AN EXPERT SYSTEMS APPROACH TO HIGHWAY CONSTRUCTION SCHEDULING

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Abstract

In this study, the authors conducted a study for a Midwestern state department of transportation (DOT) to determine ways to improve the accuracy of the engineer's estimate of time required on highway construction projects. The goal of the project was to assist design engineers in developing more realistic construction schedules for a wide variety of projects. Expert input was obtained through interviews with highway contractors, resident engineers (REs), engineering design consultants, DOT design and construction engineers, and from records of completed projects as captured in RE's diaries and other project documentation. The results of the data collection were used to create 12 scheduling templates containing the pay items that controlled the completion of the project (controlling items). The templates were incorporated into software that was developed as part of the study. Schedules developed using the templates were validated in testing by DOT design engineers and technicians using record data from completed projects.

Introduction

Construction scheduling is a complex process that requires an intimate knowledge of construction methods, materials, and equipment and production capability for the individual work activities required to complete a project. Experience teaches construction schedulers how to assess the impact of weather, labor relations, subcontractor qualifications and crew productivity, material availability and other factors, and which work activities can be done concurrently. Contractors typically identify all project work activities, their duration and the relationships among them in order to find the activities that define the project's critical path.

Engineers who prepare plans, specifications and estimates (PS&E) for state departments of transportation are responsible for establishing the contract time allowed for completion of the work. Their estimates of time are typically based on pay items—major components of the work that are related to the specifications and form the basis for measurement and payment but may not represent individual work activities. While many DOT engineers have significant scheduling experience, new hires may have less field experience on which to base their selection of pay items that control the progress of the work (controlling items). One Midwestern state DOT identified the loss of institutional knowledge as a potential problem and requested research to examine ways to improve engineers' scheduling capabilities, including the proper selection and ordering of work items.

One solution to the problem would be to capture the experience of the retiring engineers who had years of estimating and scheduling experience. Chu and Hwang [1] stated many knowledge-based systems have been proposed with the knowledge from a single expert in the given field of study. However, since experts may have different experiences and knowledge in the same area, it would be advantageous and necessary to elicit and integrate knowledge from several of these experts to develop an effective expert system.

Expert systems provide a means for retaining institutional knowledge. Through the use of expert interviews, a knowledge-based model or template was created. A novice may then use the tool to solve current problems. Ismail et al. [2] proposed a computer-based expert system capable of using data from interviewed runway pavement engineers to detect pavement distress, diagnose causes of failure and recommend the most cost-effective repair strategies. Several studies have been done in the area of cost estimation to help improve estimating strategies and improve cost control and time and budgetary constraints [3-4]. Similar studies have been found inside the field of highway construction [5-7], but they focus on building parametric cost models rather than scheduling systems. A recent study used a reliability-based approach to help identify structurally deficient bridges and help prioritize the need for their repair or replacement [8]. And while other studies have identified a need for improved highway scheduling techniques [9-10], including the creation of typical models [11], no studies were found that created highway construction scheduling templates using common controlling pay items.

Researchers, acting in consultation with a project technical review panel (TRP)—made up of seven subject-matter experts from a Midwestern state's DOT and the Federal Highway Administration (FHWA)—conducted a study to determine ways to improve the accuracy of engineers' estimates of time required on DOT projects. The goal of the project was to assist design engineers develop more realistic construction schedules for a variety of typical DOT projects by capturing expert input from a variety of sources, including highway contractors, resident engineers (RE), consultants and the records of completed projects as recorded in the RE's diaries and other project documentation. Additional inputs included historical weather records, DOT standard specifications, recurring special provisions and design memoranda. This expert knowledge was used to create highway construction scheduling templates that contain the controlling items of work for twelve common highway and bridge construction projects. The development, testing and implementation of these schedules are discussed here.

Methodology

The research team obtained expert knowledge by interviewing construction professionals to determine best practices in planning the sequence and estimating of the duration of a wide variety of typical highway construction operations. DOT engineers and engineering consultants who routinely prepare plans, specifications and estimates (PS&E), and resident engineers who have experience administering DOT contracts were also interviewed to illuminate designers' strategies in project planning and scheduling. Using PS&E from typical road construction projects in the subject state, the research team documented the method of approaching the initial project planning from both the engineers' and the contractors' perspectives in preparing templates for planning and scheduling activities that lead to a probable schedule duration.

The researchers interviewed personnel at highway construction firms in two states, consultants, and DOT design engineers and resident engineers. Personnel from seven highway construction firms were interviewed regarding the procedures used in developing construction estimates and schedules, productivity rates on key items of work such as earthwork, concrete paving and asphalt paving, and factors that affect productivity either positively or negatively.

The engineer's perspective on construction scheduling was obtained by interviewing designers at a large consulting firm that performs work for the DOT and drawing upon the research team's professional engineering and scheduling experience. In addition, the seven engineers who were members of the TRP were instrumental in providing information to the researchers, including plans, specifications and estimates of time required for projects of varying complexity, and initial schedules and resident engineer's daily reports for a variety of completed projects.

Eight DOT resident engineers were interviewed during a half-day group working session to determine the potential for using project documentation as an additional source of information regarding controlling items of work, measurement of quantities of work put into place, typical sequencing of work, and the type and amount of equipment and manpower on the job each day. Another significant source of information was the project documentation found in the state's Construction Record System (CORS) database. The researchers were able to use the CORS data on completed projects to develop information on typical construction sequencing and productivity for those pay items that controlled the progress of the work (controlling items).

Results

Contractor Perspective

None of the contractors who participated in the study reported creating detailed or formal construction schedules as a separate exercise from the bidding process. Instead, the project's duration develops as a function of several key variables that are addressed while bidding, including, but not limited to:

- Quantity of major items of work to be self-performed by the bidder
- Availability of subcontractors to perform designated items of work
- Proximity of project to home office or other ongoing projects
- Availability of equipment and labor needed to perform the work
- Likely competitors for the work
- Backlog of work by the bidder
- Amount of time allowed in the contract documents

The bidding process is typically conducted in a short time frame in comparison to the time devoted to developing the plans, specifications and engineer's estimate. When projects are put out for bid, the contractor has a relatively short amount of time—typically on the order of one month—in which to examine the projects on the upcoming letting, determine which projects are a good fit for the firm, and make the decision to bid. For those projects selected, the contractor may have less than one week to perform the bid calculations and assemble the bid documents and schedule.

A commonly reported process was that a primary estimator works with a group of key personnel to outline the parameters of the project and begin working on the estimate. Because each project is unique, team members rely on experience and good communication to help identify important items that will affect the estimate. The primary estimator reads the bid documents, paying particular attention to the special provisions to identify unique requirements or restrictions. Environmental requirements and the soils report or soil boring information provided in the plans are considered key pieces of information. The estimator must have complete familiarity with the specifications, how each bid item is measured for payment, and what is included as incidental to each bid item.

Potential weather conditions are considered key in development of the project estimate. The estimator typically visits the National Oceanic and Atmospheric Administration (NOAA) or other weather reporting service website to determine the likely number of rain days per month during the project period.

Other team members verify the plan quantities, with particular attention to the items that involve the largest quantities, such as earthwork or paving. Verifying plan quantities is not the same as estimating. For example, to determine the price per foot to install a pipe culvert, the estimator must consider and price such things as the size of pipe and its depth, survey layout of the pipe, the need for trench shields, trench bracing or trench dewatering, granular backfill, and protection of adjacent utilities, among other factors. Plan quantities for this example would only include the linear feet of pipe and not provide for additional items and logic.

Depending on the size of the project, an experienced person typically visits the site and confirms key physical constraints such as stream crossings, access roads with weight or height restrictions, location of overhead utility lines or other obstructions that may impact crane or other equipment operations, traffic conditions, type and size of trees to be removed, soil, groundwater and potential flooding conditions, location of potential borrow or waste sites, equipment staging areas and other conditions. Resources such as Google Earth or other mapping utilities may be used to supplement or substitute for a site visit, depending on the complexity of the project.

Additional constraints are identified, such as requirements for night work, air and water quality permits, relative location, prices, billing terms and production capabilities of key material suppliers, noise, dust, or other daily or seasonal restrictions on construction operations, protection of endangered species or other environmental restrictions on construction operations and others. While some firms indicated use of a checklist of general items, most acknowledged that an understanding of the extent and potential impact of various constraints is developed through experience.

Depending on the firm's capabilities, the major items of work to be self-performed versus subcontracted are identified and estimators begin to work on obtaining subcontractor bids and material quotes. One of the most time-consuming functions is examining each pay item and identifying all the work activities required to execute that item. Most work activities require equipment, labor and material. As each work activity is identified, the estimator begins to "build" the crews required to complete the work. Crews are typically built around major functions such as long- and short-haul earthwork, pipe installation and paving. The equipment needed to perform each work activity is determined and production rates are computed based on fundamentals such as creating a mass diagram, determining haul distance, estimating loading time for trucks and scrapers, and finding total cycle time for travel. Resources such as the Caterpillar Handbook are used to determine the capability of equipment, but historical records and "rule of thumb" production rates are also used to get quick estimates of time required.

Contracting firms typically do not have a person whose primary job title is "scheduler." The project schedule is developed as an outgrowth of the estimating process as the office personnel (project manager and senior estimator) and field personnel (key superintendents and foremen) reach consensus on how the project will be built (methods), how the project will be executed (order of operations, application of available resources, concurrent and sequential activities), and how long the project will take (schedule). This consensus is typically developed in a pre-bid meeting in which the key personnel validate the estimate and make the final decision to commit to the numbers.

Most estimators keep track of concurrent activities mentally unless a project is complex. Creation of a bar chart schedule helps visualize the possible concurrent activities and identify the critical path and the early finish date or number of days likely to be required for the project, but formal schedules are not widely used unless required for submittal. Instead, the single most important factor in determining the construction schedule is how much time is allowed in the contract documents, and whether there are incentives for finishing sooner. This insight returns the burden for realistic construction scheduling to the engineers who create the contract documents and establish the contract time.

Determination of Contract Time

The engineer is charged with determining a reasonable time to complete the project. Contract time can be stated in terms of working days, calendar days, a completion date, or some combination of these. Calendar days and working days are defined in the state's standard specifications. Calendar days are every day shown on the calendar. Working days are calendar days with the exception of Saturdays, Sundays and holidays that are recognized by the contractor's entire workforce statewide, from May 1 through November 30. The period December 1 through April 30 is the winter exclusion period for this state during which time the contractor may perform work as long as specified restrictions regarding temperature or weather conditions are not violated, without working days being charged against the contract time. This practice of the winter exclusion is typical of northern states, although the beginning and ending dates vary by state.

As described in the state's design manual, the number of days required for each item is obtained by dividing each quantity by its respective production rate. The production rates are published in the manual for some major work activities. Engineers are encouraged in the manual to determine a logical order of work activities and to consider which activities can be performed concurrently. The designer determines the total days required and days not affecting time limit and creates the estimate of time required. A bar or arrow diagram comprised of major pay items is used to help determine the critical path and activities that will be controlling versus those that will not affect the early completion date.

Controlling Items and Scheduling Templates

A key aspect of the research was the development of scheduling templates that synthesized the knowledge gained from the diverse expert sources. The results of the research indicated that many highway projects share the same controlling items and that many common construction activities do not affect the overall project duration. A decision was made in consultation with the project TRP to develop project templates using only controlling items. In order to standardize the terminology used to describe these controlling items, the terms used for the production rates given in the state design manual were selected. Terms describing the construction of "bituminous" pavement were updated to Hot Mix Asphalt (HMA) pavement to reflect current terminology used in the state's supplemental specifications, recurring special provisions and construction inspection checklists. Terms describing sub-tasks in bridge construction were also added.

Table 1 shows the final list of 49 controlling items selected to form templates covering the construction of the most common types of highway projects in the state, as determined by the project TRP. Table 2 shows the 12 project types for which scheduling templates were developed.

The templates were incorporated into software that was developed as part of the study. Users input values or accept defaults for parameters such as the anticipated start date, projected number of working days per month, and the winter exclusion period of December 1 through April 30. Historical temperature and rainfall records can be selected to allow users to study the impact of various start dates, the likely project-specific weather throughout the calendar year, and other project-specific constraints such as protection of bat habitats or restrictions on road closure dates. An example template and associated schedule for Roadway Reconstruction are shown in Figure 1.

The 12 suggested templates may be modified by deleting unnecessary controlling items or by adding controlling items from the list in Table 1. Because the templates are constructed using only controlling items, the user can quickly generate a project schedule and estimate the project completion date, number of working days and number of calendar days. Assumptions can be easily changed to study the impact on the completion date. A complete list of the controlling items contained in each template is given in Appendix A.

Each template will generate a bar chart project schedule showing only the controlling items. Concurrent activities that may be required to complete the project but are not likely to impact project completion date are not shown. The use of standard templates allows the designer to easily modify the base parameters and study the impact on the number of working days and completion date.

Conclusion

The goal of the project was to develop scheduling templates to assist designers in the creation of more realistic construction schedules for typical highway construction projects. The knowledge input for the software tool included contractors, design engineers, resident engineers, consultants, historical project records and published research on highway construction scheduling. The research approach was to focus on controlling items for a set of typical highway construction projects. Scheduling templates for 12 types of road and bridge construction projects were developed from a list of 49 controlling items that were selected in consultation with subject-matter experts based on an examination of historical project records. The templates created during this study will allow a more standardized approach to highway construction scheduling, thereby providing design engineers across the state with standard project templates. The software tool provides flexibility for designers to modify templates and to create and share new templates developed over time.

Table 1. Controlling Items for Development of Scheduling Templates

Borrow Excavation	PC Concrete Pavement
Bridge Approach Pavement	Pipe Under-drains
Checkout / Acceptance	Place Abutment
Class A Patching	Place Bridge Deck
Class B Patching	Place Pier Cap
Class C / D Patching	Place Pile Cap
Concrete Curing	Place Columns
Concrete Structures	Precast Box Culverts
Concrete Superstructure	Precast Concrete Beam Erection
Curb / Gutter – Drainage	Precast Concrete Bridge Deck
Deck Slab Repair (Partial Depth)	Process Lime Stabilized Soil
Driving Piles	Raised Reflective Pavement Markers
Earth Excavation	Removal of Existing Concrete Deck
Earth Excavation (Shoulders / Widening)	Removal of Existing Substructure
Fabricate Bridge Deck Formwork	Removal of Existing Superstructure
Fabricate Bridge Deck Reinforcing	Seeding
Gravel or Crushed Stone Base Course	Stabilized Sub-base
Gravel or Crushed Stone Shoulders	Steel Plate Beam Guardrail
HMA Pavement	Storm Sewers (Dependent on size, depth)
HMA Shoulders	Strip Reflective Crack Control
HMA Surface Removal	Thermoplastic Pavement Marking (Hand)
HMA Pavement Removal	Thermoplastic Pavement Marking Symbol
Mobilization	Traffic Control
Paint Pavement Marking (Hand)	Tree Removal
Paint Pavement Marking (Truck)	

A follow-up study could attempt to collect the opinions of users to help improve the current set or create additional sets of templates. In addition to improving the tools for existing users, other state DOT designers could be questioned about the use of controlling items in creating such templates. Another national study could be completed to validate the model in regards to the contractor's perspective. In addition to the templates, researchers could re-examine their state's winter exclusion periods. Perhaps these periods are outdated and do not reflect technological advances in materials and equipment.

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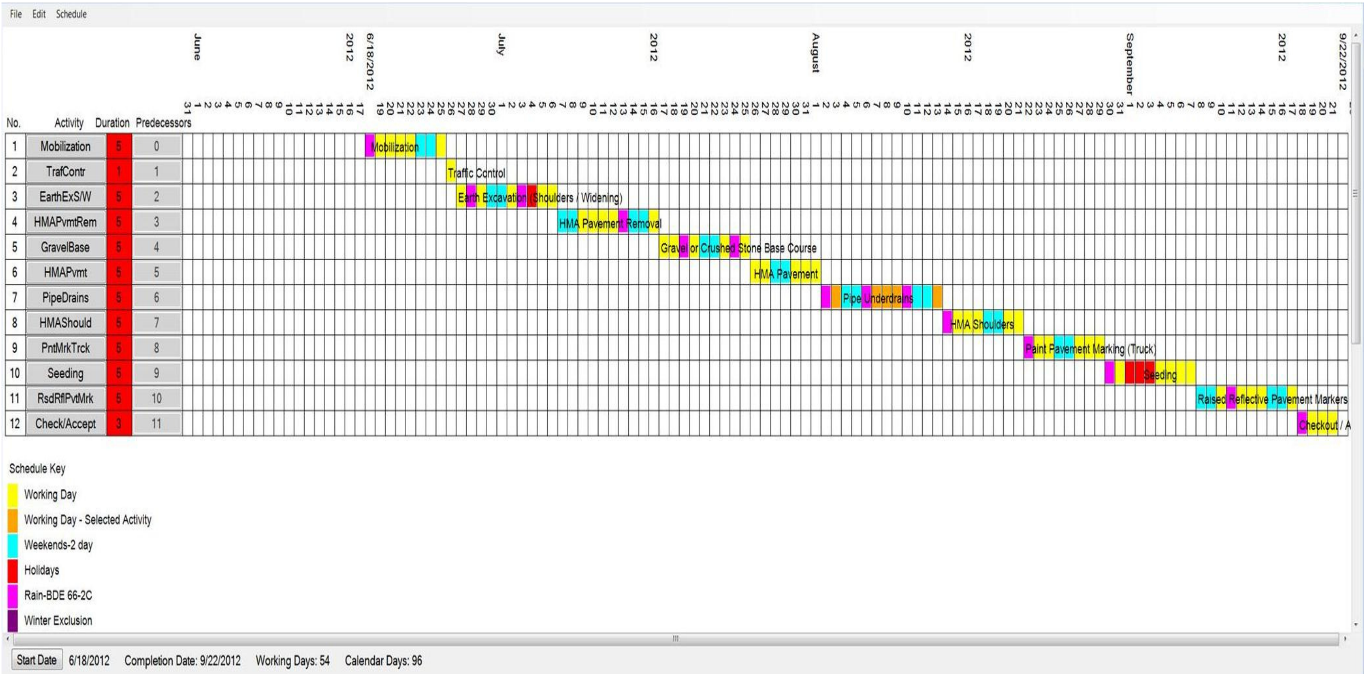
Table 2. Scheduling Templates Developed

1. Roadway Rehabilitation	**4. Intersection Reconstruction (Continued)**	Checkout / Acceptance
Mobilization	Earth Excavation (Shoulders / Widening)	**9. Bridge Rehabilitation:**
Traffic Control	Stabilized Sub-base	Mobilization
Class C / D Patching	HMA Pavement	Traffic Control
HMA Surface Removal	Thermoplastic Pavement Marking Symbol	Class C / D Patching
HMA Pavement	Seeding	HMA Surface Removal
Pipe Underdrains	Checkout / Acceptance	HMA Pavement
HMA Shoulders	**5. Interchange with Bridge Replacement:**	Paint Pavement Marking (Hand)
Paint Pavement Marking (Truck)	Mobilization	Checkout / Acceptance
Checkout / Acceptance	Traffic Control	**10. Bridge New Construction:**
2. Roadway Reconstruction:	Earth Excavation (Shoulders / Widening)	Mobilization
Mobilization	HMA Pavement	Traffic Control
Traffic Control	Replace Structure - Series	Bridge Substructure - Parallel
Earth Excavation (Shoulders / Widening)	HMA Pavement	Precast Concrete Beam Erection
HMA Pavement Removal	Paint Pavement Marking (Truck)	Precast Concrete Bridge Deck
Gravel or Crushed Stone Base Course	Seeding	Steel Plate Beam Guardrail
HMA Pavement	Steel Plate Beam Guardrail	Earth Excavation (Shoulders / Widening)
Pipe Under-drains	Checkout / Acceptance	Process Lime Stabilized Soil
HMA Shoulders	**6. Grading:**	Stabilized Sub-base
Paint Pavement Marking (Truck)	Mobilization	Bridge Approach Pavement
Seeding	Tree Removal	HMA Pavement
Raised Reflective Pavement Markers	Precast Box Culverts	Seeding
Checkout / Acceptance	Earth Excavation	Paint Pavement Marking (Hand)
3. Roadway New Alignment:	Checkout / Acceptance	Checkout / Acceptance
Mobilization	**7. Bridge Repair and Deck Overlay:**	**11. Patching & Resurfacing – PCC:**
Tree Removal	Mobilization	Mobilization
Earth Excavation	Traffic Control	Traffic Control
Process Lime Stabilized Soil	HMA Surface Removal	Class A Patching
Gravel or Crushed Stone Base Course	Deck Slab Repair (Partial Depth)	Strip Reflective Crack Control
HMA Pavement	HMA Pavement	HMA Pavement
Pipe Under-drains	Thermoplastic Pavement Marking (Hand)	Thermoplastic Pavement Marking (Hand)
HMA Shoulders	Checkout / Acceptance	Raised Reflective Pavement Markers
Paint Pavement Marking (Truck)	**8. Bridge Reconstruction:**	Checkout / Acceptance
Thermoplastic Pavement Marking Symbol	Mobilization	**12. Patching & Resurfacing – HMA:**
Seeding	Traffic Control	Mobilization
Raised Reflective Pavement Markers	Earth Excavation (Shoulders / Widening)	Traffic Control
Checkout / Acceptance	HMA Pavement	Class C / D Patching
4. Intersection Reconstruction:	Replace Structure - Series	HMA Surface Removal
Mobilization	HMA Pavement	HMA Pavement
Traffic Control	Paint Pavement Marking (Truck)	Thermoplastic Pavement Marking (Hand)
HMA Pavement Removal	Seeding	Raised Reflective Pavement Markers
Storm Sewers (Dependent on size and depth)	Steel Plate Beam Guardrail	Checkout / Acceptance

Figure 1. Scheduling Template for Roadway Reconstruction



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