9	17.6%
No response	1	
Total number of respondents	51	

2.4.3 <u>Summary of Responses from Contractors</u>

A total of 45 contractors working in sixteen (16) different states responded to the survey. Some of the contractors worked for multiple state DOTs. The two states that had the highest response from contractors are Michigan (17 out of 45, 37.8%) and South Carolina (12 out of 45, 26.7%).

1. *Do you find contracts now contain specifications requiring CPM (Critical Path Method) schedule?*

Table 2.24 Contractors on specification of CPM scheduling

	Count	Percentage
Yes, always	3	6.7%
Yes, most of the time	17	37.8%
Projects greater than $5 million	13	28.9%
Projects greater than $10 million	5	11.1%
Projects greater than $20 million	1	2.2%
Projects greater than $50 million	2	4.4%
Projects greater than $100 million	0	0%
Rarely	3	6.7
No	1	2.2%
Total number of respondents	45	

2. *If not required (or, if waived in the contract), do you still prepare a CPM schedule?*

Table 2.25 Contractors use of CPM schedule

	Count	Percentage
Yes	30	66.7%
No	15	33.3%
Total number of respondents	45	

3. *How often do you make decisions based on CPM schedule?*

Table 2.26 Contractors decision making based on CPM schedule

	Count	Percentage
Frequently	20	44.4%
Occasionally	17	37.8%
Never	8	17.8%
Total number of respondents	45	

The result of question 3, shown in Table 2.26, revealed that more than 80% (37 out of 45) of the responding contractors use CPM for making decisions on projects. Among the contractors who use CPM schedules for decision making, more than half of them (20 out of 37) use it frequently.

4. *On average, what is the cost of CPM application as a percentage of the total project cost?*

Table 2.27 Contractors on cost of CPM schedules for projects

	Count	Percentage
Below 0.5%	29	64.4%
0.5% - 2.5%	12	26.7%
Above 2.5%	4	8.9%
Total number of respondents	45	

5. *Do you use scheduling techniques other than CPM for project management? (select all that apply)*

Table 2.28 Contractors use of alternative techniques to CPM scheduling

	Count	Percentage
CPM only	13	29.9%
Milestone charts	22	48.9%
Gantt charts	26	57.8%
Other: • Excel • Short term schedule • week look ahead • Line chart • Bar chart	5	11.1%
Total number of respondents	45	

6. *Do you maintain a separate schedule for work in addition to the contract specified schedule?*

Table 2.29 Contractors use of separate schedule other than contract specified scheduling

	Count	Percentage
Yes, for all projects	11	24.4%
Yes, for most of the projects	8	17.8%
Yes, for some of the projects	15	33.3%
No	11	24.4%
Total number of respondents	45	

A good percentage of the contractors indicated that they keep a separate schedule. This response suggests that the state DOTs and RCEs may not have the actual construction schedule.

7. *Do you use CPM for assessing claims?*

Table 2.30 Contractors use of CPM scheduling to assess claims

	Count	Percentage
Yes, for all claims	5	11.1%
Yes, for selected claims	32	71.1%
No	6	13.3%
No response	2	4.4%
Total number of respondents	45	

8. *Is your CPM scheduling performed by?*

Table 2.31 Contractors' appointed personnel for CPM scheduling

	Count	percentage
In-house personnel	25	55.6%
Outside consultant	2	4.4%

Combination of in-house and outside consultants	18	40%
Total number of respondents	45	

9. Do you have a dedicated person responsible for planning and scheduling?

Table 2.32 Contractors on responsibility of appointed personnel for planning and scheduling

	Count	percentage
Yes	13	28.9%
No	32	71.1%
Total number of respondents	45	

10. What other duties does your scheduler perform?

Table 2.33 Contractors on duties of appointed scheduler

	Count	percentage
Schedule only	6	13.3%
Cost estimation	24	53.3%
Project management other than scheduling	32	71.1%
Administration	12	26.7%
Other: • Engineering • Supervision • Surveying • Project Manager/ someone from project team does CPM training organizer • Do mostly scheduling and updates	6	13.3%
Total number of respondents	45	

11. How important is CPM scheduling for the future success of your company?

Table 2.34 Contractors' evaluation of CPM scheduling on success of the company

	Count	percentage
1 (Very Important)	16	35.6%
2	7	15.6%
3	12	26.7%
4 (unsure)	8	17.8%
No response	2	4.4%
Total number of respondents	45	

2.5 Summary of Phone Interviews

Based on the online survey results, follow-up interviews were conducted. The telephone interviews were conducted between October and November of 2017. The goal of the phone interviews was to obtain additional information about other states' use of CPM. The two state DOTs that agreed to provide additional information were California and Texas. The Caltrans representative is a scheduling engineer who works in the Division of Construction, and the TxDOT representative is a transportation engineer. Tables 2.35 and 2.36 provide the list of questions asked and the response given by the representatives.

Table 2.35 Phone interview questions and answers from Caltrans

	Questions	Answers
1)	How do you measure the complexity of a project beforehand?	Caltrans is following the current specification which has three levels of CPM use. The three levels of CPM are determined based on bid amount and number of working days. Caltrans is planning to also consider project complexity.
2)	How do you separate high complexity projects and low complexity projects?	Caltrans is planning to incorporate "Risk Management Analysis" to separate the high and low complexity projects. Examples of high complexity: retrofitting Examples of low complexity: overlay
3)	What are the indicators to look for when looking into complex projects?	Caltrans has not started using risk management analysis, so they are not sure which indicators to use at this point. Caltrans uses a subjective measurement at the discretion of the RCEs.
4)	Can you think of any examples of a project with smaller bid amount but with high complexity?	A "Pile Cap" would cost less but would be high complexity. So, at the beginning as per the standard specification, the project will have a Level 1 CPM. The RCE of the respective district can make a request to move it to LEVEL 2 or LEVEL 3 if he perceives it to be a complex project. If so, there will be a Special Provision for the contract.
5)	What are some of the special contract provisions for using CPM for a project?	As described above in response to question 4.
6)	Can you predict whether a project will be delayed in the early stage of the project?	The designer sketches a rough CPM (estimates) and makes notes of the probable activities that may be affected by a delay. It is incorporated in the contractor's baseline schedule. The uncertainties during construction are considered in the "revised schedule". The contractor needs to submit a Time Impact Analysis (TIA) before the revised schedule. This is the current practice.
7)	Does using CPM on a project give a (false) assurance of on-time delivery of project? If yes, why are we really using it for?	"CPM helps the project to be on-time but it does not give an exact assurance of the project to be on-time." Basically, CPM schedule serves the following two purposes: 1. Plan for the work; because you need a plan for work before you start the work.

	2. Claim analysis.

The key findings from the Caltrans phone interview are:

1. Caltrans emphasizes CPM scheduling in their projects.
2. Caltrans has definite criteria for selecting projects for CPM. In addition to the current criteria, it is planning to include the complexity measure.
3. To incorporate the complexity criteria, Caltrans is planning to incorporate Risk Management Analysis and revise their standard specifications.
4. Caltrans recognizes that "CPM helps the project to be on-time, but it does not give an exact assurance of the project to be on-time."

Table 2.36 Phone interview questions and answers from Texas DOT

	Questions	Answers
1)	How do you select your scheduling technique?	The method is generally provided by the design section or from the notes of designers. The design division can use bar charts, milestone charts or CPM as a scheduling technique. This decision is also a discretion of the district construction engineer (DCE). The DCE can suggest using CPM for certain situations or can waive for other situations.
2)	How do you separate high complexity projects and low complexity projects?	Since there are no set of rules to select CPM scheduling technique, Texas DOT does not measure complexity explicitly.
3)	What are the indicators to look for when looking into complex projects?	"Replacement" work was mentioned as an example. When asked "does CPM helps this kind of projects," the interviewee said he is not sure. He mentioned that TxDOT uses Time Impact Analysis (TIA) following the standard specification; it justifies any change order for time on a project.
4)	Can you think of any examples of a project with smaller bid amount but with high complexity?	The TxDOT standard specification item 8.5 is meant for controlling this type of the project.
5)	What are some of the special contract provisions of using CPM for a project? Can you predict whether a project will be delayed in the early stage of the project?	The comparison made between designers' rough schedule and contractors' schedule. There may be a conflict in the schedule due to events like public/local events.
6)	Does using CPM on a project give a (false) assurance of on-time delivery of project? If yes, why are we really using it for?	The interviewee mentioned that the claim is not quantified from their data but it "makes absolute sense" to him.

The key findings from the Texas DOT phone interview are:

1. TxDOT does not have specific criteria for CPM scheduling.
2. TxDOT does not emphasize CPM scheduling on their projects.

3 METHODOLOGY

3.1 Data Synthesis and Description

The project data were synthesized from two databases provided by the SCDOT: SiteManager and Primavera. The SiteManager database, provided in Microsoft Access format, contains records regarding general information about the projects, items used in projects, change order records and daily work reports. Table 3.1 provides the list of attributes available in SiteManager. The Primavera database, provided in SQL database format, contains records regarding schedule and activities in the projects. Figure 3.1 provides the Enterprise Project Structure (EPS) of the Primavera database and Table 3.2 provides the list of those attributes in Primavera that were used in this project. It should be noted that the Primavera database contains many more attributes than those shown in Table 3.2.

Table 3.1 SiteManager database attributes and description

Variable Name	Description	Information Type
CONT_ID	Unique code identifying each project	Project
FED_ST_PRJ_NBR	A unique code for funding management purposes	Project
LEV3_OFFICE_NBR	Engineering district that manages the project	Project
LEV4_OFFICE_NBR	Resident Construction Engineer (RCE) office	Project
VEND_ID	ID for the prime contractor	Project
TOT_BID_AMT	Original bidding amount for the project	Cost
NET_C_O_AMT	Total change order amount	Cost
Total_Paid	Total amount paid	Cost
TTBID	TOT_BID_AMT plus NET_C_O_AMT	Cost
NTP_Date	Notice to proceed date	Time/Dates
Adj_Comp_Date	Adjusted completion date (original completion date and time change order)	Time/Dates
CompDate	Substantial completion date	Time/Dates
Letting_Date	Date the project was let	Time/Dates
WRK_T	Type of project (i.e. Bridge, surfacing, painting etc.)	Project
ORGC_Date	Original completion date when the project was let	Time/Dates
DESC1	A brief description of the project	Project
LOC_DESC1	A brief description of the project location	Location

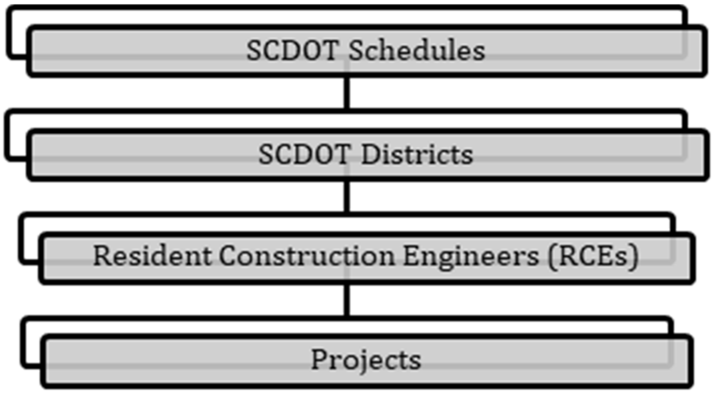

Figure 3.1 Enterprise Project Structure of Primavera database

Table 3.2 Primavera database attributes used in this project

Variable Name	Description	Information Type
PROJ_ID	Unique code identifying each project	Project
PROJ_SHORT_NAME	A short code which uniquely identifies the project	Project
WBS_SHORT_NAME	A short code assigned to each WBS element for identification	Project
PARENT_WBS_ID	The parent WBS in the WBS hierarchy	Project
TASK_ID	Unique ID for the task	Project
TASK_NAME	The name of the activity	Project

The *before* 2007 dataset consists of 1,856 projects and the *after* 2007 dataset consists of 2,097 projects. The projects are categorized by type. The 16 different project types are shown in Table 3.3. Not all project types are included in the *before* 2007 database (e.g., ASPT).

Table 3.3 Description of different project types

Type	Description
ASPT	Surface treatment
BRDG	Bridge
BRPT	Bridge paint
CGSW	Curb, gutter, sidewalk
DRST	Drainage structure
GDRL	Guardrail
GNRL	Projects span across several different categories, such as widening projects but without any dominating project type like HMAS or ASPT in terms of percentage of the project cost.
HMAS	Hot-mixed asphalt paving
LDSC	Landscaping
PCCP	Concrete pavement

PMEP	Epoxy pavement marking
PMPT	Pavement marking
PMRP	Raised pavement markers
PMTH	Thermal pavement marking
SGNL	Traffic signal
SIGN	Roadway signs

The SiteManager and Primavera databases were joined using the unique project identifier "CONT_ID" in SiteManager and the "wbs_short_name" field in the Primavera table "dbo_PROJWBS". The extracted information from the SiteManager and Primavera databases were merged together to create a new database for analysis as shown in Table 3.4.

Table 3.4 Created database for analysis

Data item	Database	Variable code	Description
Project related	SiteManager	CONT_ID	Unique identifier for the project
		TYPE	Category of project type
	Primavera	PROJ_SHORT_NAME	Unique identifier of the project
		PROJ_ID	Unique identifier of the project
		WBS_SHORT_NAME	Title of the project
		TASKS	Number of tasks associated with each project
Time-related	SiteManager	LET_DT	Letting date of the project
		NTP_DT	Notice to proceed date
		ORGC_DT	The planned completion date of the project at the award
		ADJ_COMP_DT	The adjusted completion date of the project after change order
		COMP_DT	The substantial completion date of the project
		TT_DELAY	Delay after planned completion date; (COMPDATE – NTP_DATE)
	Calculated	CO_DELAY	Delay after adjusted completion date; (ADJ_COMP_DATE – NTP_DATE)
		TT_CODE	1, if TT_DELAY > 0; 0, otherwise
		CO_CODE	1, if CO_DELAY > 0; 0, otherwise
Cost-related	SiteManager	TOT_BID_AMT	Total bid amount (USD) at the time of contract award
		NET_CO_AMT	Net change order amount (USD) for the project
		TTBID	Total bid amount after change order
Location		LEV3_OFFICE_NBR	SCDOT district

Schedule related	SiteManager	SSP_CODE	1, if there is a payment item for schedule; 0, otherwise
		SST_CODE	1, if there is an entry in Primavera for schedule; 0, otherwise
	Calculated	SSPRIM_CODE	1, if the project has a real schedule in Primavera; 0, otherwise

To determine if a project is delayed, the following criteria/variables were used:

- **CO_Delay:** Time delay (in days) measured in terms of the number of days beyond the adjusted completion date (considered only those projects with CO_delay > 0).
- **TT_Delay:** Time delay (in days) measured in terms of the number of days beyond the original completion date (considered only those projects with TT_delay > 0).

Every project in the Primavera database is referred to as an "SST" project. Some of the SST projects do not have a CPM schedule. Observations from the "OBS" table in the Primavera database show that under each RCE, there are some projects that are marked as "No CPM." Also, some of the project titles (WBS_SHORT_NAME) indicate that they do not have a CPM schedule. The projects with no CPM schedule are identified using the following criteria:

i. The projects contained in the "No CPM" or "No CPM Reqd" level in the Primavera database.
ii. Non-real CPM schedule activities. These projects have only "payout" or "cash flow only" or "estimate only" activities.
iii. Non-CPM schedule: These projects have titles that contain phrases "Non CPM" or "non cpm schedule" or "NO CPM Required."

Projects that fall into the above criteria were excluded from the SST projects and then further categorized as follows:

- **SSPRIM** – all the projects in Primavera with a real schedule. These projects are the SST projects that do not fall into the above criteria (i), (ii) or (iii).
- **SSNULL** - all the projects in SiteManager that are not SSPRIM.

A project's size is grouped into one of the following categories:

- **Small**: contract bid amount is between $0 to $ 360,000.
- **Medium**: contract bid amount is between $360,000 to $1,000,000.
- **Large**: contract bid amount is greater than $1,000,000.

A project's duration is grouped into one of the following categories:

- **Short**: original duration of the project less than 6 months.
- **Medium**: original duration of the project is between 6 to 12 months.
- **Long**: original duration of the project is more than 12 months.

3.2 Statistical Tests

Two types of statistical tests were conducted in this study. The Chi-square test was used to determine if there is a strong association between categorical variables, and the t-test was used to determine if the difference between two sample means is statistically significant.

3.2.1 Chi-square test of independence

The Chi-square test is also known as the Pearson Chi-square test. It is one of the most commonly used non-parametric tests. The advantage of using a non-parametric test lies in its minimal assumptions. The assumptions of the Chi-square test are:

- No assumption on the distribution of the sample data.
- Sample data can be distributed into distinct categories.
- The data in distinct categories are frequencies or counts.
- The categories of variables are mutually exclusive.
- The frequency of expected value in any cell of the contingency table is 5 or more in at least 80% percent of the cells. Additionally, the expected value in any cell should not be less that one.

The Chi-square test is performed to determine if the categorical variables are associated with each other. The hypothesis tested in the Chi-square test of independence is as follows.

- **H_0**: the two categorical variables (e.g., project size and delay) are independent.
- **H_a**: the two categorical variables (e.g., project size and delay) are dependent.

To perform this test, first, the two categorical variables are summarized in the form of a contingency table as illustrated below.

	Second categorical variable			
First categorical variable	**1**	**.**	**j**	**Total**
1	C_{11}	.	.	R_1
I	.	.	.	R_i
Total	C_1	.	Cn	n

Then the χ^2 test statistic is calculated as follows (Washington et. al., 2011).

$$\chi^2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\frac{(O_{ij} - E_{ij})^2}{E_{ij}} \tag{1}$$

where,

$\chi^2 =$ the test statistic

$O_{ij} =$ the observed count in cell (i, j)

$E_{ij} =$ the expected count in cell (i, j) = $E_{ij} = \frac{R_i C_j}{n}$

where, R_j and C_i are the row and column totals, respectively.

r = number of rows
c = number of columns

The degrees of freedom (df) is calculated as: df = (r-1)(c-1)

If the computed Chi-square test statistic is greater than the Chi-square value at 5% significance level and "df" degrees of freedom, then H_0 is rejected. The R statistical software was used to perform the Chi-square test.

3.3.2 Student's t-test

The null hypothesis of the t-test is:

- **H_0**: there is no difference in the means of the two samples ($\mu_1 = \mu_2$)
- **H_a**: there is a difference in the means of the two samples ($\mu_1 \neq \mu_2$)

If the variance of the two samples is equal, then the pooled two-sample t-test should be used. If the variances are not equal, then the Welch's two-sample t-test should be used. To determine if the variance is equal or not, the F-test can be used. The hypothesis for the F-test is:

- **H_0**: the variances of the two samples are equal
- **H_a**: the variances of the two samples are not equal

The F-test statistic is as follows:

$$F = s_1^2 / s_2^2 \tag{2}$$

Where,

s_1^2= variance of sample 1
s_2^2= variance of sample 2

The F-statistic implies that, the more the ratio of variances deviate from 1, the stronger the evidence of unequal sample variances.

The test statistic of the pooled two sample t-test is as follows:

$$t^* = \frac{\overline{x_1} - \overline{x_2}}{s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{3}$$

where,

$\bar{x}_1$ = mean of sample 1
$\bar{x}_1$ = mean of sample 2
n_1 = sample size of sample 1
n_1 = sample size of sample 2

and $s_p = \sqrt{\dfrac{(n_1-1)s_1^2+(n_2-1)s_2^2}{df}}$

s_1^2= variance of sample 1
s_2^2= variance of sample 2
df = degrees of freedom = $n_1 + n_2 - 2$

The test statistic of the Welch's t-test and the associated degrees of freedom are as follows.

$$t^* = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\dfrac{1}{n_1} + \dfrac{1}{n_2}}} \tag{4}$$

df = degrees of freedom = $\dfrac{(n_1-1)(n_2-1)}{(n_2-1)C^2+(1-C)^2(n_1-1)}$

where $C = \dfrac{s_1^2/n_1}{s_1^2/n_1 + s_2^2/n_2}$

Similar to the Chi-square test, if the computed test statistic is greater than the t-value at the 5% significance level and "df" degrees of freedom, then H_0 is rejected. The R statistical software was used to perform the Chi-square test.

3.3 Project Delay Estimation

To estimate the probability of a project being delayed, the PDFs of project delay were first constructed using EasyFit, a distribution fitting software (Mehrannia, 2014). Then the best fit distribution was determined using the goodness of fit statistics, as explained below.

3.3.1 Goodness of fit test

EasyFit provides three Goodness-of-Fit (GOF) statistics. They are (1) Kolmogorov–Smirnov, (2) Anderson-Darling and (3) Chi-square. The Kolmogorov-Smirnov (K-S) GOF test is based on the K-S measure of the maximum distance between theoretical CDF (cumulative distribution function) and empirical CDF (Massey, 1951). The K-S test statistic is given below.

$$D = \max_{1 \le i \le N} \left(F(X_i) - (\frac{i-1}{N}), \frac{i}{N} - F(X_i)\right) \quad (5)$$

where,

N = Number of observations in the sample
$F(x_i)$ = CDF

The Anderson-Darling (A-D) GOF test compares the fit of an observed CDF with an expected CDF. This test is a modification of the K-S GOF test. However, this test gives more weight to the tails (Anderson, 1954). The A-D test statistic is given below.

$$A^2 = -N - \frac{1}{N}\sum_{i=1}^{N}(2i-1)[\log F(x_i) + \log(1 - F(x_{N-i+1})] \quad (6)$$

where,

N = number of observations in the sample
$F(x_i)$ = CDF

In the Chi-square GOF test, the data are grouped into k intervals and it compares the expected observations against actual observation for each interval (Cochran, 1952). The Chi-square test statistic is given below.

$$\chi^2 = \sum_{i=1}^{k}((O_i - E_i) / E_i \quad (7)$$

where,

O_i = Actual observation
E_i = Expected observations

The hypothesis of the GOF tests is:

- H_0: The empirical data is a sample from the specified theoretical distribution.
- H_a: The empirical data is not a sample from the specified theoretical distribution.

The rejection decision is made based on the *p-value* or the comparison between the critical value and the test statistic. That is, if the test statistics D, A^2, and χ^2 is greater the corresponding critical value at the chosen significance level (α) then H_0 is rejected. Alternatively, H_0 is rejected if the *p-value* is smaller than the chosen significance level (α).

3.3.2 Probability of delay using the Law of Total Probability (LTP)

From the constructed PDFs, the probability of delay can be estimated by applying the Law of Total Probability (LTP). The LTP states that the marginal probability of an event happening at stage two is equal to the sum of the products of the marginal (stage one) and conditional (stage two given stage one) probabilities over all the possible ways to achieve the event (Rumsey, 2006). The LTP is mathematically expressed as,

$$P(B)=\sum_{i=1}^{k} P(A_i)\,P(B/A_i) \tag{8}$$

where,

$$P(A_i)\,P(B/A_i) = P(B \cap A_i) \tag{9}$$

$A_1, A_2, \ldots, A_k$ are events, and thus, they are partitions of an experiment. The assumptions for LTP are:

- These events are mutually exclusive
- The union of these events includes all outcomes

If B is any event and $A_1, A_2, \ldots, A_k$ are partitions of an event A, then

$$B=(B \cap A_1) \cup (B \cap A_2) \cup \ldots \cup (B \cap A_k) \tag{10}$$

To calculate the probability of delay, the following definitions and values were used.

$P(B)$ = Probability that a project will be delayed
$P(A_1)$ = Proportion of past projects that were delayed
$P(A_2)$ = Proportion of past projects that completed on time
$P(A_3)$ = Proportion of projects that completed earlier than the scheduled completion date

Therefore, by the LTP:

$$P(B)=P(B \cap A_1)+P(B \cap A_2)+P(B \cap A_3)$$

$$P(B)=P(A_1)\,P(B/A_1)+P(A_2)\,P(B/A_2)+P(A_3)\,P(B/A_3)$$

The terms $P(B/A_1)$, $P(B/A_2)$ and $P(B/A_3)$ were computed using StatAssist (Mehrannia and Pakgohar, 2014)

3.4 Predictive Analysis

3.4.1 Binary logistic regression Models

A binary logistic regression model is used when the response variable has two possible outcomes. In this study, the binary logistic model is used to estimate the probability of a project being delayed or over budget based on a set of factors associated with the project (e.g., project type, project size, project duration). A technical description of the binary logistic regression model is provided below.

Let $X = (x_1, x_2,..., x_n)$ be a set of explanatory variables; x_i can be discrete or continuous. Let Y be a binary response variable; $Y_i = 1$ if the trait (i.e. success) is present in observation *i*. The logit value of the unknown probability is modeled as a linear function.

$$\text{logit}(\Pr_i) = \ln\left(\frac{\Pr_i}{1-\Pr_i}\right) = \beta_0 + \beta_1 x_{i1} + ... + \beta_k x_{ik} \tag{11}$$

where

$\Pr_i =$ is the probability that Yi =1

Parameters β_j (j = 0,…, k) are estimated through maximum likelihood estimation. The expression on the left-hand side is usually referred to as logit or log-odd. The logit coefficient of β_j indicates how much the log-odds changes (i.e. increases if positive and decreases if negative) by every 1-unit increase of the explanatory variable x_{ij}. The following function is referred to as a logistic regression:

$$P(Y_i = 1 | X) = \frac{1}{1+e^{-(\beta_0 + \beta_{i1} + ... + \beta_{ik})}} \tag{12}$$

In this study, the response variable, Y, is whether the project completed on time or on budget. The initial model considered all explanatory variables. Then, a systematic procedure of removing and adding variables was used to find the best combination of explanatory variables. Variables were retained in the model if they have t-statistics corresponding to the 95% confidence level or higher (i.e., p-values less than 0.05).

For each revised model, a likelihood ratio test was used to test the effectiveness of that model. The null hypothesis is that the unrestricted and restricted models are statistically equivalent; the unrestricted model is the previously best model and the restricted model is the revised model. The term restricted implies that one or more variables have been removed from the model. A technical description of the likelihood ratio test is provided below (Washington et. al., 2011).

Where,

$$\chi^2 = -2\left[LL(\beta_R) - LL(\beta_U)\right] \tag{13}$$

$LL(\beta_R) =$ log likelihood of the restricted model

$LL(\beta_U) =$ log likelihood of the unrestricted model

χ^2 = Chi-Square statistic with the degrees of freedom equal to the difference in the numbers of parameters in the restricted and unrestricted models

3.4.2 Text mining and neural network

Another approach used in this study to predict project delay was the use of text mining and a neural network. The texts used in the analysis came from the change order and daily work report from the SiteManager database. The text mining was performed in two steps. In the first step, a dictionary was constructed using all pertinent words recorded in the change order and daily work report. Each word in the dictionary was then assigned a sentiment score between -5 and +5 where a +5 means the most positive sentiment and -5 means the most negative sentiment. For example, the sentiment score of the sentence *"No work performed today (rain)"* using the AFINN lexicon is as follows.

no	Work	performed	today	(rain)	Number of words	Aggregated Score
-1	0	0	0	0	5	(-1+4*0)/5 = -0.2

The aggregated sentiment scores for each comment were used to provide an overall sentiment score for a project.

In the second step, a neural network was used to predict project delay using the aggregated sentiment score. The project's sentiment score was used as an input to the neural network. Other variables included in the model were whether CPM scheduling was used and environmental conditions when the work was performed. The training data consists of three-fourths of the *after* 2007 dataset. Once the training was completed, the neural network was used to predict delay using the remaining one-fourth of the *after* 2007 dataset.

An artificial neural network resembles the biological nervous system. It is composed of highly interconnected neurons. Neurons or nodes are the basic processing units in a neural network. The nodes receive input from two sources: other nodes or from external sources. Each input in the node has associated weight, and thus, the weighted sum of all the inputs to the node can be calculated. The neural network architecture is composed of the following key elements:

- Input layer (input nodes): The nodes on this layer only receive and pass information to the next layer.
- Hidden layer (hidden nodes): The nodes in this layer uses weighted sum as input and use the activation function to calculate outputs. Outputs from this layer is used as inputs to the output layers.
- Output layer (output nodes): The nodes in this layer use activation function to calculate the final outcome.
- Activation function ($f(\sum)$): This activation function of a node defines the output from that node given weighted inputs. The commonly used activation functions are sigmoid, tanh, and ReLU.
- Learning rules: An algorithm which modifies the parameters of the neural network.

Suppose there are n inputs, **x** = {x_1, x_2, x_3, … , x_n} and one target output (t). The target output is to correctly classify (i.e., binary classification) considering the input pattern. The weights of the input is **w** = {w_1, w_2, w_3, …, w_n} respectively. The objective of training the neural network model is to determine the optimal weights (**w**) that best predict the desired outcome (t) using the inputs (**x**).

The following figure is a schematic representation of the neural network:

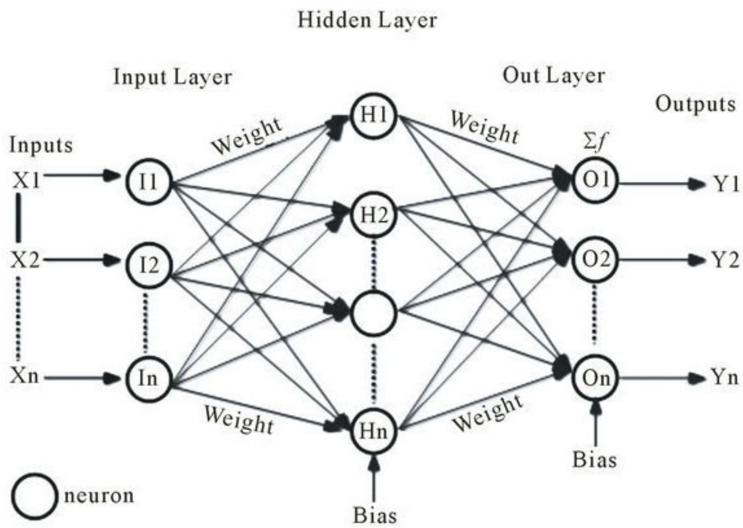

Figure 3.1 Schematic representation of the Neural network

The equation for the net weighted input is (Samarasighe, S., 2007):

$$\Sigma = u = w_1 x_1 + w_1 x_2 + \ldots + w_n x_n \tag{14}$$

The value of *u* determines the activation threshold. The threshold function calculates the activation or output (y) as a function of *u* such that,

$$f(\Sigma) = y = \begin{Bmatrix} 0; u < b \\ 1; u \geq b \end{Bmatrix} \tag{15}$$

The most powerful aspect of the neural network is its learning technique. In 1949, Hebb devised a method of learning known as "Hebbing learning." This mechanism incorporates the learning in the neurons. Another learning technique of neural network is supervised learning. With this technique, the value of the correct output is shown to the network and the weights are adjusted until the actual difference between the output of response neurons and the actual output becomes acceptable. If the classification is correct, the perceptron has classified correctly and the weights are not adjusted. Otherwise, the individual weights are adjusted using a perceptron learning algorithm. The error is calculated as:

$$Error = E = t - y$$

And the new value for the weight is:

$w_{new} = w_{old} + \beta x E$

where,

w_{new} = new value of the weight
w_{old} = old value of the weight
β = learning rate

There are three possible conditions for E for binary classification using a neural network. If E = 0, then

$w_{new} = w_{old}$

If E = 1,

$w_{new} = w_{old} + \beta \boldsymbol{x}$

If E = -1,

$w_{new} = w_{old} - \beta \boldsymbol{x}$

The perceptron in the neural network thus learns by adjusting the weights. In the learning process the perceptron changes the weights according to the above equations until it classifies correctly all the data in the training dataset.

4 FINDINGS AND DISCUSSION

4.1 Descriptive Analysis

The following analyses focus mainly on the *after* 2007 dataset. However, for comparison purposes, as requested by the Project Implementation and Steering Committee (PSIC), some analyses were also performed using the *before* 2007 dataset.

4.1.1 Overview of *After* 2007 Dataset

Table 4.1 shows the distribution of projects by type for the *after* 2007 dataset. As shown, the majority of the SCDOT projects let after February 2007 and substantially completed by August 2015 are either HMAS (48%) or GNRL (14.5%). For those projects with an entry in the Primavera database, slightly more than half of them have a CPM schedule. The paint and marking projects (BRPT, PMEP, PMPT, PMRP, and PMTH), sign (SIGN) and signal projects (SGNL) generally do not have CPM schedules. This is also true for guardrail (GDRL), drainage structure (DRST) and landscape (LDSC) projects. The results in Table 4.1 indicate that certain project types are more likely to have a CPM schedule.

Table 4.1 Distribution of projects by type for a*fter* 2007 dataset

Type	SiteManager	Entry in Primavera (SST)	Valid CPM schedule projects (SSPRIM)
ASPT	102	63	52
BRDG	98	83	77
BRPT	10	4	0
CGSW	153	107	42
DRST	13	7	2
GDRL	85	13	2
GNRL	304	242	195
HMAS	1,007	833	764
LDSC	13	7	1
PCCP	14	12	8
PMEP	21	10	0
PMPT	21	10	0
PMRP	89	41	1
PMTH	108	62	4
SGNL	47	22	8
SIGN	12	6	2
Total	2,097	1,522	1,158

Table 4.2 presents the distribution of projects by SCDOT districts; note that there were 3 projects in the dataset that were not assigned a district. The number of projects in each district range from 250 to 352, and the average number of projects in each district is 299. The district with the most number of projects is District 5, with 352 projects. All of the SCDOT districts, except District 7

use CPM schedules for more than half of their projects. The district that uses CPM schedules the most is District 2 (174 out of 287: 60.6%), followed by District 5 (209 out of 352: 59.4%).

Table 4.2 Distribution of projects by SCDOT districts for *after* 2007 dataset

Districts	Total number of Projects	Total number of SSPRIM Projects
1	333	193
2	287	174
3	283	149
4	289	168
5	352	209
6	300	157
7	250	108
Total	2,094	1,158

Table 4.3 shows the distribution of projects by size (large, medium and small). Each category contains about the same number of projects. The last column in Table 4.3 shows the number of project with CPM schedules in each category.

Table 4.3 Distribution of projects by size for *after* 2007 dataset

Project Size	Total number of Projects	Total number of SSPRIM Projects
Small Projects	702	206
Medium Projects	670	382
Large Projects	725	570
Total	2,097	1,158

Table 4.4 shows the distribution of projects by duration (short, medium, long). A higher percentage of long projects have CPM schedules (286 out of 439: 65.2%) compared to short (43.41%) and medium (55.2%).

Table 4.4 Distribution of projects by duration for *after* 2007 dataset

Project Duration	Total number of Projects	Total number of SSPRIM Projects
Short Projects	364	158
Medium Projects	1,294	714
Long Projects	439	286
Total	2,097	1,158

4.1.2 Comparison of *before* 2007 and *after* 2007 project performance

Table 4.5 shows the descriptive statistics of the *before* 2007 and *after* 2007 datasets. In the *before* 2007 dataset, 22.20% of the projects had CPM schedules. Among the projects without CPM schedules, 58.66% were delayed beyond the original contract completion date, and 25.76% were delayed beyond the adjusted completion date; the average delay beyond the original contract completion date was 124.7 days, and the average delay beyond the adjusted completion date was

75.1 days. Among the projects with CPM schedules, 47.82% were delayed beyond the original contract completion date, and 16.26% were delayed beyond adjusted completion date; the average delay beyond the original contract completion date was 130.5 days, and the average delay beyond the adjusted completion date was 34.9 days. Among the projects with CPM schedules, 56.79% were completed within the original budget.

In the *after* 2007 dataset, 55.22% of projects had CPM schedules. As shown in Table 4.5, among the projects without CPM schedules, 47.49% were delayed beyond the original contract completion date, and 16.08% were delayed beyond the adjusted completion date; the average delay beyond the original contract completion date was 28.5 days, and the average delay beyond the adjusted completion date was –14.6 days (i.e., they were completed 14.6 days before the adjusted completion date). Among the projects with CPM schedules, 54.32% were delayed beyond the original contract completion date, and 14.50% were delayed beyond adjusted completion date; the average delay beyond the original contract completion date was 54.8 days, and the average delay beyond the adjusted completion date was –9.8 days. Among the projects with CPM schedules, 55.87% were completed within the original budget.

Table 4.5 Comparison of *before* 2007 and *after* 2007 project performance

***Before* 2007 dataset**		
Total	1,856	
	Projects with CPM	**Projects without CPM**
Total	412 (22.20%)	1,444 (7.80%)
Number of TT_Delay projects	197 (47.82%)	847 (58.66%)
Number of CO_Delay projects	67 (16.26%)	372 (25.76%)
Average TT_Delay (days)	130.54	124.72
Average CO_Delay (days)	34.93	75.05
Within Budget Projects	234 (56.79%)	558 (38.64%)
***After* 2007 dataset**		
Total	2,097	
	Projects with CPM	**Projects without CPM**
Total	1,158 (55.22%)	939 (44.78%)
Number of TT_Delay projects	629 (54.43%)	446 (47.49%)
Number of CO_Delay projects	168 (14.51%)	151 (16.08%)
Average TT_Delay (days)	54.79	28.54
Average CO_Delay (days)	−9.79	−14.57
Within Budget Projects	647 (55.87%)	836(89.03%)

4.1.3 Daily work reports

The SiteManager database contains a description of work performed each day for a project. The daily observations and remarks from the RCEs provide insights into how the project progresses over time. Specifically, the "No work" comment by the RCEs suggests that no work was accomplished that particular day. Therefore, a significant number of "No work" days may lead to project delay. Table 4.6 provides a comparison between the average number of "No work" days and the average duration of projects (let *afte*r 2007) with and without CPM schedules for different project types. The number of "no work" days is a count of daily comments made by the RCEs where "No work" was input in the remarks field. The projects with CPM schedules have higher number of “no work” days than projects without CPM schedules on average. For projects with CPM schedules, the percentage of “no work” days is always more than 50% of the project duration.

Table 4.6 Comparison of no work days and duration of projects by project type

	Projects with CPM schedules (SSPRIM)			Projects without CPM schedules		
	Average No Work (Days)	**Average Duration (Days)**	**Percentage**	**Average No Work (Days)**	**Average Duration (Days)**	**Percentage**
ASPT	126.63	184.19	68.75%	106.06	179.12	59.21%
BRDG	204.69	341.61	59.92%	50.67	117.19	43.24%
BRPT	-	-	-	128.6	137.8	93.32%
CGSW	85.24	146.05	58.36%	85.29	154.29	55.28%
DRST	123.50	189.00	65.34%	72.36	155.82	46.44%
GDRL	197.00	249.50	78.96%	162.96	277.76	58.67%
GNRL	179.23	261.74	68.48%	119.74	177.82	67.34%
HMAS	167.56	203.73	82.25%	112.56	184.04	61.16%
LDSC	197.00	207.00	95.17%	208.83	165.42	126.24%
PCCP	230.50	252.00	91.47%	108.50	129.5	83.78%
PMEP	-	-	-	101.00	142.86	70.70%
PMPT	-	-	-	71.10	135.19	52.59%
PMRP	0.00	167.00	0.00%	66.74	95.27	70.05%
PMTH	126.25	154.00	81.98%	128.16	141.72	90.43%
SGNL	147.13	217.25	67.72%	272.31	335.13	81.26%
SIGN	237.50	294.50	80.65%	198.6	365.6	54.32%
Total	167.30	220.13	68.75%	117.6	178.12	66.02%

As shown in Figure 4.1 there is no relationship between the number of “no work” days and the number of days delayed after the original completion date. That is, as the number of “no work” days increases, the number of days delayed does not also increase. Figure 4.2 shows a similar lack-of-trend between the number of “no work” days and the number of days delayed after the adjusted completion date.

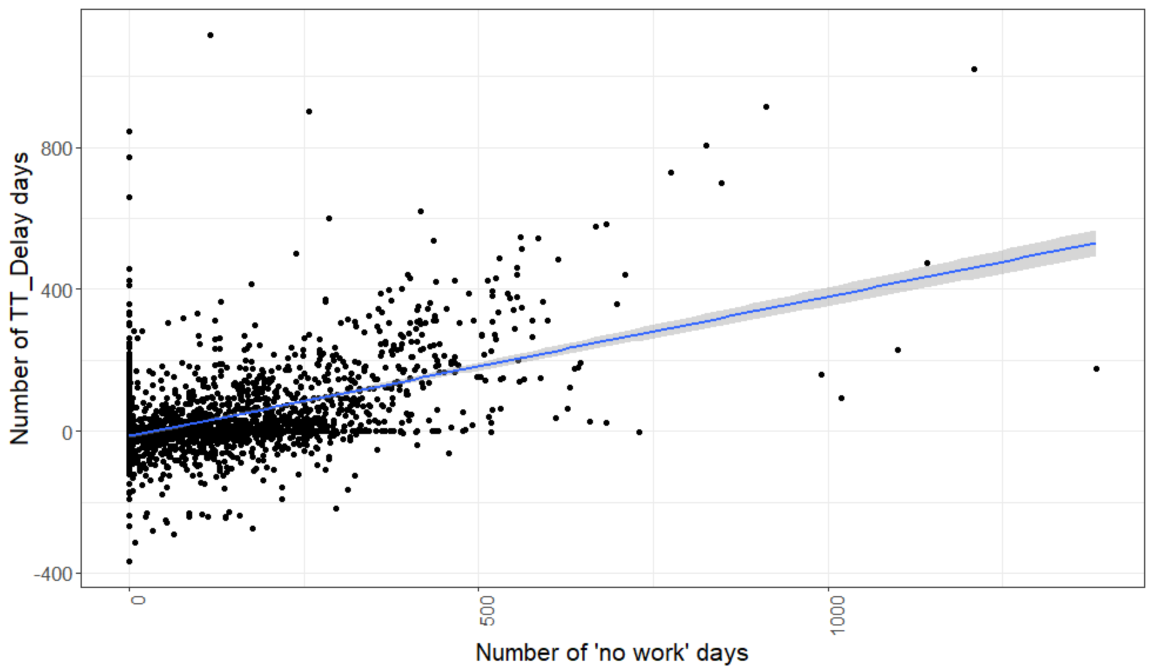

Figure 4.1 Scatterplot of number of days delayed after original completion date and number of "no work" days

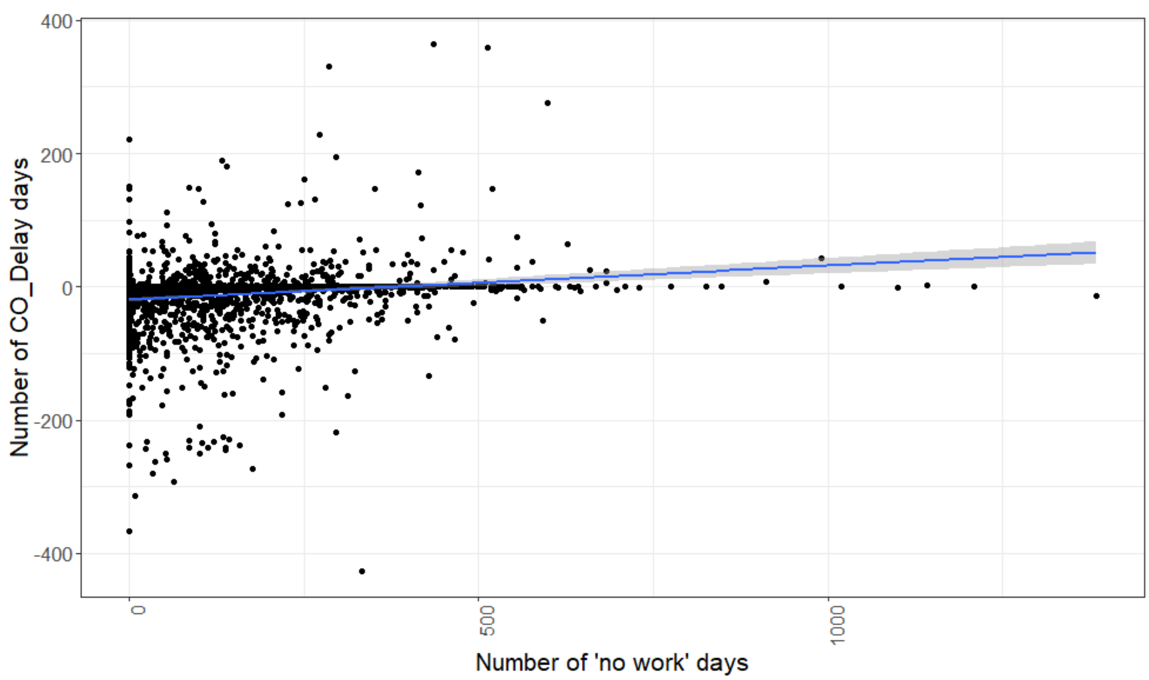

Figure 4.2 Scatterplot of number of days delayed after adjusted completion date and number of "no work" days

4.1.4 Project change orders

The SiteManager database contains change order information for each project. For each change order, the RCEs has to indicate the type and reason for the change order. Table 4.7 provides a summary of the change orders for projects let after February 2007.

Table 4.7 Number of adjusted days, adjusted amount, and frequency of change orders by type and reason

Change order types and reasons	Projects with CPM schedules (days)	Projects without CPM schedules (days)	Max. net change order Amount ($)	Frequency (#)
Additional scope	5,321	8,230	40,948,513.4	
Design Oversights	5	1,014	3,839,022.55	65
Modification by Construction Personnel	106	862	2,568,607.95	34
Decreasing/Increasing Quantities	1,242	1,83	7,358,569.81	46
Deleting/Adding Items	1,185	1,217	13,682,430.50	111
Contract Time Adjustment	1,959	2,353	424,733.32	38
Price Adjustment	0		3,719,912.47	1
Cost Savings Proposal/Suggestion		0	-0.01	1
Final Quantity Adjustment		252	0.00	1
Other	32	0	1,253,283.07	16
Extension	767	192	431,810.85	10
Plan Revision	25	2,014	7,653,643.17	31
Utility Conflict/Accommodation		139	16,499.75	2
Time Extension for Payment Distribution		4	0.00	1
Contract modification	2,944	8,085	-12,771,123.2	
Design Oversights	121	0	718,590.43	44
Modification by Construction Personnel	296	953	-1,994,544.30	131
Traffic Control Modification		0	0.00	203
Decreasing/Increasing Quantities	31	0	-10,761,758.50	298
Deleting/Adding Items	0	185	-2,649,781.97	92
Contract Time Adjustment	2,496	6,833	24,886.45	143
Price Adjustment		0	-0.02	1
Cost Savings Proposal/Suggestion		0	-70,993.71	3
Final Quantity Adjustment	0	0	-1,398,776.65	43
Other	0	0	2,629,770.07	12
Extension		84	927,090.81	3
Plan Revision	0	30	-195,605.79	7
Standard change order	27,065	47,147	-11,295,068.8	
Design Oversights	0	922	3,419,239.98	299
Modification by Construction Personnel	2,881	1,594	4,020,857.40	814
Traffic Control Modification	0	-40	266,122.46	18
Decreasing/Increasing Quantities	372	1,427	-21,758,436.99	1244
Deleting/Adding Items	712	3,799	14,285,869.85	1685

Change order types and reasons	Projects with CPM schedules (days)	Projects without CPM schedules (days)	Max. net change order Amount ($)	Frequency (#)
Contract Time Adjustment	18,425	26,854	704,290.38	559
Price Adjustment		0	11,910.00	1
Incentive/Disincentive Payment		0	180,000.00	2
Price Adjustment	0	0	524,452.59	39
Claims Settlement	0	316	1,097,580.86	8
Cost Savings Proposal/Suggestion		-45	-1,718,549.02	19
Final Quantity Adjustment	1	10	-16,123,720.05	237
Other	20	11,35	3,009,332.51	122
Extension	462	155	148,490.56	15
Plan Revision	216	502	544,145.50	45
Utility Conflict/Accommodation	0	432	26,775.00	8
Time Extension for Payment Distribution	536	5,378	63,600.00	51
Weather Delay	4,004	4,708	2,970.20	110
Contract completion date adjustment for flex time contract	-564		0.00	6
Deletion	0	0	-4,841,847.6	
Design Oversights		0	0.00	1
Modification by Construction Personnel	0		-31,968.29	3
Decreasing/Increasing Quantities	0	0	-1,474,674.74	9
Deleting/Adding Items	0	0	-3,216,187.07	6
Final Quantity Adjustment		0	-43,938.40	1
Other		0	-75,079.13	1
Plan Revision		0	0.00	1
Extension	1,311	3,346	24,816,903.7	
Design Oversights		0	49,176.00	1
Modification by Construction Personnel		0	0.00	1
Decreasing/Increasing Quantities		70	3,960,944.76	8
Deleting/Adding Items	183	0	852,975.79	10
Contract Time Adjustment	290	410	0.00	14
Extension	838	2,693	19,564,207.90	96
Plan Revision		173	389,599.23	1
Partnering	0	0	71,716.6	
Modification by Construction Personnel	0	0	5,165.24	4
Decreasing/Increasing Quantities		0	1,463.22	1
Deleting/Adding Items		0	38,069.52	24
Cost Savings Proposal/Suggestion		0	0.00	1
Other		0	27,018.62	17
Supplemental agreement	2,181	4,871	18,089,938.0	
Design Oversights	383	109	2,583,943.13	104
Modification by Construction Personnel	62	703	1,080,903.24	315
Traffic Control Modification	0	0	45,851.38	14
Decreasing/Increasing Quantities	331	144	3,232,072.81	100

Change order types and reasons	Projects with CPM schedules (days)	Projects without CPM schedules (days)	Max. net change order Amount ($)	Frequency (#)
Deleting/Adding Items	234	429	8,025,935.01	526
Contract Time Adjustment	1,171	2,011	336,545.16	58
Price Adjustment		21	66,297.76	3
Incentive/Disincentive Payment		0	411,261.14	4
Price Adjustment	0	0	1,311,617.38	10
Claims Settlement		5	210,000.00	1
Claims Settlement		0	-174,885.06	5
Cost Savings Proposal/Suggestion	0	0	-2,066,649.75	18
Final Quantity Adjustment	0	16	299,604.06	54
Other		489	562,124.91	6
Extension	0	922	2,161,838.90	15
Plan Revision		22	3,477.91	3
Utility conflict/accommodation	1,465	4,016	1,011,934.2	
Modification by Construction Personnel		0	-7449.96	4
Deleting/Adding Items		0	151,120.20	2
Contract Time Adjustment	943	2,815	0.00	46
Other		71	0.00	1
Extension		0	11,800.00	1
Plan Revision	522	1,130	856,463.94	34

Table 4.8 summarizes the top reasons from Table 4.7 for adjusting project length and adjusting project cost. It also provides the top reason for those frequently made change orders. As shown, the top reasons for adjusting project duration for projects with and without CPM schedules are "contract time adjustment" and "extension." The top reasons for adjusting project cost are "deleting / adding items" and "decreasing / increasing quantities." The top reasons for frequently made change orders are "deleting / adding items", "decreasing / increasing quantities", "contract time adjustment" and "extension."

Table 4.8 Summary of change order types and reasons

	Projects with CPM schedules	Projects without CPM schedules	All projects	
	Top reason for adjusting days	**Top reason for adjusting days**	**Top reason for adjusting amount ($)**	**Top reason for frequently made change orders**
Additional scope	Contract Time Adjustment	Contract Time Adjustment	Deleting / Adding Items	Deleting / Adding Items
Contract modification	Contract Time Adjustment	Contract Time Adjustment	Decreasing/Increasing Quantities	Decreasing / Increasing Quantities
Standard change order	Contract Time Adjustment	Contract Time Adjustment	Decreasing / Increasing Quantities* Deleting/Adding Items	Deleting / Adding Items
Deletion	-	-	Deleting / Adding Items*	Decreasing / Increasing Quantities
Extension	Extension	Extension	Extension	Extension
Partnering			Deleting / Adding Items	Deleting / Adding Items
Supplemental agreement	Contract Time Adjustment	Contract Time Adjustment	Deleting / Adding Items	Deleting / Adding Items
Utility conflict / accommodation	Contract Time Adjustment	Contract Time Adjustment	Plan Revision	Contract Time Adjustment

* negative quantity

4.1.5 Change order remarks

In addition to type and reasons, the change orders include remarks made by the RCEs. The remarks are textual data. The keywords from the remarks were analyzed. Figure 4.3 shows the frequency of keywords. The top three most frequently used single words are “days”, “contract”, and “date.” Figure 4.4. shows the frequency of two-word combinations. The top three two-word combinations are “completion date”, “contract completion”, and “change order.”

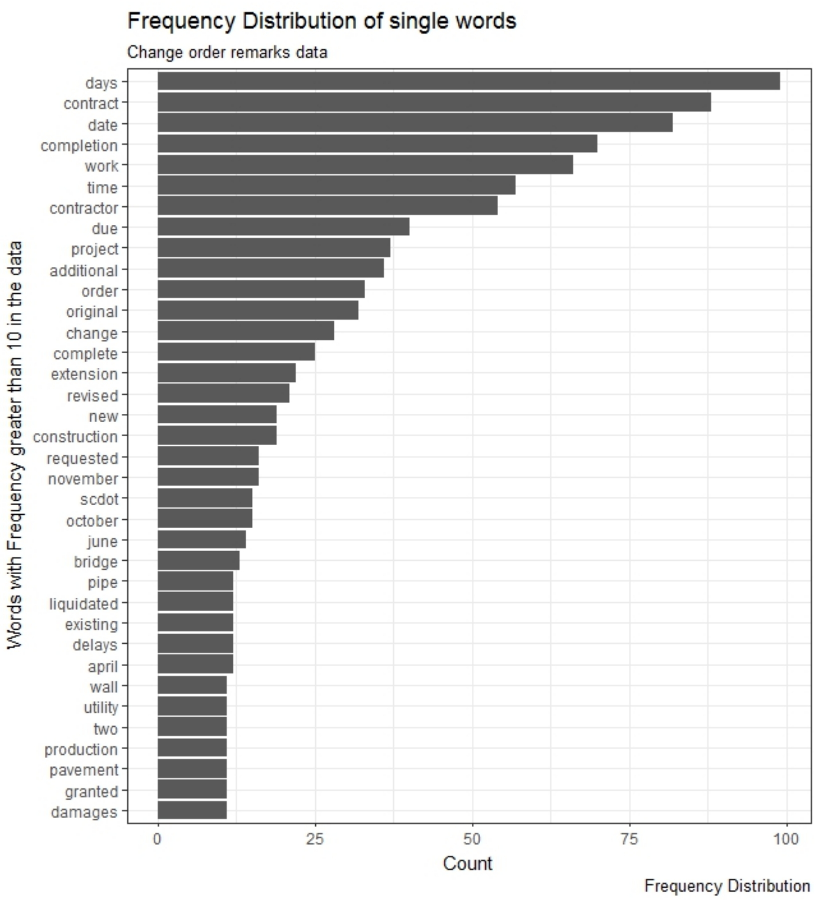

Figure 4.3 Frequency of single keywords in change order remarks

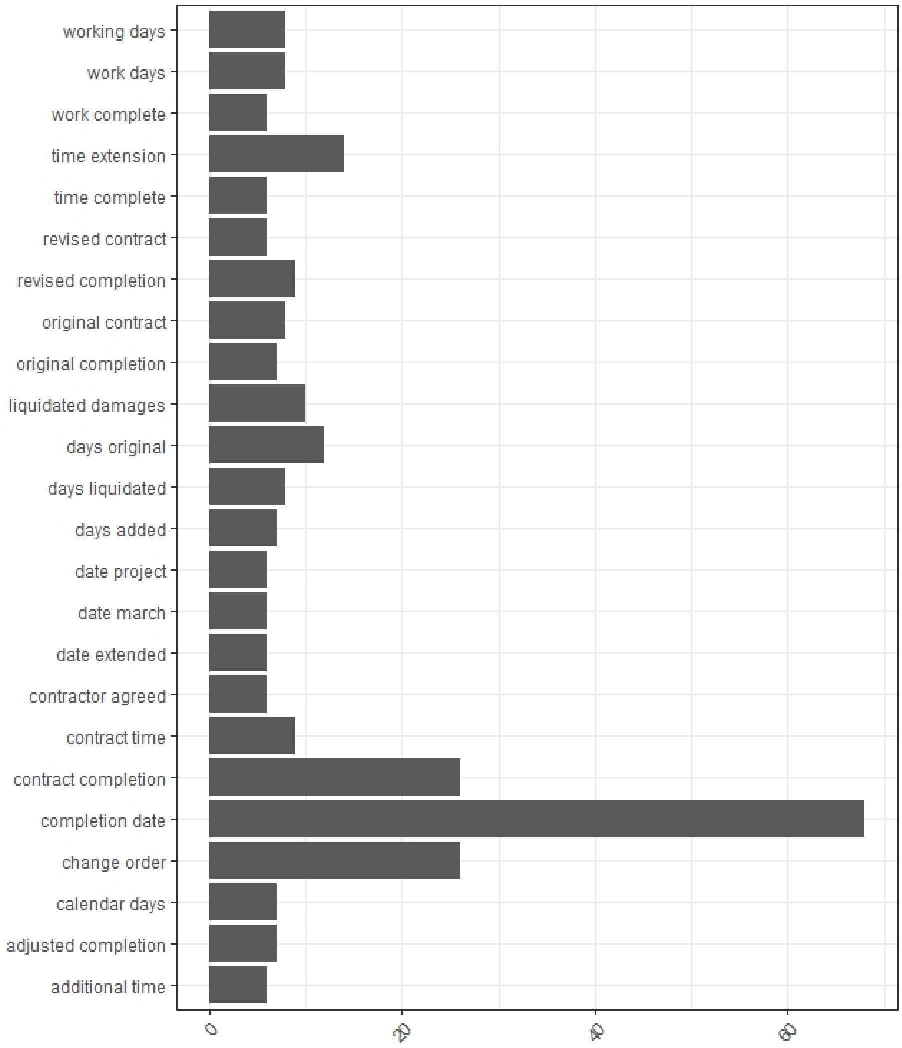

Figure 4.4 Frequency of two-word combination in change order remarks

A sentiment analysis was performed on the single keywords in the change order remarks. For this analysis, the AFINN lexicon was used; The AFINN lexicon assigns words with a score between −5 and 5, with negative scores indicating negative sentiment and positive scores indicating positive sentiment. Figure 4.5 shows the results of sentiment analysis on the single words from the change order remarks. As shown, the most positive sentiment key word is "work" and most negative sentiment keyword is "delays."

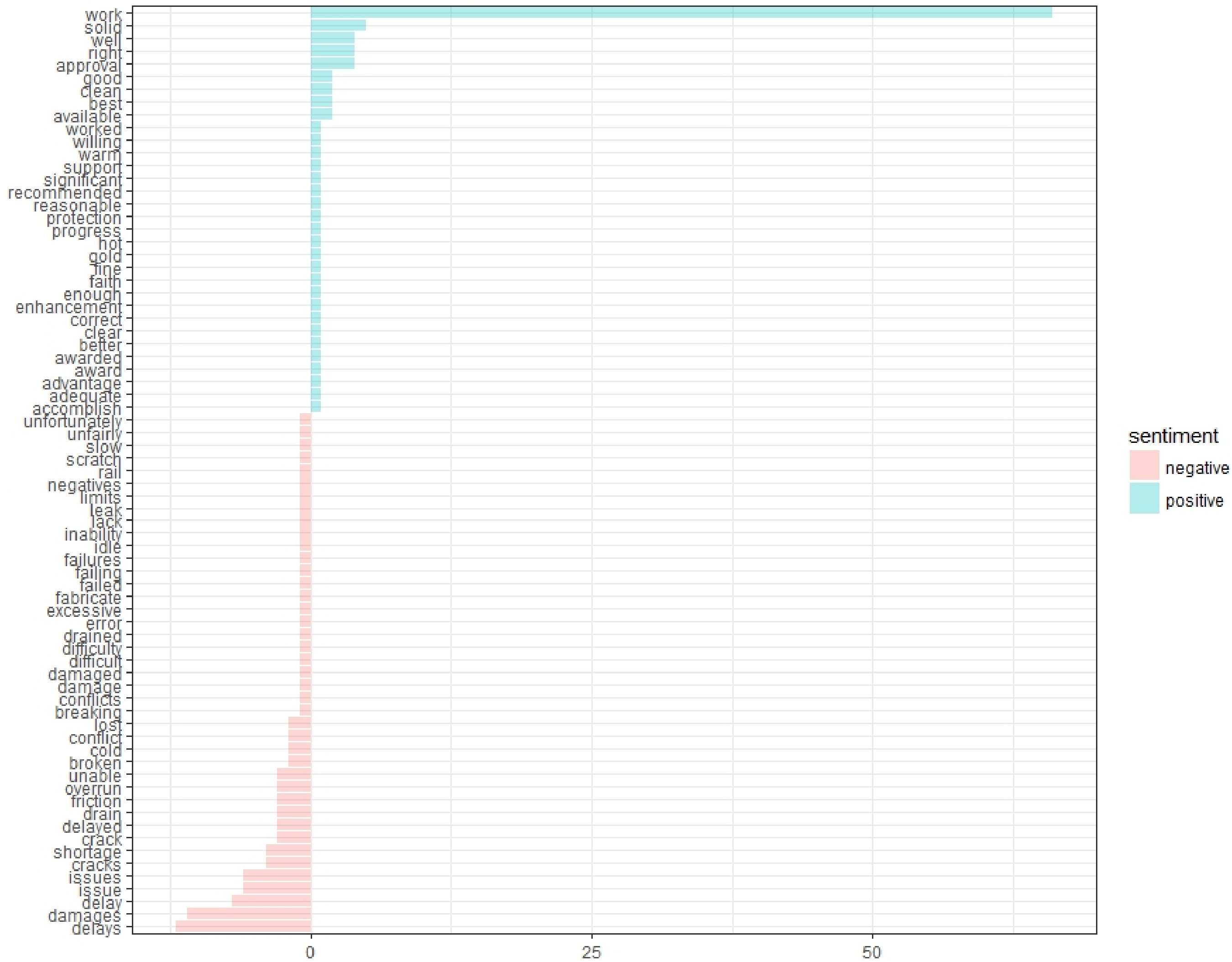

Figure 4.5 Sentiment analysis of change order remarks using AFINN lexicon

4.2 Effectiveness of CPM Scheduling

Table 4.9 provides a summary of the delayed projects by project type for the *after* 2007 dataset. The results in Table 4.9 indicate that more than half (nTT_Delay: 629 out of 1,075, 58.51% and nCO_Delay: 168 out of 319, 52.66%) of the delayed projects have a CPM schedule. Fewer projects with CPM schedules are delayed beyond the adjusted completion date.

Table 4.9 Summary of delayed projects by project Type

Project Type	Total number of projects	Number of projects delayed after original completion date (nTT_Delay[1])		Number of projects delayed after adjusted completion date (nCO_Delay[2])	
		Delayed SSPRIM	Delayed projects	Delayed SSPRIM	Delayed projects
ASPT	102	18	38	10	20
BRDG	98	48	58	11	13
BRPT	10	0	5	0	1
CGSW	153	19	64	6	23
DRST	13	1	6	0	3
GDRL	85	2	63	0	3
GNRL	304	108	161	27	39
HMAS	1,007	423	506	113	153
LDSC	13	1	10	0	0
PCCP	14	2	6	0	0
PMEP	21	0	11	0	9
PMPT	21	0	6	0	2
PMRP	89	0	35	0	14
PMTH	108	1	69	0	32
SGNL	47	5	29	1	5
SIGN	12	1	8	0	2
Total	2,097	629	1,075	168	319

1. nTT_Delay – Number of projects with a TT_Delay delay greater than zero.
2. nCO_Delay – Number of projects with a CO_Delay delay greater than zero.

Figures 4.6 and 4.7 provide a comparison of delay between SSPRIM and SSNULL projects. The results in Figure 4.6 indicate that when considering TT_Delay, a higher percentage of SSPRIM projects are delayed (54.32%) compared to SSNULL projects (47.5%). However, when considering CO_Delay, as shown in Figure 4.7, a lower percentage of SSPRIM projects are delayed (14.51%) compared to SSNULL projects (16.08%).

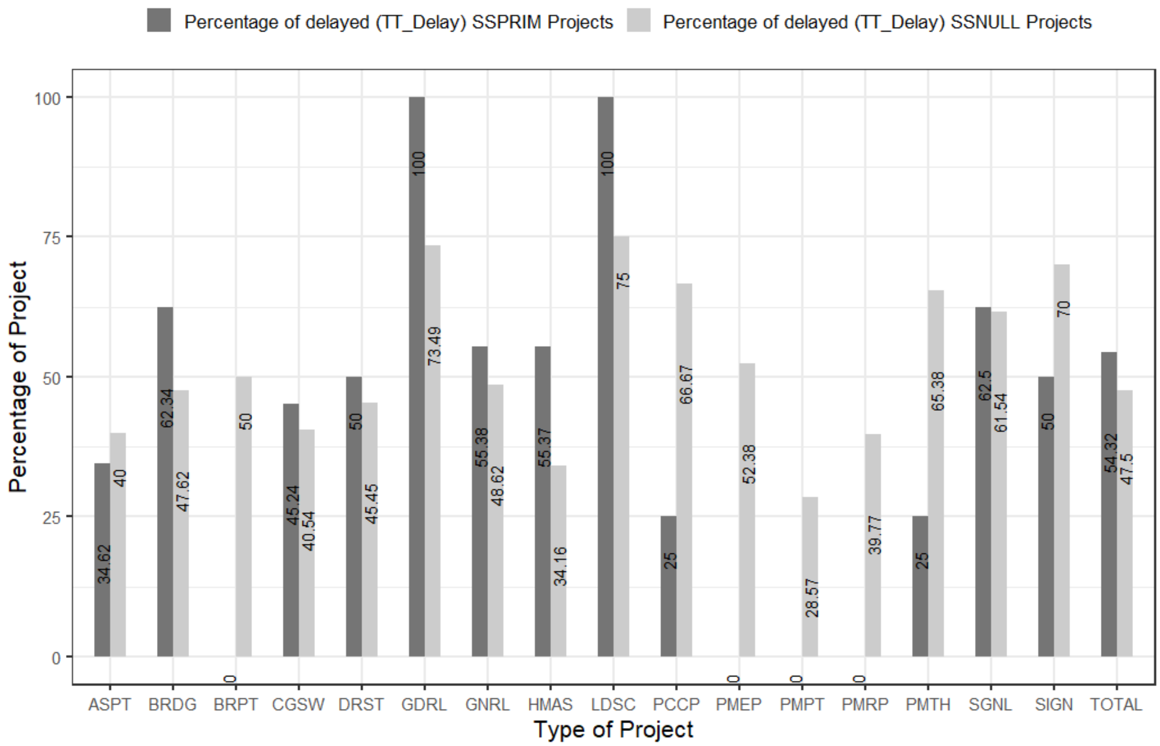

Figure 4.6 Comparison of delay (TT_Delay) between SSPRIM and SSNULL projects by type

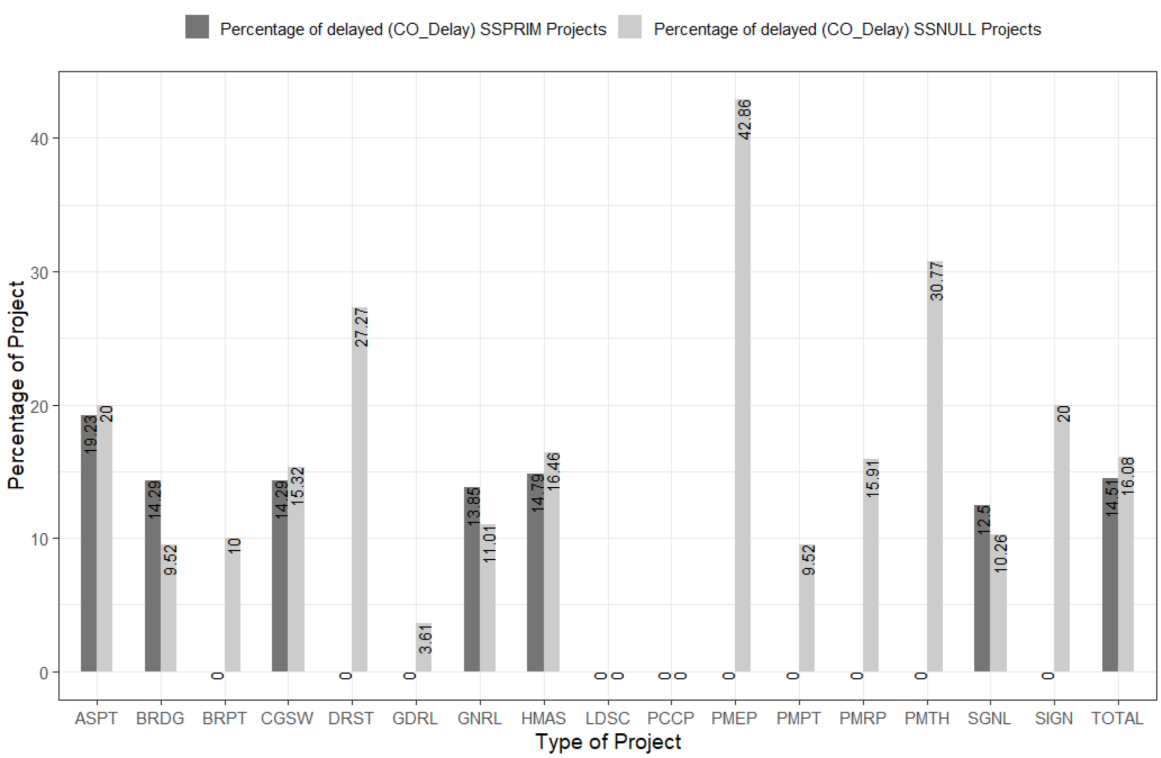

Figure 4.7 Comparison of delay (CO_Delay) between SSPRIM and SSNULL projects by type

Table 4.10 shows the total number of projects and SSPRIM projects in each project size category and the number of projects that were delayed in terms of original completion date (TT_Delay) and adjusted completion date (CO_Delay), respectively. As shown, the large-sized projects have a higher percentage of projects with CPM schedules (570 out of 725, 78.62%) compared to small and medium-sized projects. In each category, the number of projects that were delayed based on the adjusted completion date (nCO_Delay) is lower than those measured based on the original completion date (nTT_Delay).

Table 4.10 Comparison of the number of SSPRIM projects and the number of delayed projects by Project Size

Project Size		Small	Medium	Large	Total
Total number of Projects		702	670	725	2,097
Total number of SSPRIM Projects		206	382	570	1,158
Number of Delayed Projects	nTT_Delay[1]	275	338	462	1,075
	nCO_Delay[2]	85	104	130	319

Table 4.11 shows the total number of projects and SSPRIM projects in each project duration category and the number of projects that were delayed in terms of original completion date (TT_Delay) and adjusted completion date (CO_Delay), respectively. As shown, based on the original completion date (nTT_Delay), longer duration projects have a higher percentage of projects with CPM schedules (48.1%) compared to short (58.8%) and medium (49.6%). This finding is also true based on the adjusted completion date (nCO_Delay).

Table 4.11 Comparison of the number of SSPRIM projects and the number of delayed projects by Project Duration

Project Duration		Short	Medium	Long	Total
Total number of Projects		364	1,294	439	2,097
Total number of SSPRIM Projects		158	714	286	1,158
Number of Delayed Projects	nTT_Delay[1]	175	642	258	1,075
	nCO_Delay[2]	66	200	53	319

4.3 Identification of Factors Associated with Project Delay

The Chi-square test for independence was used to determine if there is a statistically significant association between projects with CPM schedules and delayed projects by project type, SCDOT district, project size and project duration. The null hypothesis (H_0) is that the number of projects with CPM schedules are independent of the number of delayed projects. The number of projects delayed beyond the original completion date (nTT_Delay) and adjusted completion date (nCO_Delay) were used as measures of delay. The results of the Chi-Square test for numerous projects subsets in *after* 2007 dataset are presented in Table 4.12.

As shown in Table 4.12, when considering TT_Delay, there is a statistically significant association between projects with CPM schedules and delayed projects for hot-mixed asphalt paving (HMAS) projects. The association is also statistically significant for Districts 1 and 7, large-sized project, and medium-term projects. When considering CO_Delay, the association is statistically significant for District 5, large-sized, and short-term projects.

Table 4.12 Chi-square Test Results for Project Types, SCDOT Districts, and Project Size, and project Duration for *after* 2007 dataset

	Number of projects delayed after original completion date (nTT_Delay)			**Number of projects delayed after adjusted completion date (nCO_Delay)**		
	Delayed Projects with CPM (%)	**Delayed Projects without CPM (%)**	**p-value**	**Delayed Projects with CPM (%)**	**Delayed Projects without CPM (%)**	**p-value**
Chi-square test results for project Types						
ALL	**54.32**	**47.50**	**0.002**	14.51	16.08	0.339
ASPT	34.62	40	0.7208	19.23	20	>0.999
BRDG	62.33	47.62	0.334	14.29	9.52	0.8357
CGSW	45.24	40.54	0.7323	14.28	15.32	>0.999
GNRL	55.38	48.62	0.3112	13.84	11	0.5957
HMAS	**55.35**	**34.02**	**<0.001**	14.75	16.60	0.553
Chi-square test results for SCDOT Districts						
1	**73.57**	**62.14**	**0.035**	20.21	15.71	0.367
2	57.47	49.55	0.233	14.37	15.04	>0.999
3	46.31	41.79	0.519	13.42	17.91	0.381
4	55.36	54.55	0.986	20.83	23.14	0.746
5	36.36	34.26	0.771	**4.31**	**11.89**	**0.014**
6	53.50	47.55	0.361	15.29	14.69	>0.999
7	**60.19**	**43.66**	**0.014**	14.81	14.79	>0.999
Chi-square test results for project Size						
Small	35.92	40.52	0.293	8.74	13.51	0.102
Medium	48.43	53.13	0.260	15.18	15.97	0.864
Large	64.91	59.35	0.237	**16.14**	**24.52**	**0.022**
Chi-square test results for project Duration						
Short	48.1	48.06	>0.999	**13.29**	**21.84**	**0.049**
Medium	**52.66**	**45.86**	**0.017**	14.85	16.21	0.551
Long	61.89	52.94	0.087	14.33	7.84	0.066

For the Chi-square test, the number of delayed projects was used. For the t-test, the average delay in days (TT_Delay and CO_Delay) was used. The null hypothesis (H_0) is that there is no statistical difference between the average number of delay (in days) between SSPRIM and SSNULL projects. Like the Chi-square test, the t-test was conducted for all projects by type, SCDOT district, size, and duration, and their results are shown in Table 4.13 to Table 4.16. The results from Table 4.13 indicate that, when considering the TT_Delay, the bridge (BRDG), general (GNRL), and hot-mixed asphalt paving (HMAS) projects with CPM schedules have a statistically significant higher average delay than projects without CPM schedules.

Table 4.13 t-test results for different project types (considering original and adjusted completion date for delay) for *after* 2007 dataset

Project Type	Projects with CPM schedules (SSPRIM)		Projects without CPM schedules (SSNULL)		Improvement from having a schedule (%)	t-value	Variance	p-value
	Mean delay (days)	S.D. (days)	Mean delay (days)	S.D. (days)				
t-test results for project type considering Delay (in days) after original completion date (TT_Delay)								
All	**121.47**	**143.59**	**95.61**	**106.93**	**-27.05**	**3.384**	**Not Equal**	**0.0007**
ASPT	81.5	105.88	94.4	89.03	13.66	-0.408	Equal	0.686
BRDG	**156.44**	**221.58**	**50.7**	**54.98**	**-208.56**	**2.905**	**Not Equal**	**0.005**
CGSW	66.16	69.08	75.98	79.17	12.92	-0.469	Equal	0.64
GNRL	**153.76**	**187.15**	**86.57**	**89.96**	**-77.62**	**3.076**	**Not Equal**	**0.002**
HMAS	**114.11**	**121.52**	**70.88**	**105.48**	**-60.99**	**3.025**	**Equal**	**0.003**
t-test results for project type considering delay (in days) after adjusted completion date (CO_Delay)								
All	32.20	50.13	38.85	52.31	17.11	-1.158	Equal	0.248
ASPT	46.5	56.12	44.5	52.13	-4.50	0.083	Equal	0.935
BRDG	27.55	23.72	7.5	3.54	-267.27	1.152	Equal	0.274
CGSW	18.5	29.51	32.41	48.13	42.92	-0.659	Equal	0.517
GNRL	47.15	91.13	29.92	30.81	-57.60	0.876	Not Equal	0.387
HMAS	28.81	37.05	34.23	42.01	15.81	-0.766	Equal	0.445

The results in Table 4.14 indicate that there is no statistically significant difference in the average delay between projects with and without CPM schedules for any of the SCDOT Districts.

Table 4.14 t-test results for different SCDOT districts (considering original and adjusted completion date for delay) for *after* 2007 dataset

SCDOT District	Projects with CPM schedules		Projects without CPM schedules		Improve-ment for having a schedule (%)	t-value	Variance	p-value
	Mean Delay*	SD (days)	Mean Delay*	SD (days)				
t-test results for SCDOT districts considering delay (in days) after original completion date (TT_Delay)								
1	163.73	152.93	133.60	138.73	-22.55	1.50	Equal	0.135
2	96.14	156.54	77.86	82.31	-23.48	0.813	Not Equal	0.418
3	69.96	77.22	68.91	74.64	-1.52	0.076	Equal	0.939
4	101.68	113.68	87.21	94.68	-16.59	0.846	Equal	0.398
5	131.64	146.27	110.71	145.60	-18.91	0.782	Equal	0.435
6	125.88	153.34	87.38	69.98	-44.06	1.914	Not Equal	0.057
7	133.52	154.04	89.92	100.44	-48.49	1.87	Not Equal	0.062
t-test results for SCDOT districts considering delay (in days) after adjusted completion date (CO_Delay)								
1	43.90	60.73	29.25	27.91	-50.08	0.811	Not Equal	0.421
2	26.35	30.39	29.09	29.78	9.41	-0.258	Equal	0.798
3	24.28	38.55	28.38	25.07	14.44	-0.286	Equal	0.776
4	26.17	35.25	45.68	57.12	42.71	-1.664	Not Equal	0.101
5	44.18	65.98	51	53.68	13.38	-0.266	Equal	0.792
6	45.52	72.03	44.08	38.27	-3.24	0.065	Not Equal	0.948

7	15.35	15.88	43.35	82.88	64.59	-1.482	Not Equal	0.147

The results in Table 4.15 indicate that the small projects with CPM schedules have a statistically significant lower average delay than projects without CPM schedules.

Table 4.15 t-test results for different project sizes (considering original and adjusted completion date for delay) for *after* 2007 dataset

Project Size	Projects with CPM schedules		Projects without CPM schedules		Improvements for having a schedule (%)	t-value	Variance	p-value
	Mean Delay (days)	SD (days)	Mean Delay (days)	SD (days)				
t-test results for project size groups considering delay (in days) after original completion date (TT_Delay)								
Small	67.01	65.89	82.52	98.64	18.79	-1.50	Not Equal	0.136
Medium	88.57	106.63	99.12	89.58	10.64	-0.85	Equal	0.396
Large	150.28	163.88	119.18	128.77	-26.09	1.956	Not Equal	0.052
t-test results for project size groups considering delay (in days) after adjusted completion date (CO_Delay)								
Small	**16.61**	**11.75**	**36.12**	**54.73**	**54.01**	**-2.70**	**Not Equal**	**0.009**
Medium	28.31	35.64	40.26	54.84	29.68	-1.28	Not Equal	0.205
Large	37.71	60.84	41.95	45.42	10.11	-0.436	Not Equal	0.664

The results in Table 4.16 indicate that when considering TT_Delay, short-term and long-term projects with CPM schedules have a statistically significant higher average delay than projects without CPM schedules.

Table 4.16 t-test results for different project durations (considering original and adjusted completion date for delay) for *after* 2007 dataset

Project Duration	Projects with CPM schedules		Projects without CPM schedules		Improvements for having a schedule (%)	t-value	Variance	p-value
	Mean Delay (days)	SD (days)	Mean Delay (days)	SD (days)				
t-test results for project Duration considering delay (in days) after original completion date (TT_Delay)								
Short	**100.05**	**103.31**	**56.58**	**77.85**	**(76.83)**	**2.621**	**Not Equal**	**0.009**
Medium	104.77	129.59	85.7	96.92	(22.25)	1.585	Not Equal	0.115
Long	**166.15**	**174.43**	**72.5**	**46.46**	**(129.17)**	**4.805**	**Not Equal**	**0.0**
t-test results for project Size considering delay (in days) after adjusted completion date (CO_Delay)								
Short	27.33	20.68	43.77	67.18	36.56	-1.093	Not Equal	0.278
Medium	31.67	50.07	36.94	46.86	37.56	-0.765	Equal	0.445
Long	36.07	35.33	60.58	23.29	40.45	0.063	Not Equal	0.949

The following presents the Chi-square test and t-test results for the *before* 2007 dataset. Table 4.17 shows the Chi-Square test results for the *before* 2007 dataset. The results indicate that when considering TT_Delay, there is a statistically significant association between projects with CPM schedules and delayed projects for general (GNRL) and hot-mixed asphalt paving (HMAS) projects. The association is also statistically significant for Districts 3 and 4, all project sizes, and short-term and medium-term projects. When considering CO_Delay, the association is statistically significant for GNRL and BRDG projects. The association is also statistically significant for Districts 4 and 7, medium-sized and large-sized projects, and short-term and medium-term projects.

Table 4.17 Chi-square test results for different project types, SCDOT districts, project sizes, and project durations for *before* 2007 dataset

	Number of projects delayed after original completion date (nTT_Delay)			Number of projects delayed after adjusted completion date (nCO_Delay)		
	Delayed Projects with CPM (%)	**Delayed Projects without CPM (%)**	**p-value**	**Delayed Projects with CPM (%)**	**Delayed Projects with CPM (%)**	**p-value**
Chi-Square test results for project types						
ALL	**47.82**	**58.66**	**<0.001**	**16.26**	**25.76**	**<0.001**
BRDG	56.00	26.09	0.551	16.00	26.09	0.189
CGSW	60.00	62.50	>0.999	20.00	16.67	>0.999
GNRL	**51.55**	**62.50**	**0.007**	**18.04**	**26.76**	**0.017**
HMAS	**40.79**	**56.05**	**0.002**	**14.47**	**27.53**	**0.002**
Chi-square test results for SCDOT districts						
1	71.05	60.00	0.099	22.37	27.74	0.421
2	56.86	64.46	0.415	33.33	28.92	0.183
3	**48.21**	**63.96**	**0.045**	12.50	22.52	0.14
4	**26.47**	**46.70**	**0.005**	**7.35**	**23.34**	**0.01**
5	36.36	55.47	0.158	10.39	21.05	0.053
6	49.02	61.45	0.158	19.61	28.31	0.292
7	48.48	59.56	0.338	**9.09**	**33.09**	**0.012**
Chi-square test results for project size groups						
Small	**59.57**	**71.19**	**0.005**	19.15	23.25	0.2949
Medium	**43.24**	**57.64**	**0.003**	**15.54**	**26.42**	**0.009**
Large	**27.63**	**47.40**	**0.002**	**10.53**	**27.60**	**0.002**
Chi-square test results for project duration groups						
Short	**45.57**	**58.60**	**0.043**	**15.19**	**31.23**	**0.006**
Medium	**45.41**	**58.91**	**0.0005**	**16.59**	**27.29**	**0.002**
Long	54.81	58.33	0.59	16.35	17.89	0.822

Table 4.18 to Table 4.21 show the t-test results for the *before* 2007 dataset. The results from Table 4.18 indicate that when considering CO_Delay, general (GNRL) projects with CPM schedules have a statistically significant lower average delay than projects without CPM schedules.

Table 4.18 t-test results for different project types (considering original and adjusted completion date for delay) for *before* 2007 dataset

Project Type	Projects with CPM schedules (SSPRIM)		Projects without CPM schedules (SSNULL)		Improvement from having a schedule (%)	t-value	Variance	p-value
	Mean delay (days)	S.D. (days)	Mean delay (days)	S.D. (days)				
t-test results for project type considering Delay (in days) after original completion date (TT_Delay)								
All	130.54	202.89	124.72	157.47	-4.66	0.44	Not Equal	0.660
BRDG	159.79	435.05	129.16	150.24	-23.72	0.645	Not Equal	0.52
CGSW	94.83	79.62	94.8	103.82	-.04	0.0007	Equal	0.999
GNRL	138.46	133.49	128.68	170.59	-7.59	0.536	Not Equal	0.592
HMAS	109.82	133.39	105.37	117.78	-4.22	0.255	Equal	0.798
t-test results for project type considering delay (in days) after adjusted completion date (CO_Delay)								
All								
BRDG	65.25	121.51	88.20	95.05	26.02	-0.615	Equal	0.541
CGSW	43	7.07	52.75	44.40	18.48	-0.292	Equal	0.785
GNRL	**32.23**	**43.79**	**86.44**	**146.97**	**62.72**	**-2.160**	**Not Equal**	**0.032**
HMAS	27.45	43.11	47.84	58.36	42.62	-1.553	Equal	0.123

The results in Table 4.19 indicate that when considering TT_Delay, District 1 projects with CPM schedules have a statistically significant higher average delay than projects without CPM schedules. On the other hand, District 2 projects with CPM schedules have a statistically significant lower average delay than projects without CPM schedules. When considering CO_Delay, Districts 2 and 3 projects with CPM schedules have a statistically significant lower average delay than projects without CPM schedules.

Table 4.19 t-test results for different SCDOT districts (considering original and adjusted completion date for delay) for *before* 2007 dataset

SCDOT Districts	Projects with CPM schedules		Projects without CPM schedules		Improve-ment for having a schedule	t-value	Variance	p-value
	Mean Delay*	SD (days)	Mean Delay*	SD (days)				
t-test results for SCDOT districts considering delay (in days) after original completion date (TT_Delay)								
1	**181.43**	**168.51**	**124.58**	**164.76**	**-45.63**	**2.221**	**Equal**	**0.027**
2	**87.21**	**86.92**	**146.44**	**151.50**	**40.44**	**-2.014**	**Not Equal**	**0.046**
3	103.63	105.76	145.72	186.06	28.89	-1.139	Not Equal	0.256
4	96.56	80.13	106.03	110.45	8.93	-0.346	Equal	0.730
5	128.04	127.44	117.58	171.78	-8.89	0.305	Equal	0.761
6	164.32	461.05	121.52	134.79	-35.22	0.833	Not Equal	0.406
7	71	77.46	96.90	135.49	26.73	-0739	Equal	0.461
t-test results for SCDOT districts considering delay (in days) after adjusted completion date (CO_Delay)								
1	56.12	68.19	56.08	64.85	0.06	0.002	Equal	0.998
2	**19.29**	**16.4**	**77.69**	**84.27**	**75.16**	**-2.824**	**Not Equal**	**0.006**
3	**14.42**	**7.06**	**61.36**	**64.68**	**76.49**	**-1.903**	**Not Equal**	**0.062**
4	44.8	33.58	64.32	66.44	30.35	-0.643	Equal	0.523

5	22.88	15.06	117.23	245.84	80.49	-1.077	Not Equal	0.285
6	50.1	111.28	98.91	133.09	49.35	-1.003	Equal	0.317
7	16.33	12.66	60.6	62.03	73.05	-1.222	Equal	0.228

The results in Table 4.20 indicate that when considering TT_Delay, there is no statistically significant difference in the average delay for all project sizes. When considering CO_Delay, medium-sized projects have a statistically significant lower average delay than projects without CPM schedules.

Table 4.20 t-test results for different project sizes (considering original and adjusted completion date for delay) for *before* 2007 dataset

Project Size	Projects with CPM schedules		Projects without CPM schedules		Improve-ments for having a schedule (%)	t-value	Variance	p-value
	Mean Delay (days)	SD (days)	Mean Delay (days)	SD (days)				
t-test results for project size groups considering delay (in days) after original completion date (TT_Delay)								
Small	86.67	85.91	87.73	135.03	1.22	-0.036	Not Equal	0.972
Medium	90.09	100.35	103.25	124.43	12.75	-0.786	Not Equal	0.432
Large	161.88	251.69	166.44	183.02	2.74	-0.208	Not Equal	0.835
t-test results for project size groups considering delay (in days) after adjusted completion date (CO_Delay)								
Small	37.36	41.62	84.12	162.88	55.56	-0.808	Not Equal	0.421
Medium	**18.78**	**15.39**	**65.63**	**69.02**	**71.38**	**-3.231**	**Not Equal**	**0.002**
Large	44.69	73.63	74.09	99.03	39.67	-1.641	Not Equal	0.103

The results in Table 4.21 indicate that there is no statistically significant difference in the average delay for all project durations.

Table 4.21 t-test results for project duration (considering original and adjusted completion date for delay) for *before* 2007 dataset

Project Duration	Projects with CPM schedules		Projects without CPM schedules		Improve-ments for having a schedule (%)	t-value	Variance	p-value
	Mean Delay (days)	SD (days)	Mean Delay (days)	SD (days)				
t-test results for project Duration considering delay (in days) after original completion date (TT_Delay)								
Short	103.03	102.58	87.16	93.00	-18.2	0.942	Equal	0.347
Medium	112.92	133.17	113.42	146.29	0.44	-0.031	Equal	0.975
Long	180.05	318.32	180.34	204.76	0.16	-0.008	Not Equal	0.993
t-test results for project Size considering delay (in days) after adjusted completion date (CO_Delay)								
Short	28.33	34.90	72.19	79.42	60.75	-1.89	Not Equal	0.061
Medium	29.08	33.44	75.18	149.00	61.32	-1.893	Not Equal	0.060
Long	52.65	98.32	79.88	103.05	34.09	-0.989	Equal	0.325

4.4 Predictive Analysis

4.4.1 Logistic regression models

Preliminary analyses using correlation matrices indicated that delay did not vary linearly with any of the examined factors such as contract bid amount, project duration, net change order amount. For this reason, logistic regression models were developed instead of the linear regression models. Specifically, binary logistic regression models were developed to predict whether a project will be delayed. The explanatory variables examined include project type, project location, bid amount, net change order amount, original duration of the project, duration from letting to NTP, duration from letting to first work date, and whether CPM scheduling was used. As shown, the only statistically significant variable is the total project bid amount. The positive coefficient of the explanatory variable (TOT_BID_AMT) suggests that a project with a higher total bid amount will have a higher likelihood of being delayed.

Delay binary logistic regression model				
Variables	Estimates	Std. Error	z-value	p-value
Constant	-2.26E-01***	5.454e-2	-4.066	4.78e-05
TOT_BID_AMT	2.13E-07***	3.006e-8	7.08	1.44e-12

Level of significance: "***" 0.001

A binary logistic regression model was also developed to predict whether a project will be completed within budget or not. The best fit binary logistic regression model is shown below. This model suggests that the likelihood of completing a project within budget is dependent on SCDOT district. It is also dependent on project duration and whether or not the project used a CPM schedule; their negative coefficients indicate that having a CPM schedule and longer duration will decrease the likelihood of being on budget.

Budget binary logistic regression model				
Variables	Estimates	Std. Error	z-value	p-value
Constant	2.219***	0.1849	12.005	<0.0001
DISTRICT				
1(base)				
2	0.4875**	0.1849	2.636	0.0084
3	0.5878**	0.1909	3.080	0.00207
4	1.279***	0.2041	6.268	<0.0001
5	0.3548*	0.1751	2.026	0.0427
6	0.6052**	0.1884	3.213	0.0013
7	0.4636*	0.201	2.306	0.0211
SSP_CODE				
YES	-0.002156***	0.003768	-5.721	<0.0001
NO (base)				
PLAN.DUR	-1.8129***	0.1228	-14.764	<0.0001

Level of significance: "***" 0.001; "**" 0.01; "*" 0.05

4.4.2 Neural network models

Neural network models were developed to predict whether a project will be delayed beyond the original completion date (TT_Delay) using the change order remarks and texts from the daily work report. The predictor variables used in the neural network model included remarks from the RCEs in the early stage (i.e., first week) of the project, use of CPM scheduling in the project, and environmental conditions noted by the RCEs during the course of the project. The model was trained using three-fourths of the *after* 2007 dataset and evaluated using the remaining one-fourth. The developed neural network model is shown in Figure 4.8 and the performance of the model is presented in the following confusion matrix:

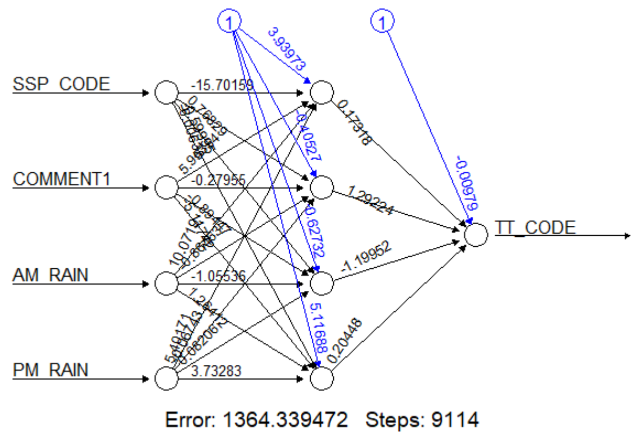

Figure 4.8 Neural network model for delay prediction

	Predicted: No Delay	Predicted: Delay
Actual: No Delay	906 (TN: True Negative)	749 (FP: False Positive)
Actual: Delay	943 (FN: False Negative)	1,057 (TP: True Positive)

The accuracy of the model is 53.7% (i.e., (TP+TN) / (TP+FN+TN+FP)). That is, it correctly predicted a project will be delayed 53.7% of the time. This finding suggests that there is nearly 50/50 chance that a project will be delayed.

4.5 Estimating Probability of Project Delay

4.5.1 Probability distribution fitting for all projects

For this analysis, 2,083 of 2,097 projects in *after* 2007 dataset was used; the reason is that 14 projects had an NTP date prior to letting date. Among the 2,083 projects, 1,061 were delayed, 696 projects were completed earlier than the scheduled completion date and 326 projects were completed as per the schedule. The probability of occurrence for each category is provided below and the statistical details of total delay and non-dimensional construction time (t) obtained from the statistical software R are given in Table 4.22.

- Probability of early completion = 696/2083 = 0.334
- Probability of a project being delayed = 1061/2083 = 0.51

- Probability of on-time completion = 326/2083 = 0.15

Table 4.22 Statistical details of completion time of a*fter* 2007 Projects

Statistic	Total Delays (days)	Non-dimensional Construction time (t)	t-delayed	t-early
Range	1483	30.16	29.20	0.95
Mean	41.91	1.37	1.87	0.77
Variance	14433.21 ($days^2$)	2.53	4.41	0.05
Standard Deviation	120.14	1.59	2.1	0.23
Standard error	2.63	0.03	0.06	0.008
Skewness	2.55	9.66	7.55	-1.13
Kurtosis	15.96	124.97	73.39	-1.13
Min	-366	0.05	1.004	0.05
First quartile	-5	0.96	1.133	0.64
Median	2	1.012	1.364	0.85
Third quartile	65	1.371	1.867	.96
Max	1117	30.21	30.21	.99

None of the 65 PDFs in EasyFit provided a good fit for non-dimensional construction time when all 2,083 projects are considered. All three GOF tests rejected the null hypothesis. To illustrate, consider the Burr (4Parameter) distribution which was found to be the best fit distribution in the (Love et al., 2013) study for the 276 Australian construction projects. As shown by the Probability-Probability (P-P) plot in Figure 4.9, the Burr (4 Parameter) CDF considering all 2,083 transportation projects does not fit well with the empirical CDF. In the P-P plot, the errors in the fit are represented by the distance between the data and the ideal fit represented by a 45-degree line. The reason why the Burr (4 Parameter) CDF and the other 64 well-known CDFs do not fit well against the empirical CDF is that the discontinuity in the cumulative density function at t =1 as shown in Figure 4.10. This is due to a large number of projects completed exactly on time (326 out of 2083 projects). For this reason, in this project, the CDF fitting was done separately, one for delayed projects and one for early completion projects.

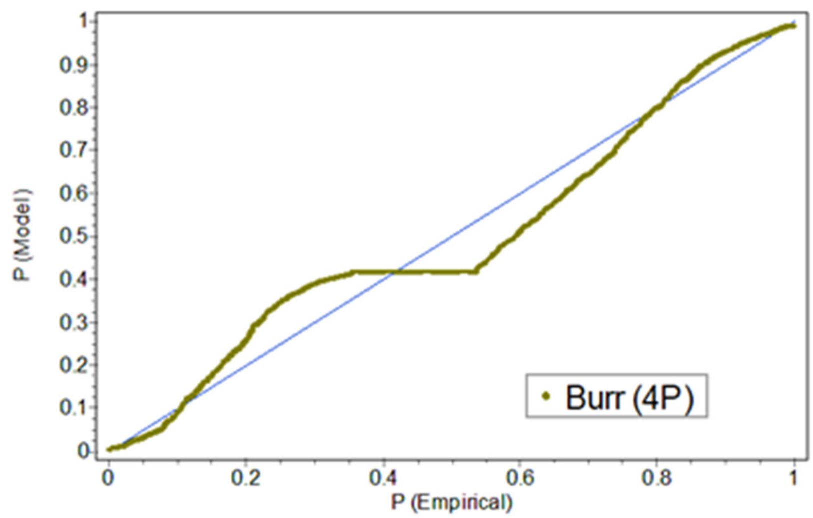

Figure 4.9 P-P Plot of Burr (4 Parameter) distribution

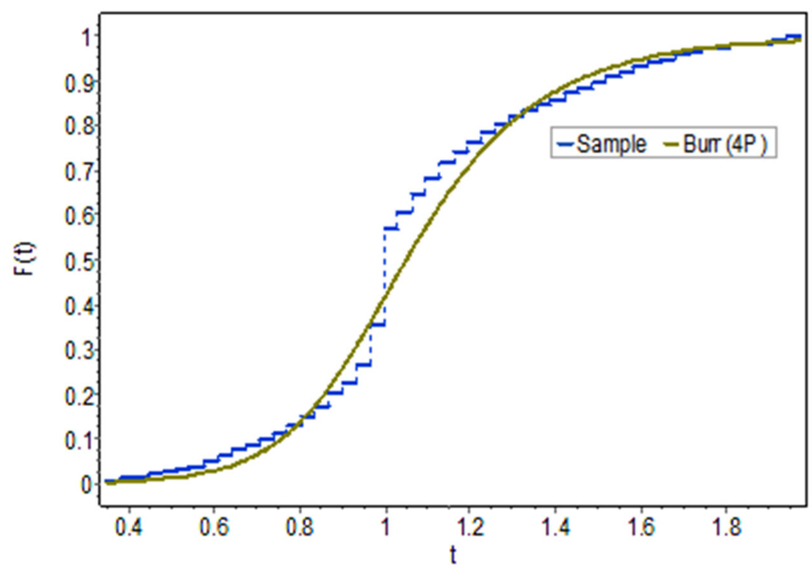

Figure 4.10 Empirical CDF vs. Burr (4 Parameter) CDF

4.5.2 Probability distribution fitting for delayed and early completion projects

As a result of not finding any distribution that fits well when considering all projects, the projects were partitioned into three groups: delayed projects, on-time projects, and early completion projects. The probability distribution fitting was done separately for delayed projects and early completion projects. The best fit distribution for delayed projects was found to be the Pearson 6 (4 Parameter). The K-S test statistic is 0.01918 and the p-value is 0.82235. The A-D test statistic is 0.40626. The Chi-square test statistic is 5.261 and the p-value is 0.87308. The critical values for all three GOF tests at significance levels 0.2, 0.1, 0.05, 0.02 and 0.01 are all greater than the test statistics for the respective tests. Therefore, the null hypothesis cannot be rejected, and thus, it can be concluded that the data comes from a Pearson 6 (4 Parameter) distribution. The CDF and

PDF of the fitted Pearson 6 (4 Parameter) distribution for the delayed projects are shown in Figure 4.11 and Figure 4.12, respectively.

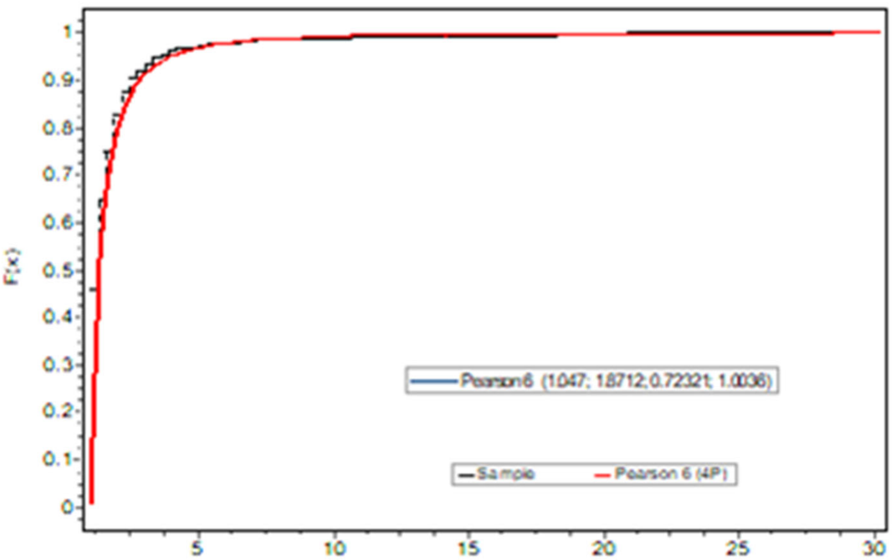

Figure 4.11 CDF of Pearson 6 (4Parameter) – distribution of delayed projects

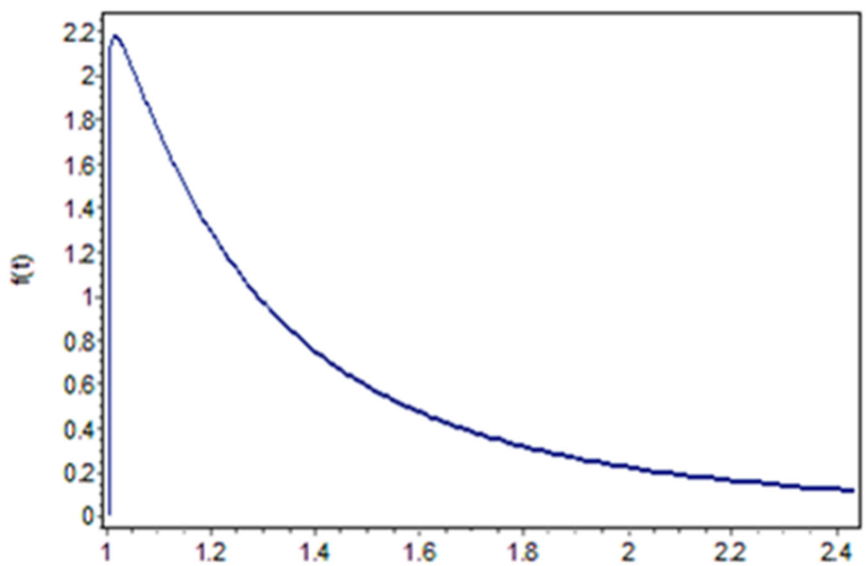

Figure 4.12 CDF of Pearson 6 (4Parameter) – distribution of delayed projects

The CDF of Pearson 6 (4Parameter) distribution is,

$$F(x) = I_{(x-\gamma)/(x-\gamma+\beta)}(\alpha_1, \alpha_2) \tag{16}$$

Where,

α_1 = Continuous shape parameter ($\alpha_1 > 0$)

To calculate the probability of delay, the following definitions and values are used.

B = Probability of experiencing delay
A_1 = Probability that a project is delayed (0.51)
A_2 = Probability that a project is completed on time (0.156)
A_3 = Probability that a project is completed earlier than the scheduled completion date (0.3341)
Therefore, by the LTP:

$$P(B) = P(B \cap A_1) + P(B \cap A_2) + P(B \cap A_3) \quad (17)$$

$$P(B) = P(A_1)\,P(B/A_1) + P(A_2)\,P(B/A_2) + P(A_3)\,P(B/A_3) \quad (18)$$

$$P(A_1) + P(A_2) + P(A_3) = 0.51 + 0.156 + 0.3341 = 1$$

From the fitted Pearson 6 (4 Parameter) distribution, $P(B/A_1)$ can be computed in StatAssist (Mehrannia et.al., 2014). $P(B/A_1)$ for $t>1.05$ is 0.901. It is self-evident that both $P(B/A_2)$ and $P(B/A_3)$ are 0. The probability of $t>1.05$ is calculated as follows. $t>1.05$ means that the actual project duration is 1.05 times the scheduled project duration (or 5% longer than then the scheduled project duration).

$$P(B) = 0.51 * 0.901 + 0.156 *0 + 0.3341*0 = 0.46$$

Similarly, $t > 1.10$, 1.15, 1.20, 1.25, 1.3 and 1.5 are calculated and summarized in Table 4.23. The mean delay is calculated as 36.57% ($t = 1.36$) and the probability that the duration of a project is extended by more than the mean delay is calculated as follows.

$P(B/A_1) = 0.47$, $P(B/A_2) = 0$, $P(B/A_3) = 0$

$$P(B) = 0.51*0.47 + 0156*0 + 0.3341*0 = 0.24$$

Table 4.23 Probability of delay (t > 1.0)

Non-dimensional construction time (t_1)	$P(B/A_i)$ $P(t > t_1)$	Probability of delay P(B) $P(t > t_1)$
1.05	0.901	0.46
1.10	0.807	0.41
1.15	0.727	0.370
1.20	0.657	0.335
1.25	0.597	0.305
1.30	0.545	0.278
1.50	0.392	0.2

The best fit distribution for the early completion projects was found to be the Johnson SB. The A-D GOF test accepted the null hypothesis at 0.05, 0.02 and 0.01 significance levels. Whereas, the K-S GOF test accepted the null hypothesis only at significance levels 0.02 and 0.01. The last GOF test, the Chi-square test rejected the null hypothesis at all significance levels considered. The CDF and PDF of the fitted Johnson SB distribution for early completion projects are shown in Figure 4.13 and Figure 4.14, respectively.

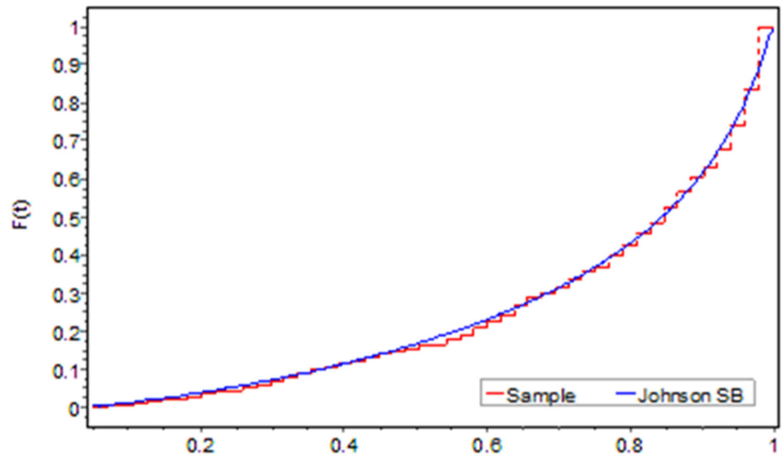

Figure 4.13 Comparison of CDF of empirical data and Johnson SB – distribution for early completion project

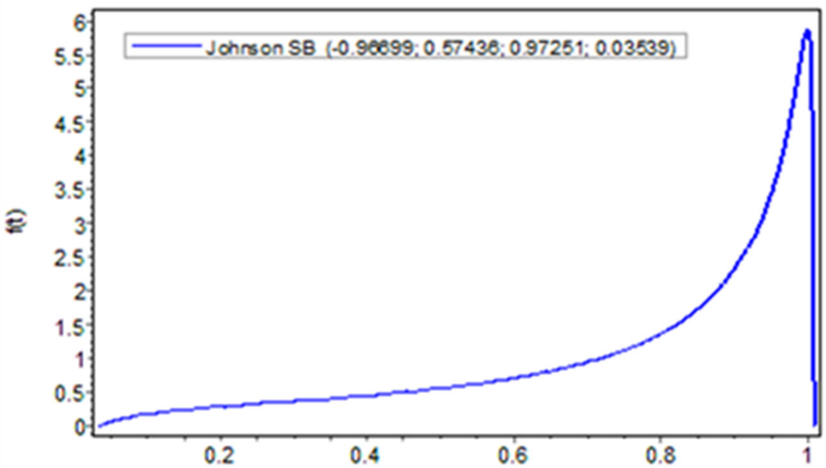

Figure 4.14 Comparison of CDF of empirical data and Johnson SB – distribution for early completion project

The PDF of the Johnson SB distribution is mathematically expressed as follows.

$$f(x)=\frac{\delta}{\lambda\sqrt{2\prod}\,z(1-z)}\exp\left(-\frac{1}{2}\left(\gamma+\delta\ln\left(\frac{z}{1-z}\right)\right)^2\right) \tag{19}$$

The corresponding CDF is,

$$F(x)=\phi\left(\gamma+\delta\ln\left(\frac{z}{1-z}\right)\right) \tag{20}$$

Where,

$$z=\frac{x-\xi}{\lambda} \tag{21}$$

γ = continuous shape parameter

δ = continuous shape parameter (δ >0)
λ = continuous scale parameter
ξ =continuous location parameter
Domain: - ξ ≤ x ≤ ξ + λ

ϕ = Standard normal CDF

The PDF fitting was also done for six project types, 1) surface treatment (ASPT), 2) bridge construction (BRDG), 3) curb, gutter and sidewalk construction (CGSW), 4) general (GNRL), 5) hot-mixed asphalt paving (HMAS), and 6) thermal pavement marking (PMTH), to analyze the statistical characteristics of project type and delay. As done previously, the probability distribution was fitted for delayed projects and early completion projects separately. For delayed projects, the Lognormal (3Parameter) was found to be the best fit distribution for all 6 project types, and for the early completion projects, the Generalized Extreme Value distribution was found to be the best fit distribution for all 6 project types considered. The GOF test results are shown in Table 4.24.

The PDF of Lognormal (3 Parameter) distribution is mathematically expressed as follows.

$$f(x)=\frac{\exp(-\frac{1}{2}(\frac{\ln(x-\gamma)-\mu}{\sigma})^2)}{(x-\gamma)\sigma\sqrt{2\Pi}} \tag{22}$$

The corresponding CDF is:

$$F(x) = \phi\,(\frac{\ln\,(x - \gamma) - \mu}{\sigma}) \tag{23}$$

Where,
σ- Continuous parameter (σ >0)
μ - Continuous parameter
γ - Continuous location parameter

The Generalized Extreme Value distribution is three-parameter distribution and the PDF of this distribution is mathematically expressed as follows.

$$f(x) = \begin{cases} \frac{1}{\sigma}\exp\,(-(1+k\,z)^{-\frac{1}{k}}\,(1+k\,z)^{-1-\frac{1}{k}} & k \neq 0 \\ \frac{1}{\sigma}\exp\,(-z - \exp\,(-z)) & k = 0 \end{cases} \tag{24}$$

The corresponding CDF is:

$$F(x)=\begin{cases} \exp(-(1+k\,z)^{-\frac{1}{k}} & k\neq 0 \\ \exp(-\exp(-z)) & k=0 \end{cases} \tag{25}$$

Where,

$$z = \frac{x - \mu}{\sigma} \tag{26}$$

k = continuous shape parameter

σ = continuous scale parameter (σ > 0)
μ = continuous location parameter

Table 4.24 Goodness of fit statistics of lognormal (3 Parameter) and generalized extreme value distributions

	Delayed project			Early completion projects		
Type of project and total sample size	**Surface treatment N=102**					
Fitted distribution	**Lognormal (3P)**			**Generalized Extreme Value**		
Sample size	N = 38			N = 46		
Parameters	σ= 1.7261 μ=0.98397, γ=1.0034			k=-0.88657, σ = 0.1855, μ = 0.80238		
Test statistics	D 0.07003	A^2 0.16775	χ^2 2.7359	D 0.07678	A^2 0.30402	χ^2 1.3665
Type of project and total sample size	**Bridge construction N=98**					
Fitted distribution	**Lognormal (3P)**			**Generalized Extreme Value**		
Sample size	N = 58			N = 30		
Parameters	σ= 1.4675, μ=-1.5101, γ=1.0128			k=- 0.82718, σ = 0.193, μ = 0.8116		
Test statistics	D 0.07309	A^2 0.44245	χ^2 3.5507	D 0.14134	A^2 0.88205	χ^2 2.641
Type of project and total sample size	**Curb, gutter and sidewalk construction N=152**					
Fitted distribution	**Lognormal (3P)**			**Generalized Extreme Value**		
Sample size	N = 63			N = 66		
Parameters	σ= 1.1772, μ = -1.1425, γ = 0.98462			k=-0.63153, σ = 0.29186, μ =0.62388		
Test statistics	D 0.06319	A^2 0.23407	χ^2 3.0286	D 0.08074	A^2 0.73951	χ^2 6.5389
Type of project and total sample size	**General N=302**					
Fitted distribution	**Lognormal (3P)**			**Generalized Extreme Value**		
Sample size	N = 159			N = 105		
Parameters	σ = 1.3444, μ = -0.93279, γ = 0.99745			k = -1.0105 , σ = 0.26213, μ = 0.77165		
Test statistics	D 0.08142	A^2 0.62187	χ^2 22.424	D 0.12628	A^2 2.2158	χ^2 9.1357
Type of project and total sample size	**Hot-mixed asphalt paving N=1002**					
Fitted distribution	**Lognormal (3P)**			**Generalized Extreme Value**		
Sample size	N = 501			N = 308		
Parameters	σ = 1.5064, μ =1.2221, γ = 0.99935			k = -1.0595, σ = 0.20996, μ = 081755		
Test statistics	D 0.03479	A^2 0.68642	χ^2 0.24778	D 0.10635	A^2 3.2655	χ^2 9.0911
Type of project and total sample size	**Thermal pavement marking N=108**					
Fitted distribution	**Lognormal (3P)**			**Generalized Extreme Value**		
Sample size	N = 65			N = 27		
Parameters	σ= 1.4258, μ = -1.1437, γ = 1.0162			k = -1.1423, σ = 0.26777, μ = 0.7792		
Test statistics	D 0.05953	A^2 0.24051	χ^2 1.9108	D 0.12443	A^2 0.40123	χ^2 0.80808

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research project investigated the effect of using CPM schedules on SCDOT projects. The analysis examined primarily the *after* 2007 dataset which consists of SCDOT projects let after February 2007 and substantially completed by August 2015; for comparison purposes the before 2007 dataset was also examined. Among the *after* 2007 projects with CPM schedules, 54.32% were delayed beyond the original contract completion date compared to 47.49% for projects without CPM schedules. Conversely, among the projects with CPM schedules, 14.50% were delayed beyond the adjusted completion date compared to 16.08% for projects without CPM schedules. To understand these results, additional analyses were conducted by stratifying the data into the following categories: project type, project size, project duration, and project location.

Based on the analysis of the *after* 2007 dataset, it was found that the types of projects that are more likely (> 50%) to have CPM schedules are: general (GNRL) and hot-mixed asphalt paving (HMAS). The types of projects that are less likely (≤ 50%) to have CPM schedules are Paint and marking (BRPT, PMEP, PMPT, PMRP, and PMTH), sign (SIGN) and signal (SGNL), guardrail (GDRL), drainage structure (DRST) and landscape projects (LDSC). Among the projects with CPM schedules, 54.32% were delayed beyond the original contract completion date and 14.50% were delayed beyond adjusted completion date. These statistics are similar when compared against the *before* 2007 dataset, where among the projects with CPM schedules, 47.82% were delayed beyond the original contract completion date and 16.26% were delayed beyond adjusted completion date.

An examination of the delayed projects in the *after* 2007 dataset showed that there was no statistically significant association between projects with CPM schedules and delayed projects for the majority of cases. The cases where there was statistically significant association based on delay after the original completion date are: HMAS projects, Districts 1 and 7, large-sized projects, and medium-term projects. When delay is based on the adjusted completion date, the cases where there were statistically significant association between projects with CPM schedules and delayed projects are: District 5, large-sized projects and short-term projects.

An examination of the delayed projects in the *before* 2007 dataset showed that there was no statistically significant association between the projects with CPM schedules and delayed projects for the majority of cases. The cases where there was statistically significant association based on delay after original completion date are: GNRL, HMAS, Districts 3 and 4, all project size categories, short-term and medium-term projects. When delay is based on the adjusted completion date, the cases where there was statistically significant association are: GNRL, HMAS, Districts 4 and 7, large and medium-sized projects, and short and medium-term projects.

An examination of the number of days delayed beyond the original and adjusted completion date by project type, district, size and duration in the *after* 2007 dataset showed that based on project type and adjusted completion date, there was no statistically significant difference between projects with and without CPM schedules. However, in terms of the number of days delayed beyond the original completion date, there was a statistically significant difference for BRDG, GNRL, and HMAS projects. There was no statistically significant difference between projects with and without CPM schedules for all districts, either based on original or adjusted completion date. When projects are examined by size, the only statistically significant difference is for small-sized projects based on adjusted completion date. Lastly, when projects are examined by duration, there is no statistically significant difference based on adjusted completion date; however, based on the original completion date, there is a statistically significant difference for short-term and long-term projects.

An examination of the average number of days delayed beyond the original and adjusted completion date by project type, district, size and duration in the *before* 2007 dataset showed that based on project type and original completion date, there was no statistically significant difference between projects with and without CPM schedules. However, in terms of the number of days delayed beyond the adjusted completion date, there was a statistically significant difference for GNRL projects. There was a statistically significant difference between projects with and without CPM schedules in Districts 1 and 2 when delay is based on the original completion date and for Districts 2 and 3 when delay is based on the adjusted completion date. When projects are examined by size, the only statistically significant difference is for medium-sized projects based on adjusted completion date. Lastly, there was no statistically significant difference between projects with and without CPM schedules for all project duration categories, either based on the original or adjusted completion date.

While the analyses of the data by categories resulted in a few statistically significant results, no overall pattern in the results by category could be discerned. It should be noted that some of these statistically significant results could be due to how the data were stratified. The possible reasons why projects with CPM schedules have not always outperformed projects without CPM schedules include:

- Projects with CPM schedules are those with a significant amount of risk and complex scope whereas projects without CPM schedules are those with low risk and limited scope.
- The use of a mechanistic scheduling tool does not address the root causes of project delay.
- Having a CPM schedule does not automatically allow one to manage the risks associated with construction projects and the CPM schedule does not assist in mitigating delays.
- The current method of selecting/waiving CPM schedules for a project is either not consistent or not focused on projects where CPM could reduce the risk of delay.
- Deterministic task duration in the CPM schedules are selected to be close to the average duration and does not consider possible variations.
- Contractors may be managing the project with a different schedule than the one submitted to the SCDOT.

Various predictive models were explored to predict whether a project will be delayed or over budget. The explanatory variable “contract bid amount” was found to be statistically significant in the developed delay binary logistic regression model. That is, the higher the contract bid amount, the more likely a project will be delayed. This finding is consistent with how the SCDOT and other state DOTs identify projects that require CPM scheduling. The budget binary logistic regression model indicates that whether a project is completed within budget is dependent on the explanatory variables “CPM schedule”, “SCDOT Districts”, and “Project Duration.” Specifically, a project having a CPM schedule and longer duration will be less likely to complete on budget.

The text mining analysis of the change order remarks indicated that the top three most frequently used single words are “days”, “contract”, and “date,” and the top three two-word combinations are “completion date”, “contract completion”, and “change order.” A sentiment analysis was also performed on the single keywords in the change order remarks. The most positive sentiment key word is “work” and most negative sentiment keyword is “delays.” Using the identified keywords and their sentiment, a neural network model was developed to predict the probability of a project being delayed. In the model, CPM scheduling and environmental conditions (i.e. rain) were also considered as predictor variables. The model correctly predicted a project will be delayed 53.7% of the time.

Another approach developed to estimate the probability of a project being delayed is through the use of probability density functions and Law of Total Probability (LTP). The best-fit distribution for delayed projects was found to be the Pearson 6 (4 Parameter), and the best-fit distribution for the early completion projects was found to be the Johnson SB. Using these best-fit distribution parameters and LTP, a project’s probability of delay can be determined.

5.2 Recommendations

The current SCDOT CPM scheduling criteria involves examining project risks as shown in Table 5.1.

Table 5.1 Scheduling specification for SCDOT (SCDOT, 2013)

Levels of Schedule	Selection Criteria	Scheduling Technique	Software	Monthly Update
1-Minimal Scheduling	Design field review or estimate development	Four-week look-ahead	MS Word or Excel	
2-Standard CPM		CPM Narrative	Primavera Project Mangement 5.0 or Primavera Contractor5.0	Yes. (Narrative)
3-Standard CPM with Monthly Cumulative Payment	Bid amount exceeds $20 million	CPM Narrative	Primavera Project Mangement 5.0 or Primavera Contractor5.0	Yes. (Narrative)

As shown, the SCDOT’s CPM scheduling decision is made based on the field review. Although not formally documented, the SCDOT’s field review considers project complexity, project uncertainty, construction sequences, etc. It is recommended that the SCDOT adopt a more structured approach for selecting projects that require CPM scheduling. For example, Virginia DOT considers four different criteria (project complexity, schedule constraints, project uncertainty, delay consequence) as shown in Figure 5.1 (Virginia DOT, 2006).

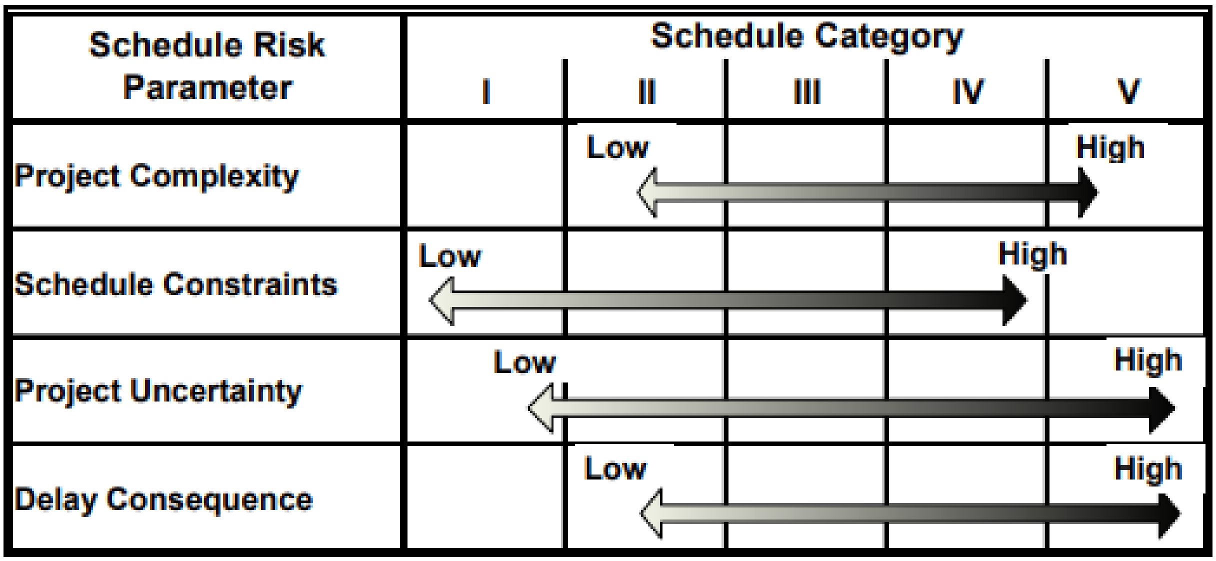

Figure 5.1 Virginia DOT selection criteria for CPM schedules

Additional options for associating delay risk with requiring a CPM schedule include:

- Implement a scheduling criteria based on a combination of project bid amount and project duration. Some state DOTs are already implementing this procedure (e.g., Caltrans)
- Examine the total number of bid items in a project. A project with a larger number of bid items may need more project control.
- Identify projects with unique activities such as high traffic control. Such projects may require more detailed management practices.

Additionally, the SCDOT may consider incorporating the probabilistic information about project delay into the schedules. While predicting which project will be delayed from the project characteristics has been found to be difficult, the analysis shows that the delay of SCDOT projects follows a well-known probability distribution One could provide a range for the activity duration in the CPM schedule instead of simply using the expected duration. Alternatively, one could use the probability model discussed in Chapter 4 to extend all the activity durations in a CPM schedule such that no than 10% of the SCDOT projects will be delayed.

Based on the survey conducted as a part of this study, both resident construction engineers and contractors indicated that the contractors sometimes maintain a separate schedule for work. As a result, the schedules do not necessarily reflect the actual construction schedules. To overcome this issue, the SCDOT should consider requesting both cost and resource loaded schedules. A resource loaded schedule will help the SCDOT tracks productivity and ensures that the contractor provides a practical schedule. Lastly, the SCDOT should consider including a provision in future contracts to ensure that all personnel (SCDOT and contractors) are using the same schedule for project management.

6 REFERENCES

Ahmed, S. M., Azhar, S., Castillo, M., & Kappagantula, P. (2002). Construction Delays in Florida: An Empirical Study. Final report. Department of Community Affairs, Florida, US.

Aibinu, A. A., & Jagboro, G. O. (2002). The effects of construction delays on project delivery in Nigerian construction industry. International Journal of Project Management, 20(8), 593–599. doi:10.1016/S0263-7863(02)00028-5

Al-Kharashi, A., & Skitmore, M. (2009). Causes of delays in Saudi Arabian public sector construction projects. Construction Management and Economics, 27(1), 3–23. doi:10.1080/01446190802541457

Al-Momani, A. H. (2000). Construction Delay: A Quantitative Analysis. International journal of project management, 18(1), pp. 51–59.

Anderson, T. W., & Darling, D. A. (1954). A Test of Goodness of Fit. Journal of the American statistical association, 49(268), pp. 765–769.

Arditi, D., & Gunaydin, H. M. (1998). Factors That Affect Process Quality in the Life Cycle of Building Projects. Journal of Construction Engineering and Management, 124(3), 194–203. doi:10.1061/(ASCE)0733-9364(1998)124:3(194)

Assaf, S. A., & Al-Hejji, S. (2005). Causes of delay in large construction projects. International Journal of Project Management, 24(4), 349–357. doi:10.1016/j.ijproman.2005.11.010

Assaf, S. A., Al-Khalil, M., & Al-Hazmi, M. (1995). Causes of Delay in Large Building Construction Projects. Journal of Management in Engineering, 11(2), 45–50. doi:10.1061/(ASCE)0742-597X(1995)11:2(45)

Bordat, C., Mccullouch, B. G., & Labi, S. (2004). An Analysis of Cost Overrun and Time Delays of INDOT Projects. Retrieved 12 March 2016, from http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1482&context=jtrp

Chan, D. W. M., & Kumaraswamy, M. M. (1996). An evaluation of construction time performance in the building industry. Building and Environment, 31(6), 569–578. doi:10.1016/0360-1323(96)00031-5

Cochran, W. G. (1952). The $\chi 2$ Test of Goodness of Fit. The Annals of Mathematical Statistics, pp. 315–345.

Construction Schedules (2013), Retrieved November 17, 2017 from Supplemental Specifications SCDOT website, http://www.scdot.org/doing/technicalPDFs/supSpecs/Construction_Schedules_11-4-13.pdf

Crossett, J., & Hines, L. (2007). Comparing State DOTs' Construction Project Cost and Schedule Performance: 28 Best Practices from Nine States. Final Report Project 20-24, TransTech

Management, Washington D.C. 2007. Retrieve from: http://onlinepubs.trb.org/onlinepubs/archive/NotesDocs/20-24(37)A_FR.pdf.

Crossett, J., & Schneweis, K. (2011). Measuring Performance among State DOTs: Sharing Best Practices-Construction and Budget Performance Update. NCHRP Report 20-24 (37) A (01), Transportation Research Board, Washington, D.C., 2011.

Davis, E. W., (1974). CPM Use in Top 400 Construction Firms. Journal of the Construction Division., ASCE, 100(1), 39-49

Doloi, H., Sawhney, A., Iyer, K. C., & Rentala, S. (2012). Analysing factors affecting delays in Indian construction projects. International Journal of Project Management, 30(4), 479–489. doi:10.1016/j.ijproman.2011.10.004

Galloway, P. D. (2006). Survey of the Construction Industry Relative to the Use of CPM Scheduling for Construction Projects. Journal of Construction Engineering and Management, 132(7), 697–711. doi:10.1061/(ASCE)0733-9364(2006)132:7(697)

Gantt, H. L. (1910). Work, Wages and Profit, The Engineering Magazine, New York, 1910.

Galway, L. (2004). Quantitative Risk Analysis for Project Management. WR-112-RC, RAND Corporation working paper.

Gunduz, M., Nielsen, Y., & Ozdemir, M. (2013). Fuzzy Assessment Model to Estimate the Probability of Delay in Turkish Construction Projects. Journal of Management in Engineering, 31(4), p. 04014055-1 – 04014055-14.

Hebb, D. (1949). The Organization of Behavior, Wiley, New York.

Hildreth, J., & Munoz, B. (2005). An introduction to the management principles of scheduling. Report No. TR-05-04. Blacksburg, VA: Virginia Department of Transportation.

Hugh, H. (2003). NCHRP Report 483-Bridge Life Cycle Cost Analysis (BLCCA). Washington. DC Transp. Res. Board.

Isidore, L. J., & Back, W. E.(2002). Multiple Simulation Analysis for Probabilistic Cost and Schedule Integration. Journal of Construction Engineering and Management, 128(3), pp. 211–219.

Kaliba, C., Muya, M., & Mumba, K. (2009). Cost escalation and schedule delays in road construction projects in Zambia. International Journal of Project Management, 27(5), 522–531. doi:10.1016/j.ijproman.2008.07.003

Kelleher, A. H. (2004). An investigation of the expanding role of the critical path method by ENR's top 400 contractors (M.Sc Thesis), University of Virginia.

Khallaf, R., Yoon, S., Hastak, M. & Nautung, T. (2016). Simplified Construction Scheduling for Field Personnel. Project No. FHWA/IN/JTRP-

2016/27. Indiana Department of Transportation. Retrieved from: https://docs.lib.purdue.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=3135&context=jtrp

Kim, S.Y., Tuan, N. V., and Ogunlana, S. N. (2009). Quantifying Schedule Risk in Construction Projects Using Bayesian Belief Networks. International Journal of Project Management, 27(1), pp. 39–50.

Klemenstowksi, L.J., (1978). PERT/CPM and Supplementary Analytical Techniques: AN Analysis of Aerospace Usage (MS Thesis), Air Force Institute of Technology, Wright-Patterson AFB, Dayton OH.

Love, P. E. D., Sing C. P., Wang, X., Edwards, D. J., & Odeyinka, H. (2013). Probability Distribution Fitting of Schedule Overruns in Construction Projects. Journal of the Operational Research Society, 64(8), pp. 1231–1247.

Liberatore, M. J., Pollack-Johnson, B., & Smith, C. A. (2001). Project management in construction: software use and research directions. Journal of Construction Engineering and Management, 37(4), 101–107.

Medhat, W., Hassan, A., & Korashy, H. (2014). Sentiment analysis algorithms and applications: A survey. Ain Shams Engineering Journal, 5(4), 1093-1113. doi:10.1016/j.asej.2014.04.011

Mahamid, I., Bruland, A., & Dmaidi, N. (2012). Causes of Delay in Road Construction Projects. Journal of Management in Engineering, 28(3), 300–310. doi:10.1061/(ASCE)ME.1943-5479.0000096

Mansfield, N. R., Ugwu, O. O., & Doran, T. (1994). Causes of delay and cost overruns in Nigerian construction projects. International Journal of Project Management. doi:10.1016/0263-7863(94)90050-7

Massey Jr, F. J. (1951). The Kolmogorov-Smirnov Test for Goodness of Fit. Journal of the American Statistical Association, 46(253), pp. 68–78.

McCullough, R. B. (1999). CPM Schedules in Construction Claims From the Contractor's Perspective. AACE International Transactions, 1-4.

Mehrannia, H., & Pakgohar, A. (2014). Using easy fit software for goodness-of-fit test and data generation. International Journal of Mathematical Archive, 5(1), ISSN 2229-5046

Ogunlana, S. O., Promkuntong, K., & Jearkjirm, V. (1996). Construction delays in a fast-growing economy: Comparing Thailand with other economies. International Journal of Project Management, 14(1), 37–45. doi:10.1016/0263-7863(95)00052-6

Park, Y.-I., & Papadopoulou, T. C. (2012). Causes of cost overruns in transport infrastructure projects in Asia: Their significance and relationship with project size. Built Environment Project and Asset Management, 2(2), 195–216. doi:10.1108/20441241211280873

Rowings, J. E., Harmerlink, D. J., & Rahbar, F. (1993). A multi-project scheduling procedure for transportation projects. Project No. HR-339. Ames, IA: Iowa Department of Transportation. Retrieved from: https://www.iowadot.gov/research/reports/Year/2003andolder/fullreports/hr339.pdf

Salkind, N. J. (2006). Encyclopedia of Measurement and Statistics. Sage Publications.

Samarasighe, S. (2007). Neural networks for applied sciences and engineering: from fundamentals to complex pattern recognition. Auerbach imprint of Taylor & Francis Group, LLC.

Sambasivan, M., & Soon, Y. W. (2007). Causes and effects of delays in Malaysian construction industry. International Journal of Project Management, 25(5), 517–526. doi:10.1016/j.ijproman.2006.11.007

Santoso, D. S., & Soeng, S. (2016). Analyzing Delays of Road Construction Projects in Cambodia: Causes and Effects. Journal of Management in Engineering, 32(6), 5016020. doi:10.1061/(ASCE)ME.1943-5479.0000467

SCDOT (2013). "Construction Schedules", Retrieved January 19, 2017 from Supplemental Specifications of SCDOT website, https://www.scdot.org/business/technicalPDFs/supSpecs/Construction_Schedules_11-4-13.pdf

Shi, J. J., Cheung, S. O., & Arditi, D. (2001). Construction Delay Computation Method. Journal of Construction Engineering and Management, 127(1), pp. 60–65.

R: The R Project for Statistical Computing. Retrieved July 30, 2017, from https://www.r-project.org/

Rumsey, D. J. (2006). Probability for Dummies. John Wiley & Sons.

Tavakoli, A., & Riachi, R. (1990). CPM use in ENR top 400 contractors. Journal of Management in Engineering, 53(3), 160. doi:10.1017/CBO9781107415324.004

VADOT (2006). "Schedule Submittal Requirements (2006), Retrieved December 22, 2017 from Construction Scheduling website, http://www.virginiadot.org/business/resources/const/0602_SubmittalRequirements.pdf

Washington, S.P., Karlaftis, M.G., & Mannering, F.L. (2011). Statistical and Econometric Methods for Transportation Data Analysis, 2nd ed. Boca Raton, FL: Chapman & Hall/CRC

Yates, J. K. (1993). Construction Decision Support System for Delay Analysis. Journal of Construction Engineering and Management, 119(2), 226–244.