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Introduction

The prediction or estimation of project time is a problem faced throughout the project management industry, from computer software development projects to large commercial building projects. For example, Stamelos, Angelis, Morisio, Sakellaris, and Bleris (2003) document that software development projects suffer from schedule overruns caused by insufficient initial time estimates. Chan and Chan (2004) document the need to benchmark construction time estimation and performance for housing projects.

Various tools exist to estimate and/or predict project time or duration, including highly-valued scheduling software (Besner & Hobbs, 2006). However, the greatest single deterrent to reliable project time estimates is uncertainty. To date, capturing the uncertainty of a project relies heavily on the knowledge and experience of the estimator, and on *ad hoc* and subjective techniques, leaving the estimate with a great deal of "bias," factors that unduly increase project estimates. These estimates often include omissions, errors, overconfidence in estimates, or a general failure to recognize special-cause events (Leach, 2003). In addition, one project time estimator may derive a project time completely different from another estimator; however both estimators may have sound logic for the project times derived.

Attempts to remedy these problems include various techniques, including resource-constrained schedules, stochastic methods, Program Evaluation and Review Technique (PERT), Monte Carlo simulation, and sensitivity analysis (Herroelen & Leus, 2005). However, these methods have not proven satisfactory in industry, and their potential for doing so is perceived as being very low (Besner & Hobbs, 2006). Leach (2003) documents the need for improved systems that provide reliable and repeatable project times.

Purpose of the Research

The purpose of this study is to demonstrate and validate a simple, yet formalized approach for providing reliable and robust project times. The estimation system presented uses a template-based approach, one that uses a train of critical project activities and their production rates. The template-based approach is not new to this study; however, the literature lacks validation of the reliability and repeatability of this approach. To validate the template-based approach, this study used highway construction projects (available from the project sponsor, the State of Louisiana's Department of Transportation and Development, LaDOTD). Although this study used highway projects, application of the techniques used in this study extends to all types of projects.

To create valid and reliable project time estimates this research seeks to demonstrate that the three key components of the template-based system (the critical train of activities, the productivity rates, and the total baseline estimate) are individually valid. If any one is not substantiated, then the calculated project time will be suspect: an incorrect critical chain will incorrectly determine the overall project duration and yield a project with little face validity, incorrect production rates will incorrectly predict the expected mean and yield mean values with little face validity, and an incorrect prediction of overall baseline time will impact the validity of the system's results.

Hypothesis A: There exists a unique critical train of activities for projects with common characteristics, called a "project template";

Hypothesis B: Mean values of productivity rates (allowing for variations in project characteristics) provide as good an estimation for prediction of project time as more complex estimates; and

Hypothesis C: Estimated project times using the proposed system will provide as good or better estimates when compared to actual project completion times.

Literature Review of Project Time Estimation Methods

The project time estimation (PTE) literature contains the efforts by many researchers to develop project time estimation systems (PTES). These systems estimate project time by generating a predictive schedule, usually based on deterministic procedures, but may include procedures to deal with project uncertainties. Some of these systems were developed for the transportation industry, such as the Texas system (Hancher, McFarland, & Alabay, 1992), the Louisiana system (McCrary, Corley, & Leslie, 1995), and Kentucky developed computer-based PTES (Hancher & Werkmeister, 2000). In that industry, the Federal Highway Administration's guidelines for project time determination are summarized in their document, *Guide for Construction Contract Time Determination Procedures* (FHWA, 2002). PTES for other industries include those for public housing development (Chan & Chan, 2004), for utility construction (AbouRizk, Knowles, & Hermann, 2001), for the completion of computer programming and systems projects (Benbasat & Vessey, 1980), for information systems (Hallows, 2005), and for general application see Demeulemeester and Herroelen (2002).

These works document that project time is generally estimated using eight (8) techniques, used individually or in combination: (1) subjective *ad hoc*, (2) estimated cost, (3) stochastic methods, (4) quantity/production rate, (5) traditional network modeling, (6) simulation (4D modeling), (7) resource-constrained networks, and (8) the template-based method (NCHRP, 1981; Thomas, Jones, Willenbrock, Hester, & Logan, 1985). Each technique is briefly described below.

Subjective Ad Hoc Techniques.

The subjective *ad hoc* method, commonly used to estimate project time, is a highly deterministic method that uses the estimator's personal, *ad hoc*, experience to estimate expected time; expected uncertainty is implicit to the expected time estimate. Since this method is highly subjective, reproducibility is limited and estimated project times are highly variable (Kane, 1991).

Estimated Cost Techniques.

This deterministic technique rests on the assumption that project time is directly proportional to the total estimated cost of the project, again uncertainty is an implicit variable:

$$ProjectTime = \frac{\text{ProjectCost}}{\text{AverageCost/Day}}$$

Although this method is the quickest, it is the least desirable because it needs constant updating to ensure that the average cost per day is based on the most current labor techniques, types, and factors (FHWA, 1985, 2002).

Stochastic Methods.

This approach for project time estimation attempts to use statistical techniques, such as multiple regression, Markov's chain, or ANOVA (analysis of variance) to quantify both the baseline time and uncertainty, using project characteristics. The estimating equation usually takes some derivation of the form:

$$Time = \beta_0 x_o^a + \beta_1 x_1^b + \cdots + \beta_n x_n^k$$

The independent variables (x_0, x_1, … x_n) in the above equation, represent a characteristic of the project, such as lines of computer code, quantities of material, budget dollar values, or a combination of these (or other) characteristics (Anderson & Sungur, 1999). The regression analysis determines the coefficients *a, b, k*, and the β 's (Chan & Chan, 2004; Chong, 2005; Skitmore & Ng, 2003).

Quantity/Production Rate (QPR) Technique.

This technique, a more detailed version of the Estimated Cost Technique, uses the project's baseline estimate of work quantities to calculate project time using the following equation:

$$ProjectTime = \sum_i \left[\frac{PlannedQuantity}{AverageQuantity / Day} \right],$$

where *i* is a set of "selected" work activities that most affect project time,
PlannedQuantity is the estimated quantity for work Activity *i*, and
AverageQuantity/Day is the assumed or historical production rate for work Activity *i*.

The validity of QPR project time estimates rests on several key assumptions: (1) The selected work activities control the project time, and therefore must be carefully chosen to match the project (McCrary et al., 1995). (2) The selected activities must be completed sequentially, not concurrently. And (3) the production rates must be developed from a project process similar to that expected for the project under consideration.

Traditional Network Modeling Technique.

Several network tools developed during the 1950's and 1960's, specifically the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT), often used with Monte Carlo simulation (T. Williams, 2004) or Fuzzy Logic (Liberatore, 2002), provide the ability to estimate project time, and capture project uncertainty, using mathematical network techniques. To be valid, network models, similar to previous techniques, require accurate determination of controlling activities and production rates. In addition, the model must accurately describe the precedence relationships among activities. One major problem with PERT and Monte Carlo simulation is that their present use and potential value are among the lowest in the project management industry (Besner & Hobbs, 2006).

Visual Simulation and "4D" modeling.
In this category are a host of modern tools that literally simulate construction processes using graphic models of construction operations, resources, equipment, and their interactions. Examples of these tools include graphic simulation tools, such as *Vensim* (VentanaSystems, 2005), and 4D scheduling tools (Koo & Fischer, 2000). Although these methods are proving to be effective tools for modeling project processes, their implementation is greatly hindered by difficulty in use, model building, and model validation (Shi, 1999; Tam, Tong, & Tse, 2002).

Resource-constrained networks.
Resource-constrained project scheduling considers how limited project resources (labor, material, machines, etc.) affect project production. Demeulemeester and Herroelen (2002) attribute the formalization of these methods to Graham, Lawler, Lenstra, and Rinnooy Kan (1979). The latest development in network scheduling, called Critical Chain Scheduling (attributed to (Goldratt, 1997)), recognizes that projects are constrained by both resources and uncertainty. This method relies on two important principles: (1) activities are constrained by resources, so the "critical chain" is the set of activities created by resource-constraining the project network, and (2) "buffers" are added to the schedule to protect against uncertainties.

In a very thorough validation study of a similar method, the critical chain technique, Herroelen and Leus (2001) conducted an experimental analysis on 110 test (not real) projects. Herroelen and Leus simulated each project 160 times by varying both project factors and activity duration. Their results lead to the conclusion that using the mean value for project activity duration provides the "safest" estimate of total project duration.

The Template-Based Approach.
Each PTE technique presented above has strengths and weaknesses. A particularly appealing approach, called "template-based," combines the ease and simplicity of the QPR technique, the computational rigor of network techniques, the clarity of bar charts for presentation, the constraints of resources, and simulates (or captures) the expertise of experienced estimators. The template-based approach, being a hybrid of several approaches, has the following key characteristics (Herbsman & Ellis, 1995):

- It provides a train of controlling activities (critical train), thus capturing the scope of the project;
- It provides the temporal relationships (a networked framework) among the critical train of activities, thus capturing the complexity of the project; and
- It includes pre-determined production rates to capture the characteristics of the project. Expected mean values are used for estimated activity times.
- Project uncertainty is captured in three ways: (1) by calculating production rates using historically similar values, (2) by estimating project time using similar project types, and (3) by using a modifier to increase/decrease mean values as needed when historically similar values are not available.

The challenge with the template-based approach, as with simulation, is that, due to the expert knowledge needed for development (knowledge that takes a great deal of time to capture), validation of the final system is often ignored or neglected. Development of these templates can be undertaken by any project management organization, however most known template-based systems were developed in the transportation industry, in Texas (TTI, 1992), in Louisiana (McCrary et al., 1995), in Kentucky (Hancher & Werkmeister, 2000), and in Virginia (R. C. Williams, 2006). Chan and Chan (2004) document the use of this approach in combination with regression analysis for public housing projects.

Summary of Literature Review.
Although there are many methods for project time estimation, each and every method estimates project time by modeling both the normal time expectation and the exceptional events (uncertainty or risk) that increase that normal time expectation (Demeulemeester & Herroelen, 2002; Isaksson & Stille, 2005). For those methods that use a network or chain of activities, normal time is modeled using the expected mean time of each activity. Risk, typically, is modeled in one of three ways: (1) by the explicit addition of buffers (slack time), (2) by multiplication of the expected mean time by an explicit modifier (for each activity), and (3) by the implicit inclusion in production, resource, and activity characteristics. In addition, current research is looking into other ways for modeling project time (Demeulemeester & Herroelen, 2002).

What little validation of these methods that does exist, is dominated by the use of machine generated test instances, which may not emulate real-life instances (Herroelen, 2005). For example, Herroelen and Leus (2001) validated their approach based on the 110 test projects of Patterson (1984), making no attempt to validate the project time estimates using actual projects, the purpose of this study.

Validation of the Template-based Approach

The steps required to develop a template-based, computerized, PTES are similar to those given by Herbsman and Ellis (1995), with slight modification as follows:

- Phase 1: Determine Template Sets (construction categories);
- Phase 2: Determine the Activities List for each set;
- Phase 3: Determine the Construction Train (sequence of activities);
- Phase 4: Calculate Production Rates;
- Phase 5: Create the Computerized Project Time Estimation System;
- Phase 6: Validate Production Rates; and
- Phase 7: Validate the Final Project Time Estimates.

The researchers followed these steps very closely in the development of the system under consideration in this study, as documented by McCrary, et al. (1995).

Nominal Group Technique (NGT). NGT uses a structured approach to take a group of individuals, with diverse ideas on a particular subject, and bring them to a group consensus. For this project, the researchers used the following approach:

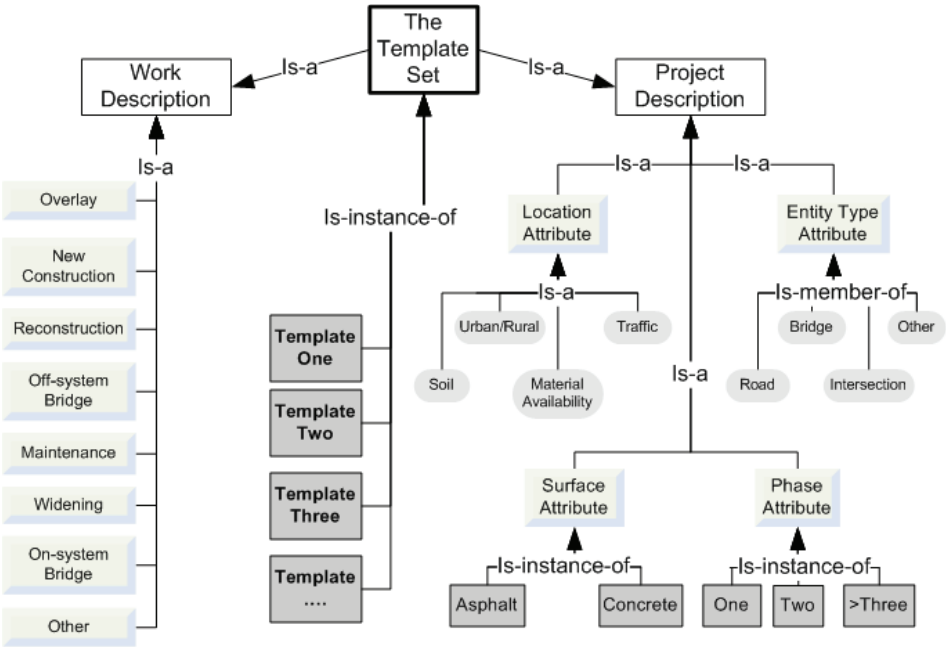
1st. Silent Deliberation: Each individual considers the question alone, silently.
2nd. Round-robin Feedback: Each individual, in turn, shares his ideas with the group.
3rd. Discussion: Each idea is discussed.
4th. Voting: Individuals vote privately on the priority order of the ideas discussed.
5th. Consensus: The result of the voting is shared with the group. Discussion of the idea continues until the voting shows that a consensus has been reached.

The researchers emphasized the following points: (1) Nominal thinking must dominate the discussion; (2) Individual input is very important; (3) Common occurrences are critical; (4) Group discussion should be focused; and (5) Group consensus is necessary.

Phase 1: Initial Determination of Template Sets (Workshop Session One).

A template, critical for a template-based system, is both a set of characteristics common among a variety of projects, and a critical train of activities that capture the project's work. The knowledge–characteristics about work and projects–captured in the template set can be represented by the semantic network (Figure 1) showing that The Template Set includes both "Work Descriptors" and "Project Descriptors." The knowledge captured by The Template Set provides the ability to distinguish and choose a template set to match the actual construction project being modeled. Principles of decision-support engineering (Wilson, 2005) tell us that a semantic network provides four options for building a knowledge-based system: (1) *ad hoc* or random (not considered acceptable, and therefore eliminated), (2) backward chaining or deductive (reasoning from general to specific), (3) forward chaining or inductive (reasoning from specific to general), and (4) combinations of inductive and deductive reasoning.

Figure 1. Semantic Network of the Knowledge in Contract Time Templates.



To determine the appropriate knowledge-based system to support project time determination, the project sponsors chose their preference among the four grouping options shown in Table 1. The research team developed these options to capture from 70% to 90% of LaDOTD construction projects. Each grouping is unique in characteristics, placing each one at a different spot on the deductive/inductive continuum; deductive at the left of Table 1 (see page 6), and inductive at the right. Each grouping is described below:

- Deductive: Organized by work type (this was the *de facto* method used to manually calculate project time estimates at LaDOTD).
- Mostly Deductive: The research team developed this grouping from the project sponsor's "Construction Program Report," which organizes knowledge using a combination of work types and project types.
- Mostly Inductive: Combines project types with project characteristics (used to develop the Texas PTES).
- Inductive: This grouping, also developed by the research team, captures knowledge from both the essential "project characteristics" and "construction characteristics" needed to uniquely identify a project.

When the researchers used the NGT to present these groupings to the construction engineers, the consensus response found the "Mostly Deductive" set to best represent their projects.

Phase 2: Determine and Validate Activities List. (Workshop Session Two)

In Session Two of the workshop, the research team presented the construction engineers with a list of construction and project features (from column 2 of Table 1, and in column 1 of Table 2). Using the NGT, the researchers asked the construction engineers to determine if the list of features represents all construction and project characteristics that have a significant impact on project time. When complete, the construction engineers made insignificant modifications to the original list.

Further in Session Two, the researchers divided the project managers into two

Table 1. Comparison of Template Groupings Options: From Deductive to Inductive for Types of LaDOTD Projects.

Deductive—by work type	Mostly Deductive-by work and project types	Mostly Inductive-by project types and project characteristics	Inductive-by construction and project characteristics
1. Overlay and Widen 2. New Construction/ Reconstruction 3.Construction of Additional Lanes 4. Bridge and Major Drainage 5. Other	Widen and Overlay 1. simple overlay-aggregate shoulder 2. simple overlay-overlay asphalt shoulder 3. simple overly-in-place stabilized shoulders 4. cold plane & overlay, overlay asphalt shoulder 5. cold plane & overlay, in-place stabilized shoulders 6. in-place base & overlay, aggregate shoulders 7. in-place base & overlay, in-place stabilized shoulders 8. widen & overlay, aggregate shoulders 9. widen & overlay, in-place stabilized shoulders New Construction/ Reconstruction 10. From 2 lanes to 5 lanes 11. 2 lane reconstruction 12. Interstate reconstruction Rehabilitation 13. Mostly rural interstate 14. Urban interstate 15. Urban streets Bridge and Major Drainage 16. Culverts 17. Rehabilitation and widening 18. Pile-supported girder span 19. Footing & Pile-supported girder span 20. Cast-in-place/Precast Clearing, Earthwork, and Utilities 21. Rural clearing 22. Urban clearing 23. Rural clearing and earthwork	1. Overlay 2. Widen Freeway 3. Widen Non-Freeway 4. New Location Freeway 5. New Location Non-Freeway 6. Rehabilitate Existing Road 7. Interchange 8. Upgrade Freeway To Standards 9. Upgrade Non-Freeway To Standards 10. Bridge Widening/ Rehabilitation 11. Bridge Replacement Choose a descriptor that describes the project for each of the underlying categories: 1. Geographic location: Urban, Rural, Suburban. 2. Quantity of work: Large, Medium, Small. 3. Traffic conditions: High, Moderate, Light. 4. Complexity: High, Medium, Low. 5. Soil conditions: Good, Fair, Poor.	1. Choose Finished Surface Type (select only one) - Asphalt - Asphalt/Widened - Concrete - Concrete/Widened - None 2. Choose Existing Surface Type (select only one) - Asphalt - Asphalt/Removed - Concrete - Concrete/Removed - None 3. Choose the Construction Type (a) Road - Number of lanes - Linear length of project - Divided roadway - None (b) Bridge Type - Cast-in-place - Precast - Structural steel - None (c) Intersection Type - At grade - Elevated - None (d) Other 4. What Time of Year will the Project begin? 5. What is the Phasing Factor? 6. Input the following Location Factors - District - Soil type - Urban/Rural - Material availability 7. What is the Contractor Factor?

smaller groups to create and validate the characteristics for each template. Using the characteristics list (the column "Template Features" of Table 2), each member, working alone, selected the characteristics required to estimate project time for the 23 templates listed in column 2 of Table 1. Then, the small group considered each individual's selections, and came to a consensus on the characteristics required to define each template. This process was repeated for each template. The results of this group work are shown as "Templates" in columns 1–23 of Table 2 (see page 7).

Phase 3: Plan and Validate Critical Train. (Workshop Session Three and Final)

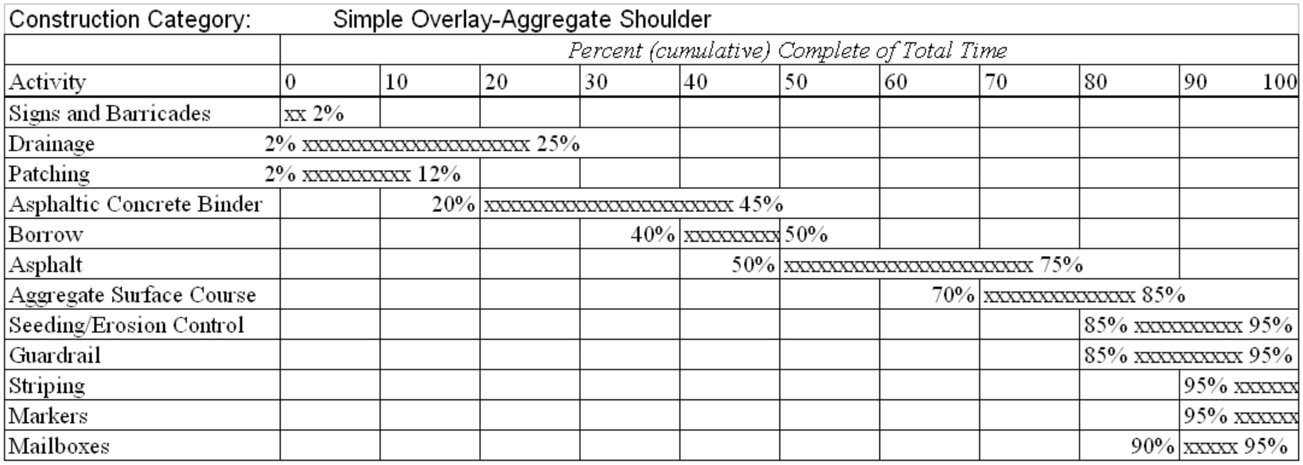
During the third and final workshop session, small teams of 5 project managers created a critical train (bar chart) for each template by identifying and sequencing the major construction work items required. Each project manager was given a blank worksheet [with the "Percent (cumulative) Complete of Total Time" not filled in], similar to that shown in Figure 2. Typically, a bar chart's horizontal axis represents time, but the horizontal axis for the critical train chart represents percent of total

Table 2. Features List Defining Each Template Set.

TEMPLATE FEATURES	TEMPLATES																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Bridge Characteristics																							
a. Pile supported girder span																					x		
b. Pile/footing supported girders																						x	
c. Cast-in-place slab span/Precast																							x
d. Bridge Widening/Rehabilitation												x								x			
e. Other (culverts)																			x				
f. N/A	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x					
2. Significant Detours												x								x	x	x	x
3. Drainage Structures: Major	x	x	x	x	x	x	x	x	x	x	x								x				
3. Drainage Structures: Minor												x	x	x	x	x	x	x			x	x	x
3. Drainage Structures: none																				x			
4a. Earthwork: Major											x							x	x		x	x	x
4b. Earthwork: Minor	x	x	x	x	x	x	x	x	x	x		x	x	x	x					x			
4c. Earthwork: none																x	x						
5. Existing Surface																							
a. Traffic lanes																							
i) Asphalt with stabilized base	x	x	x	x	x	x	x	x	x	x	x												
ii) Asphalt with raw base																							
iii) Concrete					x			x	x			x	x	x	x								
iv) N/A																x	x	x	x	x	x	x	x
b. Shoulder																							
i) Asphalt with stabilized base		x		x			x			x			x	x									
ii) Asphalt with raw base																							
iii) Concrete												x											
iv) N/A	x		x								x				x	x	x	x	x	x	x	x	x
c. Bridge Removal																			z		z	z	z
6. Subgrade Characteristics																							
a. Low, Wet, Poorly Drained																x	x	x	x		x	x	x
b. Wet, Soft, Under Pavement										x	x	x											
c. High, Dry, Well Drained	x	x	x	x	x	x	x	x	x				x	x	x					x			
7a. Road Length, up to x miles	6	6	6	6	6	6	6	6	6	3	6	6	5	5	5	5	5	5	1	1	1	1	1
7b. Bridge Spans: 1 through 3																			x				
7c. Bridge Spans: 4 or more												x								x	x	x	x
7c. Multiple Bridge Spans																			x	x	x		x
8. Phasing Impact																							
a. None or minor	x	x	x	x	x	x	x	x	x							x	x	x					
b. Moderate											x		x	x	x				x		x		x
c. Major										x		x								x		x	
9. Proposed surface																							
a. Traffic lanes																							
i) Asphalt	x	x	x	x	x	x	x	x	x	x	x								x				
ii) Concrete				x						x		x											
iii) N/A													x	x	x	x	x	x		x	x	x	x
b. Shoulder																							
i) Asphalt		x	x	x	x		x		x		x		x	x									
ii) Concrete												x											
iii) Aggregate	x					x		x											x				
iv) N/A										x					x	x	x	x		x	x	x	x
10a. Urban														x	x		x			x		x	
10b. Rural	x	x	x	x	x	x	x	x	x		x	x	x			x		x	x	x			x
10c. Small urban										x										x	x		
11a. More than 2 Lanes										x		x	x	x	x		x				x	x	
11b. Divided												x	x	x								x	
12. Significant Traffic Volume and Maintenance												x	x	x	x				x	x	x	x	x
13. Significant Utilities										x						x	x				x	x	x

1. Each column of Table 2 represents one of the 23 templates.
2. An “x” in a cell shows that a feature (row) is contained in that template (column).
3. Number values in row “7a” represent the maximum length of the roadway for using the template, in miles.

Figure 2. Critical Train for Template 1 – Simple Overlay-Aggregate Shoulder from Workshop Session Three



Construction Category: Simple Overlay-Aggregate Shoulder

	Percent (cumulative) Complete of Total Time									
Activity	0	10	20	30	40	50	60	70	80	90 100
Signs and Barricades	xx 2%									
Drainage	2% xxxxxxxxxxxxxxxxxxxxx 25%									
Patching	2% xxxxxxxxxx 12%									
Asphaltic Concrete Binder		20%	xxxxxxxxxxxxxxxxxxxxxxxx 45%							
Borrow				40%	xxxxxxxxx	50%				
Asphalt					50%	xxxxxxxxxxxxxxxxxxxxxxxx 75%				
Aggregate Surface Course							70%	xxxxxxxxxxxxxx 85%		
Seeding/Erosion Control									85% xxxxxxxxxx 95%	
Guardrail									85% xxxxxxxxxx 95%	
Striping										95% xxxxxx
Markers										95% xxxxxx
Mailboxes									90%	xxxxx 95%

time *complete; in other words, %complete = 100×time/total time.*

Working alone with a blank version of Figure 2, each project manager developed a bar chart of critical activities, based only upon their expertise, by assigning to each activity two numeric values: (1) a start value representing when this activity typically begins, as a percent (cumulative) complete of the total project time, and (2) a finish value representing when this activity typically ends, as a percent (cumulative) complete of the total project time. Then each team combined their individual bar charts to generate a consensus bar chart, the critical train. Figure 2 shows a completed critical train (for template 1). This process was employed to develop each of the 23 templates.

Based upon the results of these workshops, Hypothesis A is accepted. In other words, using the NGT, the project managers did come to a consensus on the content of the templates.

Phase 4: Calculate Production Rates

Prior to this study, the project sponsor (LaDOTD) estimated project times using hand-calculated production rates of approximately 80 work activities developed from historical project records. To study the viability and feasibility of continuing the use of historical productivity rates, the research team performed a production rate extraction study.

<u>Production Rate Extraction Study</u>

The production rate extraction study used the historical records of three actually completed projects. Historical records from these projects included baseline project time estimates (manually calculated) and daily reports (containing estimates of the amount of work performed each day). Ideally, the sum of the work completed in the daily report will equal the baseline estimate of work. However, although daily reports quantify the work completed during the day, they do not quantify the time spent performing the work, making a productivity estimate difficult (i.e., *Time*, the denominator of *Quantity/Time*, remains undefined). For example, assume that 10 hours of work actually occurred one day on several unique work activities. With no record or breakdown of time spend on each activity, what time-value should reasonably be associated with each activity? Perhaps only one and the same individual worked on every activity, thus spending only a portion of the 10 hours on each activity. Or, perhaps a different crew of people worked on each activity separately.

To solve this problem and define the value of $Time_i$, where "i" is a single day in the life of a project (where "n" is the total days), the researchers tested four time assignment assumptions, as follows: On any day where the field engineer recorded a quantity of work in the daily report, the day's production was calculated using each of the following techniques:

Technique 1: Full Day Assignment: assumes that a full day's work occurred, so $Time_i = 1$ day. At the end of the project, all daily time values are summed, $\sum_{1}^{n} Time_i$, as *Total Time* and divided into the *Total Work Quantity* to arrive at a *Mean* production rate per day. The result of this method produces the mean of the daily quantities.

Technique 2: Fractional Day Assignment: assumes that the time-on-task is less than or equal to 1 day. This assumption is calculated using the *Daily Work Quantity* (found in the daily report) divided by the *Mean* (from Technique 1). The $Time_i$ for each day is assigned as follows:

- When the Daily Quantity ≤ *Mean*;

  $$_{i}\ Time = \frac{DailyWorkQuantity}{Mean} \text{ day;}$$

- When the Daily Quantity > *Mean*; $Time_i = 1$ day.

Technique 3: Half-day Assignment: assumes that time-on-task is equal to either a half- or a full-day only. Again, the time is calculated using the Daily Quantity (found in the daily report) divided by the *Mean* (from Technique 1 above). The $Time_i$ for each day is assigned as follows:

- When the Daily Quantity ≤ *Mean*; $Time_i$ = 0.5 days;
- When the Daily Quantity > *Mean*; $Time_i$ = 1 day.

Technique 4: Multiple Day Assignment: assumes that time-on-task can be any value between 0 to 3 days (in just one-24 hour period). Occasionally, the Daily Quantity from the daily log will exceed the *Mean*. When the Daily Quantity is greater than the *Mean*, a value for $Time_i$ greater than 1 day is possible. If a single 24-hour period is divided into eight-hour work-day periods, then a maximum $Time_i$ value of 3 work-days (24/8) is possible per actual day. The computation for $Time_i$ using this method is as follows:

- When the Daily Quantity ≤ (0.5 x *Mean*); *Time = DailyWorkQuantity/ Mean* (day);
- When (0.5 x *Mean*) < Daily Quantity ≤ (1.5 x *Mean*); $Time_i$ = 1 day;
- When (1.5 x *Mean*) < Daily Quantity ≤ (2.0 x *Mean*); $Time_i$ = 1.5 days;
- When (2.0 x *Mean*) < Daily Quantity ≤ (2.5 x *Mean*); $Time_i$ = 2.0 days;
- When (2.5 x *Mean*) < Daily Quantity ≤ (3.0 x *Mean*); $Time_i$ = 2.5 days;
- When Daily Quantity > (3.0 x *Mean*); $Time_i$ = 3.0 days.

Daily Quantities were taken from the daily reports of these three projects and work times were calculated using the four different time techniques described above.

The results of the extraction study provided a trial estimate using only Technique 1, shown in Table 3, for the test projects. The calculated times were examined by the research team, along with project administrators, and compared to the actual working days and the original project time estimate for each project. As shown in Table 3, the research team's estimate of project time using Technique 1 (Row 3) was closer to the Actual Working Days (Row 2) than the original baseline estimates (Row 1). The research team and project administrators agreed that developing production rates from historical project records produced reasonable rates.

Table 3. Comparison of Times From the Production Rate Extraction Study

Row No.	Time Estimated	Time, days		
		Project 1	Project 2	Project 3
1	Project sponsor estimate	90	225	220
2	Actual Working Days	57	101	87
3	Researcher's Trial Estimate (Technique 1)	51	204	122

Full Study

Using the production extraction techniques discussed above, the research team calculated the production rates for approximately 100 constructed projects. The research team randomly selected the construction projects, from a total set of over 900 projects, to obtain an unbiased sample for developing the 23 project templates. To maintain statistical significance, a minimum of eight projects were selected for each project set.

In the end, the research team reviewed approximately 18,000 pages of daily reports (the equivalent of nearly 50 calendar years of construction). Production rates were developed for all 340 activities in the 23 templates, plus another 220 activities not in the templates, for a total of 560 production rates.

Phase 5: Create the Computerized Project Time Determination System

As one research team proceeded with the production rate analysis (described above), another research team proceeded simultaneously to develop the Computer-based Project Time Estimation System (CPTES). The CPTES is a computer program designed to be used by the Contracts Section of the LaDOTD. The CPTES used the original templates created by the construction engineers during the Project Time Workshop described earlier.

The Project Details Screen (Table 4) is where most of the activity in the CPTES program takes place. A value must be inserted in each cell of "Quantity" column.; a zero (0) entry is appropriate for a work item that does not appear in the project.

As the user enters numbers in the "Quantity" column (Table 4 see page10), the calculated project time will increase automatically based on pre-programmed fields in the spreadsheet. Notice that two project time values are reported at the bottom of the form:

- The top line shows the "Project Time without (activity) Overlap in Days." This duration is simply the sum of the values in the Duration column of the worksheet and represents a project in which all activities occur sequentially without any activity overlap.
- The lower line reports the "Project Time with (activity) Overlap in Days." This duration is the project time determined through the application of the template chosen for this project and allows for overlap among the work activities as determined from typical construction practice.

Phases 6 and 7: Validate Production Rates and Final Project Time Estimates

Methodology

With the CPTES in place and operational, only validation of the production rates and the resulting project times remained (Hypotheses B and C). To validate production rates, the researchers took quantities from 36 different projects and calculated four different time estimates using the techniques explained earlier in this paper. The production rates were then calculated for each time-on-task technique. The calculated production rates were inserted into the project templates along with actual completed quantities to estimate project time (PT) for each of the four different time-on-tasks techniques (called treatments below).

Table 4. The Project Details Screen.

Created by User _1 **LaDOTD: Simple Overlay, Aggregate Shoulder**
Created on 5/12/2005 State Project No. 111 Route 111

Items	Description	Prod Rate	Units	Quantity	Duration
713(01)	Signs and Barricades	1	LumpSum	**5**	5
701	Drainage	20	LF per Day	**60**	3
805	Box Culverts	100	Un-Det	**300**	3
704(01)	Patching	424	SqYd/Day	**6000**	14
501(01)	Asphaltic Concrete Binder	860	Tons/Day	**7800**	9
230(08)	Borrow	746	CuYd/Day	**5000**	6
501(01)	Asphaltic Concrete Wearing	860	Tons/Day	**6000**	6
401(02)	Aggregate Surface Course	447	CuYd/Day	**600**	1
717	Seeding/Erosion Control	200	Un-Det	**600**	3
704	Guard Rail	129	LF per Day	**800**	6
S	Mailboxes	14	Ea per Day	**60**	4
731(02)	Markers	561	Ea per Day	**6000**	10
732	Striping	4	Miles/Day	**15**	3

Estimated Project Time without Overlap in Days 74.1
Estimated Project Time with Overlap in Days 56.3

- Treatment 1: Full Day Assignment Technique, PT1.
- Treatment 2: Fractional Day Assignment Technique, PT2.
- Treatment 3: Half-day Assignment Technique, PT3.
- Treatment 4: Multiple Day Assignment Technique, PT4.

Two other project time values were included in the validation process:

- Treatment 5: The project sponsor's original project time estimate, and
- Treatment 6: Actual project duration.

Validation

To test Hypothesis B (validate the treatments of productivity values), the researchers used the Friedman non-parametric test for the following statistical hypothesis:

- Ho: $PT1 = PT2 = PT3 = PT4 = PT5 = PT6$
- Ha: $PT1 \neq PT2 \neq PT3 \neq PT4 \neq PT5 \neq PT6$

Where: PT_i = Project time calculated using time-on-task method *i*.

If results from the Friedman test lead one to accept the null hypothesis, the time calculation techniques do not produce significantly different production rates. If results from the Friedman test lead one to reject the null hypothesis, then the Dunnett test is used to compare pairs of times to determine if they are significantly different. The project time from each of the five methods is compared to the actual project duration to determine which method is the least different from, or the most similar to, the actual project duration (PT_6).

The Friedman Test

The Friedman test is a rank-order type of statistical test, which uses blocks (the 36 projects) and treatments (the 6 project time techniques) to determine differences among results. The test procedure is described below:

- Step 1: For each project time treatment (1 through 6), rank the projects from shortest to the longest time.
- Step 2: Assign a rank value to each project time. The shortest project time is assigned a value of 1, ties are assigned half-values. The rankings for all 36 projects are shown in Table 5 (see page 11).
- Step 3: Compute the rank sums, *R*, as shown at the bottom of Table 5.
- Step 4: Compute the Sum of the .
- Step 5: Compute the Friedman number using the equation:

$$F_r = \frac{12}{IJ(I+J)} \sum R_i^2 - 3J(I+1) \cdot \qquad (1)$$

where:
I = number of treatments (project time methods) = 6,
J = number of blocks (projects) = 36, and
$\sum R_i^2$ = sum of the squared rank sums for all treatment = 114,765.5.

For this research, the value of

$$F_r = \frac{12}{(6)(36)(6+1)}(114{,}765.5) - (3)(36)(6+1) = 154.84$$

- Step 6: Determine the Friedman critical value, F_c. Values of F_c are widely available from sources such as Devore (1995). For this study, testing was performed at a 1% level of significance (" = 0.01) yielding: $F_c = 15.085$.
- Step 7: Compare F_r to F_c. When $F_r \geq F_c$ (as is the case here $154.84 \geq 15.085$) then the null hypothesis is rejected, the means are NOT equal, and the Dunnett test is performed.

The Dunnett Test

The Dunnett test is a pairwise test of rank-order values in which the time from each treatment group (project time estimation technique) is compared to the actual project duration (Treatment 6) for this study. The procedure for the Dunnett test is as follows:

- Step 1: Rank order the Rank Sums. These results are shown in Table 6, row 2.
- Step 2: Calculate the value of "p" (row 3). The value of "p" equals the number of columns between the two treatments, including the two columns of the treatments being compared, so from column 1 to 5 = 5, from column 2 to 5 = 4, 3 to 5 = 4, 4 to 6 = 3, and 5 to 6 = 3.
- Step 3: Calculate ΔR_i for each pair, using $\Delta R_i = |R_i - R_6|$ (row 4).
- Step 3: Calculate *SE* using $SE = \sqrt{JI(I+1)/6}$, where *I* and *J* are as previously defined in the Freidman test, so $\sqrt{(36)(6)(6+1)/6} = 15.87$ (r (row 5).
- Step 4: Calculate the Dunnett *q* where $q = \Delta R_i / SE$ (row 6).
- Step 5: Determine the Dunnett critical value q' (row 7), taken from Zar (1974).
- Step 6: Compare q to q' (row 8). When q' is less than q the difference between them is statistically significant (reject the null hypothesis).

Results

The results in Table 6 (see page 12) show that the project time calculated using average production rates (method 1) produces values that are closest (statistically insignificant) to the actual construction time (method 6). In other words, average productivity rates provide the best estimate of construction time. Therefore Hypothesis B is valid.

Table 5. Friedman Ranked Data

		A. Contract Time (Days)						B. Contract Time Ranks					
		Treatments						Treatments					
		1	2	3	4	5	6	1	2	3	4	5	6
Projects (Blocks)	1	11	9	9	11	45	14	3.5	1.5	1.5	3.5	6.0	5.0
	2	63	50	46	61	65	57	5.0	2.0	1.0	4.0	6.0	3.0
	3	32	25	24	31	45	25	5.0	2.5	1.0	4.0	6.0	2.5
	4	24	20	20	23	45	28	4.0	1.5	1.5	3.0	6.0	5.0
	5	50	40	38	48	64	79	4.0	2.0	1.0	3.0	5.0	6.0
	6	59	43	42	58	110	90	4.0	2.0	1.0	3.0	6.0	5.0
	7	89	66	63	88	115	83	5.0	2.0	1.0	4.0	6.0	3.0
	8	95	68	67	94	140	115	4.0	2.0	1.0	3.0	6.0	5.0
	9	11	8	9	10	45	14	4.0	1.0	2.0	3.0	6.0	5.0
	10	61	43	43	60	120	104	4.0	1.5	1.5	3.0	6.0	5.0
	11	33	23	23	31	85	72	4.0	1.5	1.5	3.0	6.0	5.0
	12	43	33	31	42	65	41	5.0	2.0	1.0	4.0	6.0	3.0
	13	62	45	43	61	100	77	4.0	2.0	1.0	3.0	6.0	5.0
	14	15	12	12	15	45	28	3.5	1.5	1.5	3.5	6.0	5.0
	15	63	47	45	61	100	99	4.0	2.0	1.0	3.0	6.0	5.0
	16	93	70	71	88	115	82	5.0	1.0	2.0	4.0	6.0	3.0
	17	35	28	28	34	60	31	5.0	1.5	1.5	4.0	6.0	3.0
	18	30	24	24	29	45	38	4.0	1.5	1.5	3.0	6.0	5.0
	19	72	54	53	71	80	65	5.0	2.0	1.0	4.0	6.0	3.0
	20	62	44	43	61	110	63	4.0	2.0	1.0	3.0	6.0	5.0
	21	73	50	50	70	125	83	4.0	1.5	1.5	3.0	6.0	5.0
	22	43	32	31	42	103	67	4.0	2.0	1.0	3.0	6.0	5.0
	23	18	13	13	17	45	23	4.0	1.5	1.5	3.0	6.0	5.0
	24	41	31	30	40	60	61	4.0	2.0	1.0	3.0	5.0	6.0
	25	31	24	24	29	60	44	4.0	1.5	1.5	3.0	6.0	5.0
	26	39	29	31	37	100	59	4.0	1.0	2.0	3.0	6.0	5.0
	27	33	24	26	31	70	49	4.0	1.0	2.0	3.0	6.0	5.0
	28	30	23	24	28	50	48	4.0	1.0	2.0	3.0	6.0	5.0
	29	40	29	30	37	70	80	4.0	1.0	2.0	3.0	5.0	6.0
	30	13	10	10	12	45	28	4.0	1.5	1.5	3.0	6.0	5.0
	31	57	47	43	56	110	129	4.0	2.0	1.0	3.0	5.0	6.0
	32	35	30	27	34	60	84	4.0	2.0	1.0	3.0	5.0	6.0
	33	8	7	7	8	45	17	3.5	1.5	1.5	3.5	6.0	5.0
	34	58	44	43	58	100	50	4.5	2.0	1.0	4.5	6.0	3.0
	35	14	11	10	14	45	10	4.5	3.0	1.5	4.5	6.0	1.5
	36	51	40	37	50	75	75	4.0	2.0	1.0	3.0	5.5	5.5
							R = Rank Sums =	150.5	61.5	48.5	119.5	210.5	165.5
							R^2=	22650	3782	2352	14280	44310	27390
							$\sum(R^2)$ =	114765.5					

In addition, Table 6 rows 1 and 3 show that Method 1 produces time estimates closer to the actual project duration than does the current process (method 5) used by the project sponsor. Therefore, Hypothesis C is also valid. These results clearly demonstrate what the project sponsors expected, that their current project time estimation procedure over-estimates project time.

It should be noted that even though Method 1 most closely matches actual project times, the project sponsor may choose to use to use Methods 2, 3, or 4, to intentionally calculate a shorter project time. Reasons for shorter project time could be appropriate for projects needing time compression where delay costs could be significant.

Also, note that project times computed using Methods 2 and 3, in Table 6 row 3 (the rank ordered sums, R), are about one third of the time currently required by contractors to complete projects. As a result, choosing either of these methods may cause a shock in the construction community. On the other hand, project time computed using Method 4 is about 70 percent of actual project time. Project time calculated using Method 4 might represent a good compromise time that would keep a contractor on the job until the project was complete but not be so much shorter than current values as to create a serious problem in completing a project.

Implementation Experience

Over the course of the first several months of initial implementation, the CPTES was installed and users in LaDOTD's Contracts Section were trained; full documentation of the CPTES system was also provided, including a "User's Manual," "CPTES Conceptual Design Report," "CPTES System Design Report," "Calculated Production Rate Report," and system code. The CPTES was a welcomed addition to the Project Branch administrator's office. The program was used on just over 100 projects, most of these being relatively simple construction projects. For complex projects, CPTES was used but the defaults were often over-ridden as project managers were somewhat uncomfortable with the production rates and templates.

Although the project sponsor did not keep formal records on how well actual project times compared to CPTES times, users' confidence in CPTES's ability to accurately estimate project times remained high throughout its use, which eventually ended due to lack of system support (Thibodeaux, 2005). However, project sponsors are encouraged to continue the use of formalized project time estimation techniques (FHWA, 2002). Kentucky finished its implementation of a computerized template-based system in 2000 (Hancher & Werkmeister). Texas originally implemented the Hancher et al. system (1992), and continues its use today (Chong, 2005). And recently, the State of Virginia implemented a computerized template-based system (R. C. Williams, 2006). In addition, manual approaches similar to the template-based approach for project time estimation are recommended for use in information systems projects by Hallows (2005), Schwalbe (2006), and Lewis (2001).

Conclusions and Recommendations

This study demonstrates the feasibility and the validity of a template-based system as follows: 1) This study recommends the use of a mostly deductive approach for categorizing template sets; 2) The study finds that a "critical train" of activities can reasonably be determined by a consensus of project managers; And, 3) The study finds that daily mean estimates of productivity provide a "robust" estimate of overall productivity and total project times. These methods are strongly recommended as the preferred methods to calculate project time estimates. These findings are consistent with those found by Herroelen and Leus (2001) in their analysis of the critical chain scheduling.

This research substantiates the idea that project time estimation procedures overestimate construction time, providing no real understanding of the dynamic nature of projects, and therefore providing too much buffer in the project time estimate, and the conclusion is consistent with the work of Davenport (1999). Historically, Louisiana projects use about 80 percent of the available project time to complete construction, as shown in Table 6 row 3. Project time calculations should be based on statistically determined production rates, using procedures demonstrated in this research; these production rates need continual updating as construction techniques change. Adopting a more quantitative method will ensure that, when current personnel retire or change positions, new personnel can become familiar with the system with minimum disruption and variation in project time estimation.

Table 6. Results from the Dunnett's Test comparing results from different contract time estimation methods with actual construction time

	Rank:	1	2	3	4	5	6
1	Contract Time Methods	3	2	4	1	6	5
2	R	48.5	61.5	119.5	150.5	165.5	210.5
3	p	5	4	3	2	—	2
4	$\Delta R_i = \lvert R_i - R_6 \rvert$	117.0	104.0	46.0	15.0	—	45.0
5	SE	15.87	15.87	15.87	15.87	—	15.87
6	q	7.37	6.55	2.90	0.95	—	2.84
7	q'	3.00	2.92	2.79	2.58	—	2.58
8	Result	Reject Ho	Reject Ho	Reject Ho	Accept Ho	—	Reject Ho

Additional trials are needed to study complex projects (that 10% left out of the templates), which still use *ad hoc* subjective methods to estimate project time (Thibodeaux, 2005). For these types of projects, "robust" schedules may require the use of more advanced techniques, such as Critical Chain Scheduling and Buffer Management (Goldratt, 1997) or other advanced methods, see Demeulemeester and Herroelen (2002).

One major problem encountered in this study, as in others (Demeulemeester & Herroelen, 2002; Herroelen, 2005), is the challenge of getting the project sponsor to use a new estimation technique. In this study, the project sponsor (LaDOTD) could not provide the technical computer support needed for a stand-alone, *ad hoc* computer system. Support was needed to create an interaction between the scheduling software, a knowledge base, and a database, a concept similarly demonstrated by R. C. Williams (2006).

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