Development and Application of a Production-Rate Resource for Contract Time Determination

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Abstract: Work item production rates are essential for contract time determination (CTD) procedures as they are used to estimate the duration of activities needed to complete a highway construction project. For this reason, varied sources and estimation systems provide production-rate data for a variety of work items. Yet these data sources are disjointed and do not provide for any side-by-side comparison of data. This research focuses on the development of an integrated *Production Rate Resource*, a single, easy-to-use reference of production-rate data gathered from publicly available sources. The resource was developed by gathering production-rate information from multiple sources and organizing the found data into a well-assembled Excel workbook. A proposed process for conducting CTD using the resource is included. The gathered information was tested by estimating the contract time of highway projects using the recommended process. Findings from the application led to significant improvements to the resource. The final version of the *Production Rate Resource* provides integrated production-rate data for 59 highway construction work items and a recommended process for conducting contract time estimation.
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Introduction

Contract time determination (CTD) is needed to establish the maximum duration of federally funded roadway construction projects required for contract preparation and administration. Project activities are scheduled to estimate the appropriate timeframe within which the construction of a project can be executed, ensuring timely delivery. The determination of appropriate activity production rates is essential for conducting an adequate time estimate.

The Texas Department of Transportation (TxDOT) generally relies on TxDOT's CTD System (TXCTDS), a system that was developed in the 1990s. The authors initiated a comparative analysis of production rates sourced from systems and knowledge bases available in the public domain to assess the current state of contemporaneous CTD practices.

The outcome of this effort is the *Production Rate Resource*, a reference that compares the production rates of 59 major construction work items provided by six publicly available sources. The result is a single, easy-to-use database of production rates for CTD practitioners drawing on a variety of sources.

The main objective of this research was to review the tools and techniques in use by various US public-sector entities responsible for the delivery of roadway construction projects and to create a single database resource of production-rate data from a range of systems and knowledge bases in the public domain. To achieve this main objective, this work first conducted a literature review to identify relevant, publicly available sources that would provide production-rate data and review important work items for CTD procedures. Furthermore, a process for conducting a contract time estimation using the developed resource was established. Finally, the collected production rates were tested through conducting contract time estimations of two TxDOT highway construction projects.

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Literature Review

Importance of Production Rates in CTD

Studies conducted by the Transportation Research Board to develop systems for estimating contract durations of highway construction projects concluded that "realistic production rates are the key in determining reasonable contract times" (Herbsman and Ellis 1995). This fact is evidenced by the vital use of production rates in various CTD techniques and the inclusion of production-rate baselines in multiple Department of Transportation (DOT) CTD systems.

The Federal Highway Administration (FHWA) Guide for Construction Contract Time Determination Procedures (2002) states that establishing production rates for each controlling item and adopting production rates to a particular project are essential elements in determining contract time. The FHWA also states that two CTD techniques—bar charts and the critical path method (CPM)—rely on using production rates to determine activity durations as part of their respective processes. Moreover, the guide states that "production rates may vary considerably depending on project size, geographic location, and rural or urban setting, even for the same item of work" and that "production rate ranges should be established in the State's written procedures based on project type (grading, structures, etc.), size, and location for controlling items of work."

State Department of Transportation Systems

Hancher et al. (1992) developed TxDOT's CTD System (TXCTDS). The bar chart scheduling system allows the user to

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supply a project's work item quantities and production rates to establish the project's duration. The system provides a production-rate baseline developed through surveys sent out to other DOTs, TxDOT district engineers, and Texas highway constructors.

Jeong et al. (2008) developed Oklahoma DOT's CTD System (OKCTDS). The researchers analyzed each considered activity and their production rates executed in recently completed projects and consulted with project engineers and schedulers to develop a database of 58 controlling activities.

Hancher and Werkmeister (2000) created the Kentucky CTD System (KYCTDS). The researchers relied on historical data and project engineers' experience to develop a production-rate baseline composed of 38 controlling activities with their respective ranges (lower limit, average, and upper limit).

Florida DOT's *Guideline for Establishing Construction Contract Duration* (Florida DOT 2010) dictates the establishment of a production-rate database "by using normal historical rates of efficient contractors."

Other DOTs, in states such as Idaho Transportation Department (2011), Iowa Department of Transportation (2016), Illinois Department of Transportation (2010), and Wisconsin Department of Transportation (2015), provide CTD specifications containing production-rate databases.

Other Production-Rate Databases

O'Connor et al. (2004) developed the Highway Production Rates Information System (HYPRIS), a database system that provides production rates based on observations from ongoing projects throughout Texas. The system provides observed production-rate ranges for 26 work items, including variations when particular drivers were present (i.e., work zone area size and weather conditions).

The *RSMeans Heavy Construction Cost Guide 2016* (Hale et al. 2015) is a well-known cost estimation resource composed of a significant quantity of work items related to big projects, such as highways and airports. To calculate costs, the guide includes the daily output, defined as "the amount of work that the crew can do in a normal 8-h workday, including mobilization, layout, movement of materials, and cleanup."

Previous Research on Production-Rate Databases

Despite identifying plenty of production-rate information within CTD systems and sources, few have attempted to compare production-rate data across the sources. O'Connor et al. (2004) compared their observed production rates with TXCTDS's baseline. However, the researchers do not reflect this comparison specifically in the HYPRIS system. Atreya (2007) compared Oklahoma DOT's production-rate ranges with information provided by Oklahoma contractors and with *RSMeans Cost Guide* 2007 averages. Furthermore, they compared various state CTD systems, contrasting particularities, such as how they use production rates, the logical flow of activities, and adjustment factors. Nevertheless, the OKCTDS system does not compare its production rates with other sources.

Plan for Developing the Resource

Scope and Limitations

The work was limited to the CTD systems and production-rate databases available in the public domain. The following production-rate sources were chosen: TXCTDS, HYPRIS, OKCTDS, KYCTDS, Florida DOT's *Guideline for Establishing Construction Contract Duration* (FLDOT), and the *RSMeans Heavy Construction Cost Guide 2016* (RSMeans). Only the base production rates were extracted from the selected sources, excluding modifiers such as sensitivity and adjustment factors.

Moreover, the scope specifications provided for each work item were exclusively extracted from definitions, descriptions, and scope information within each source and its corresponding state's DOT specifications book.

Uses and Desired Outputs

The *Production Rate Resource* was designed as a simple, easy-to-use source of production rates for CTD, compiling data from many sources in one single reference. Ideally, its user is able to compare the provided data and select the appropriate production rate for a desired work item. Alternatively, the user may use the breadth of information in the resource to estimate an activity's production rate using a triangular or beta distribution. The compiled resource provides the collected production rates in high, mean, and low values and displays averages for these three values while containing graphics for visual aid and scope tables detailing what each source considers included within the work item's scope.

Research Methodology

Fig. 1 illustrates the methodological process followed in conducting this research. First, clear objectives and scope limitations were established. A literature review was then conducted to select the appropriate publicly available production-rate sources and identify essential work items for CTD procedures.

Next, a prototype was designed for creating the item worksheets, which are Microsoft Excel sheets that contain the collected production-rate data for each work item, including scope information and visual aid graphics. item worksheets' averages were used to estimate the contract time of actual highway projects to analyze the collected data and consider the inclusion of more production-rate sources and work items. These inclusions resulted in improving the Item Worksheets.

To create the final resource, the new item worksheets were assembled, incorporating introductory and summary Excel sheets. The process concluded with developing a research report, documenting all activities involving the development of the *Production Rate Resource*.

Structure of the Resource

The *Production Rate Resource* encompasses the production-rate data of 59 highway construction work items. The resource is composed of sequential Microsoft Excel tabs beginning with an introduction tab, followed by the sources tab, the summary tab, and all item worksheets. Fig. 2 illustrates the described structure.

Introduction Tab

The introduction tab briefly welcomes the user to the *Production Rate Resource*. It begins with describing the resource's purpose and identifying the public domain sources used for its development. The next paragraph explains the production-rate information found in each of the item worksheets and describes how the user can select the appropriate production rates. The tab concludes summarizing the resource's content in a bullet-point scheme.

Sources Tab

The sources tab identifies the publications and databases from which the production rates were extracted. It includes the parts of each source that detail the production rates and how they were

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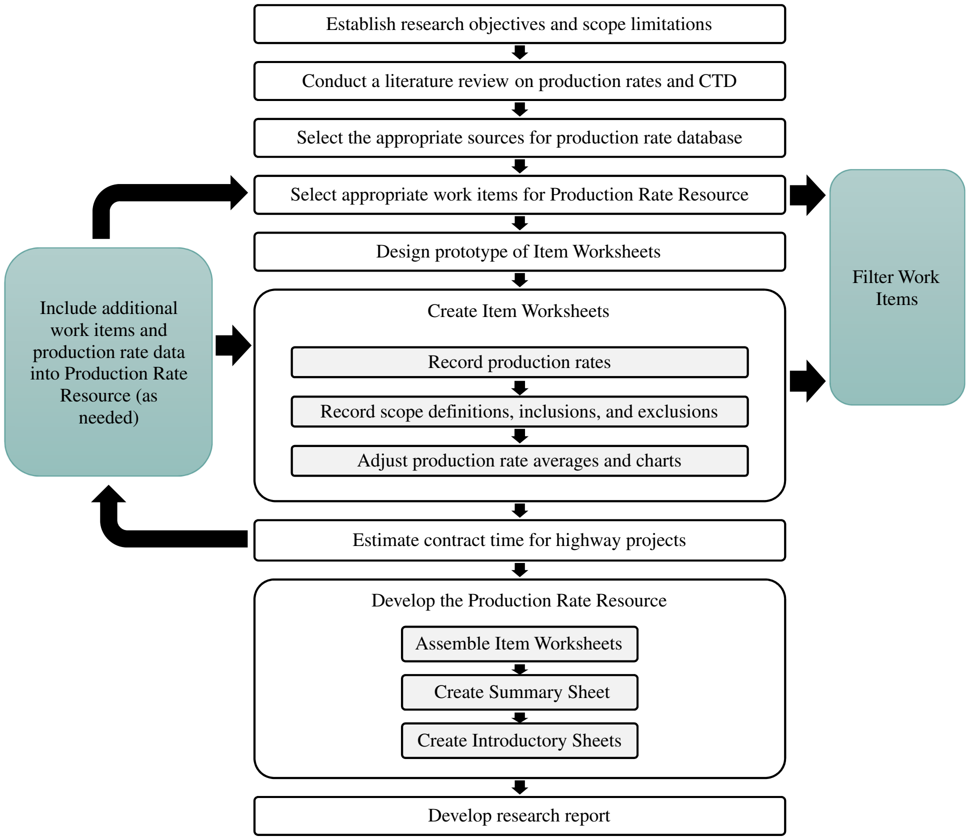

Fig. 1. Research methodology flowchart.

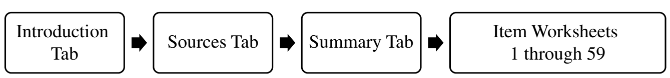

Fig. 2. *Production Rate Resource* structure.

interpreted to be introduced in the resource. Furthermore, this tab specifies scope sections that provide definitions, inclusions, and/or exclusions for each work item.

Summary Tab

The summary tab encompasses all the work items included in the resource and the respective production rates from each of the original sources in a list format. The table also contains the calculated averages, in low, mean, and high categories. Fig. 3 shows a screenshot of the summary tab.

Item Worksheets

The item worksheets are the main content of the *Production Rate Resource*. Each worksheet tab contains all production-rate information recollected for each work item and includes a production-rate table, a comparison chart, a range chart, and a scope table. Fig. 4 contains a sample of an item worksheet.

The production-rate table displays the gathered production rates. Each column represents the original sources, presenting the units and low, mean, and high production rates. The final column expresses the average production rates.

The comparison chart juxtaposes the low, mean, and high production rate values from each source and the calculated averages. The column chart allows the user to compare the variance of production-rate values between the different sources.

The range chart helps the user visualize the ranges for which the different sources consider production rates to be low, mean, or high, expressed in box and whiskers plots.

The scope table contains the scope limitation descriptions provided by the original sources and the original units used with the corresponding conversions when applicable.

Application of the Resource

Resource within CTD Processes

A contract time estimator can reference the *Production Rate Resource* to select production rates assisted with visual aid graphics and scope information tables. The low, mean, and high values are associated to productivity factors (e.g., work space and crew size) and depict the range limitations suggested by each source. The calculated averages provide reference points for comparing data variations. The estimator can benefit from having this information in activity-duration calculations for bar chart and CPM estimation procedures.

The estimator can also use the *Production Rate Resource* as a complementary reference to a desired system's baseline, providing data for excluded work items and a comparison benchmark for the included work items. Systems like TXCTDS and KYCTDS allow the inclusion of additional work items and production rates, making the *Production Rate Resource* an ideal supporting source.

Recommended CTD Process

Fig. 5 illustrates a flowchart of the recommended procedure for conducting a CTD using the *Production Rate Resource*. It covers

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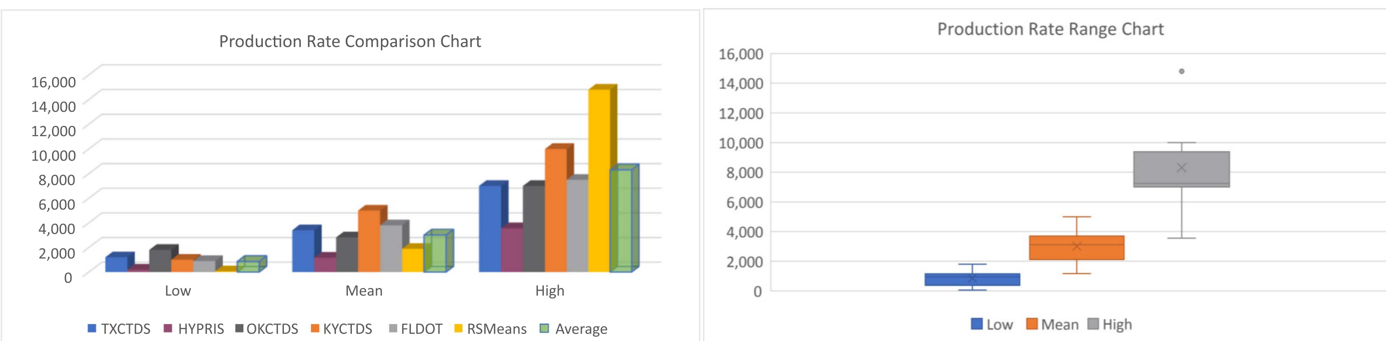
Production Rate Resource: Summary sheet

TXDOT Work Item #	Work Item Description	Units	TXCTDS			HYPRIS			OKCTDS			KYCTDS			FLDOT			RSMeans			Averages		
			Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean	High
-	Erect temporary bridge	Days	10	15	25	-	-	-	-	-	-	5	8	10	-	-	-	-	-	-	8	12	18
-	Phasing allowance	Days	-	-	-	-	-	-	1	2	5	1	3	5	-	-	-	-	-	-	1	3	5
100-1	Preparing Right of way - Clear and Grub	Acres	1	3	6	-	-	-	Inconsistent Units			1	3	6	1	-	10	0.1	2.4	10	0.8	2.8	8.0
104-1	Removing concrete - Remove old curb and gutter	LF/Day	600	1200	2000	-	-	-	-	-	-	-	-	-	-	-	-	275	380	528	438	790	1264
104-2	Removing concrete - Remove old Sidewalks	SY/Day	350	700	1100	-	-	-	-	-	-	-	-	-	1500	2500	3500	112	185	350	654	1128	1650
105	Remove old pavement	SY/Day	1000	2000	3000	-	-	-	1200	1900	2600	-	-	-	-	-	600	200	441	690	800	1447	1723
110	Excavation	CY/Day	1200	3400	7000	199	1163	3558	1800	2825	7000	1000	5000	10000	900	3800	7500	65	1887	14800	861	3013	8310
110-1	Rock Excavation	CY/Day	500	1100	1500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	500	1100	1500
132	Embankment	CY/Day	1200	3500	7000	249	1097	3000	-	-	-	800	4000	8000	-	-	-	1300	3309	10000	887	2977	7000
164	Seeding and landscaping	SY/Day	2000	4000	7000	-	-	-	7,744	11,616	18,392	2000	4000	7000	-	23500	-	-	-	-	3915	10779	10797
247	Flexible Base	SY/Day	1500	3000	4500	526	2725	5624	Inconsistent Units			Inconsistent Units			-	-	-	3800	4891	6000	1942	3539	5375
260	Lime Treated Base	SY/Day	2000	4000	6000	82	1563	3722	1900	2500	4600	-	-	-	-	-	-	1550	1683	1800	1383	2437	4031
276	Cement Treatment	SY/Day	1500	3000	4500	1416	4050	6500	-	-	-	-	-	-	-	-	-	960	1037	1100	1292	2696	4033
292	Hot mix asphalt base	TON/Day	500	1200	2000	-	-	-	270	1000	1700	500	1200	2000	-	-	-	1000	1235	1400	568	1159	1775
316	Asphalt surface treatment	SY/Day	30000	50000	70000	-	-	-	-	-	-	-	-	-	20000	-	25000	-	-	-	25000	50000	47500
340	Hot mixed asphalt	TON/Day	500	1200	2000	158	817	1460	440	900	1600	400	1000	1500	-	-	-	290	502	900	358	884	1492
354	Milling/Planing	SY/Day	5000	10000	14000	-	-	-	-	-	-	-	-	-	-	8000	-	4000	7071	12500	4500	8357	13250
358	Asphalt pavement repair	SY/Day	100	200	300	-	-	-	-	-	-	Inconsistent Units			-	-	-	-	-	-	100	200	300
360	Concrete Pavement	SY/Day	1000	3000	5000	462	1253	2154	600	1640	2400	1000	4000	8000	-	5000	-	1550	2986	5300	922	2980	4571
361	Concrete pavement repair	SY/Day	50	100	200	-	-	-	-	-	-	10	30	50	-	-	-	-	-	-	30	65	125
400-1	Excavation and backfill for structures - Cofferdams	SY/Day	100	200	300	-	-	-	-	-	-	Inconsistent Units			100	200	300	28	62	193	76	154	264
409	Piling	LF/Day	200	300	400	200	450	1,150	90	257	700	200	300	600	200	300	400	220	547	720	185	359	662
416	Drilled Shaft Foundations	LF/Day	-	-	-	40	112	279	60	120	200	-	-	-	200	300	400	5	265	700	76	199	395
420-1	Concrete structures - Footing	CY/Day	10	15	20	3	16	30	-	-	-	-	-	-	10	20	30	28	49	75	13	25	39
420-2	Concrete structures - Column - Square	CY/Day	4	7	10	8	26	40	1.75	2.5	3.3	-	-	-	4	8	12	9	17	34	5	12	20
420-3	Concrete structures - Column - Round	CY/Day	4	7	10	2.5	8	15	1.75	2.5	3.3	-	-	-	4	8	12	12	28	75	5	11	23
420-4	Concrete structures - Caps	CY/Day	4	7	10	1	8	19	1.75	2.5	3.3	-	-	-	4	8	12	-	10	-	3	7	11
420-5	Concrete structures - Abutment	CY/Day	-	-	-	Inconsistent Units			2.9	3.8	5.6	-	-	-	-	-	-	-	-	23	2.9	3.8	14.3
420-6	Concrete Structures - Approach slab	SY/Day	-	-	-	-	-	-	65	220	490	-	-	-	Inconsistent Units			-	-	-	65	220	490
422	Reinforced Concrete Slab - Bridge deck	SF/Day	162	385	756	305	895	2,157	600	730	900	-	-	-	162	423	756	3500	4250	5000	946	1337	1914

Fig. 3. Screenshot of the summary tab.

Work Item #	Work Item	Unit of measurement
110	Excavation	CY/Day

Rate Table	TXCTDS	HYPRIS	OKCTDS	KYCTDS	FLDOT	RSMeans	Average
Units	CY/Day	CY/Day	CY/Day	CY/Day	CY/Day	CY/Day	CY/Day
Low	1,200	199	1,800	1,000	900	65	861
Mean	3,400	1,163	2,825	5,000	3,800	1,887	3,013
High	7,000	3,558	7,000	10,000	7,500	14,800	8,310



Scope Table	TXCTDS	HYPRIS	OKCTDS	KYCTDS	FLDOT	RSMeans
Inclusions	The removal and transporting of in situ soils on the construction site using mechanical equipment	Removing top soil; Excavation from original elevation to the elevation which is at least 6" below the required sub-grade elevation; Disposal of material	Excavation of earth material within the right-of-way.	Includes the excavation and movement of all earth and rock on the construction site.	Excavation - Truck Haul; The removal and transporting of in situ soils on the construction site using mechanical equipment	Trench excavation; Excavating, Bulk Bank Measure; Large Volume Projects; Bulk Excavation w. Dozers
Exclusions	Rock Excavation	Survey & Layout; Access road construction/maintenance; Unsuitable material replacement; Reshaped by blade, sprinkled and rolled for sub-grade surface; Temporary drainage maintenance; Shaping slop; Rock	Muck excavation, rock excavation, and structural excavation	No specific exclusions identified in source	No specific exclusions identified in source	Hand Exc.; Chain trencher, fly wheel trencher, plow; Backfilling; Minor Structures Exc.; Rock removal, Drilling and Blasting; Ripping, Hydraulic Rock Breaking and loading; Clamshells, draglines, scrapers
Original units	CY/Day	CY/Day	CY/Day	CY/Day	CY/Day	CY/Day
Conversions	Not needed	Not needed	Not needed	Not needed	Not needed	Not needed

*Production rates with inconsistent units are excluded from average calculations and charts

Fig. 4. Item worksheet sample.

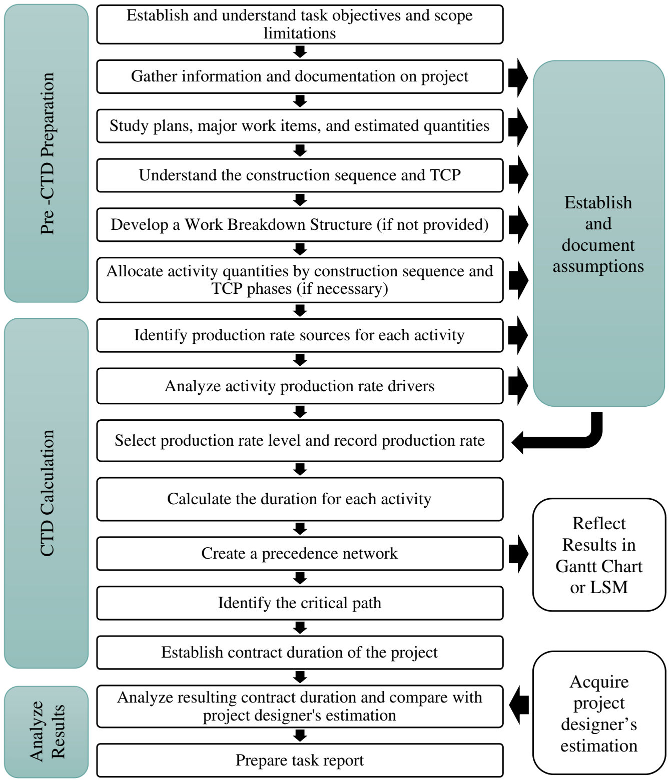


Fig. 5. CTD process flowchart.

17 steps categorized in four process sections: pre-CTD preparation, CTD calculation, establish and document assumptions, and analysis of results.

Pre-CTD Preparation

Composed of six steps, the pre-CTD section allows for the proper preparation and information gathering to obtain the most accurate estimation.

1. Establish and understand task objectives and scope limitations: Precise and identifiable objectives and scope limitations allow for an accurate assessment of the process.
2. Gather information and documentation on the highway project: These should include plans, specifications and work quantities, construction sequences, the traffic-control plan (TCP), and a work breakdown structure (WBS).
3. Study plans, major work items, and estimated quantities: This step helps to understand the physical location of important activities, identify potential critical paths, and separate activity quantities into project phases.
4. Understand the construction sequence and TCP: This step will allow for the general understanding of the project execution as these documents should dictate that certain phases of the project are to be conducted in a particular sequence.
5. Develop a WBS (if not provided): Having a detailed WBS is necessary to understand each activity's scope and determine activity sequencing. If not provided by the design team, the estimator should develop and assume a WBS.
6. Allocate activity quantities by construction sequence and TCP phases (as applicable): To achieve accurate results, activity quantities must be separated and allocated to the proper construction phase of the project. Phase shifts may require adjustment periods, and activities executed in different phases are subject to different condition and location factors.

CTD Calculation

With a developed WBS and properly allocated activity quantities, the information is ready for the CTD calculation process, described in the eight steps below:

1. Identify production-rate sources for each activity: Using the *Production Rate Resource* is highly beneficial to the estimator, providing information contained in diverse data sets. If the resource does not include particular activities, other databases should be consulted.
2. Analyze activity production-rate drivers: Analyzing important drivers that affect project activities will help determine the appropriate production-rate level. Some drivers to be considered are: work zone size, relative quantities of the activity, number and size of crews, and the equipment used for each activity.
3. Select a production-rate level and record production rate: Considering conclusions from all previous steps, the estimator is to assign a production rate level of low (L), mean (M), or high (H) for each activity.
4. Calculate the duration for each activity: A simple division calculation is required. Divide the quantity of an activity by its daily production rate to calculate the duration of an activity in working days.
5. Create a precedence network: A precedence network allows one to understand and analyze the construction sequence and verify the durations activities, phases, and the project as a whole.
6. Reflect results in a Gantt chart or linear sequence model (LSM): For ease of visualization, it is necessary to reflect the precedence network on a Gantt chart or LSM. Doing so will allow for pinpointing logic ties, activities executed in parallel, and the critical path.
7. Identify the critical path: The critical path will show the sequence of activities that determine the contract duration.
8. Establish the contract duration of the project: The estimator extracts the critical path activities and develops a table showing only these activities with their corresponding durations and predecessor. The sum of the critical path activity durations, considering completion percentage of predecessors, yields the project contract duration.

Establish and Document Assumptions

This step constitutes a section of its own since it is implemented in parallel throughout the process. In all previous steps, assumptions must be recorded as these may result in conditions and limitations. These are to be consistent with all contract duration calculations and should be documented for exceptions, considerations, and further analysis.

Analysis of Results

The final section of the process constitutes analyzing the results and preparing a final report.

1. Analyze resulting contract duration: The resulting contract duration is to be depicted for particularities in analysis criteria, project plans and document interpretation, critical path activities, quantity allocations within project phases, and production rates used. If the project designer's estimation and/or other third-party analyses are available, comparing the resulting contract duration with this information is recommended. This step allows for identifying errors and misinterpretations to reflect more accurate results.
2. Prepare task report: The final step is to document all conducted CTD activities in a report that highlights objectives, scope limitations, the executed CTD, its analysis, and conclusions and recommendations.

Case Studies

The *Production Rate Resource*'s database of calculated production-rate averages was tested by conducting two CTD estimations on actual highway projects. This task pertained to only two projects due to the availability of the information provided by the design engineers. The selected projects contain a substantial amount of activities relevant to the data collected in the *Production Rate Resource*. These case studies demonstrate the application of the recommended CTD process and served to identify improvements to the resource.

The analysis was limited to the information provided in plans, specifications, construction sequence, and TCP for each project. The estimation process required the development of a subphase level work breakdown structure and the calculation of activity durations using the *Production Rate Resource*'s averages and consulting the resource's six sources when work items were not included in the resource. The results were reflected in working days and compared with the design team's estimations for further analysis.

Case Study 1: US 80 Improvement Project

The first case study estimated the contract duration of an improvement project of US 80 in Dallas County. It consists of the improvements and construction of the southeast sector of the IH635 and US80 intersection. The project's TCP dictates for its execution in three phases, each of these composed of various stages. A total of 13 stages are specified to be executed in sequential order.

The developed WBS accounted for 179 activities across the 13 TCP stages. These activities included traffic-control periods, clean-up, and phase adjustment times. The most important drivers considered in level selection (Step 9 of the process) were the amount of relative quantities and the size of the work area. As a result, most activities were given a mean production-rate level, followed by low and high, respectively. The selected production rates were used to calculate activity durations. Through the development of a LSM, the contract duration was calculated by the sum of the durations of all activities considered executed in the critical path, yielding a total of 273 working days.

The project design team shared its contract time estimate sheet for result comparison, reflecting a contract duration of 274 working days. This estimate was developed using the TXCTDS system only. Table 1 shows an overall comparison of contract time estimations.

While yielding almost identical results, the comparison reflects significant differences at the phase level. In Phase 1, the case study yielded 23.81% more time than the design team's estimation. Phases 2 and 3 narrowed the gap with differences of 15.97% less time for Phase 2 and 13.64% more time for Phase 3. These discrepancies are due to several factors in perception, criteria, and information.

An important difference is that the design team's estimation did not allocate activity quantities by individual TCP stages, but rather limited their calculation to the three project phases. Dividing quantities by stages allows for readjusting traffic controls, clean-up, and reorganization and should consider different rates within each stage based on location factors. This approach should result in a more accurate contract time estimate.

Activity installed quantity differences ranged from 79.36% less to 653% more than the design team's estimation. These differences may have resulted from misinterpreting project documentation and/or changes in the quantity from plan revisions.

In general, this case study's assumed production rates were considerably higher than those used in the design team's analysis. This may have resulted from limitations in the production-rate level selection process, as well as from the design team's experience and access to more information.

Table 1. Overall comparison of the design team and Case study 1 estimations

Phase	TxDOT	Case study	Difference	Difference (%)
Phase 1	42	52	10	23.81
Phase 2	144	121	−23	−15.97
Phase 3	88	100	12	13.64
Project total working days	274	273	−1	−0.36

Case Study 2: US 287 Improvement Project

Case Study 2 pertains to a highway-improvement project on US 287 in Ellis County. The project covers 4.442 miles of US 287 and consists of widening the two-lane undivided highway to a four-lane urban freeway.

The documented TCP dictates for the project to be delivered in three phases, each of these containing a total of seven subphases assumed to be executed in sequential order. The most important subphases are 1A (construction of the northbound frontage road), 2A (construction of the two main lanes), and 2B (construction of the southbound frontage road).

The developed WBS accounted for 172 activities distributed in the seven TCP subphases, including 20 bridge and overpass portions reflected as lump sum activities. Similar to Case Study 1, the WBS activities also included traffic control, clean-up, and phasing allowance periods. The production-rate source and level for each activity was selected to calculate their respective durations. The level selection process relied only on the amount of relative quantities and the size of the work area.

A precedence network, expressed in a Gantt chart, was then created to identify the project's critical path. All critical path activity durations were then summed to calculate the final contract duration, yielding a total of 570 working days.

The project design team provided their estimation reflecting a total duration of 621 working days. Table 2 shows an overall comparison of working-day calculations.

The contract time estimates were considerably close with an overall difference of 8.21%. However, when compared at a subphase level, significant differences were found. Analyzing the project's three longest subphases, subphase 1A was estimated at 29.83% shorter duration than the design team's estimation,

Table 2. Overall comparison between TxDOT and Case study 2 estimations

Phase/subphase	Stations	Duration: TxDOT	Duration: Case study	Delta	Delta (%)
Phase 1					
Phase 1A	232	181	127	−54	−29.83
Phases 1B and 1C	25	33	14	−19	−57.58
Phase 2					
Phase 2A	232	315	237	−78	−24.76
Phase 2B	232	152	150	−2	−1.32
Phase 2C	25	27	9	−18	−66.67
Phase 2D	25	6	13	7	116.67
Phase 3	232	78	20	−58	−74.36
Total project contract time		621	570	−51	−8.21

subphase 2A was estimated at 24.76% shorter duration, and subphase 2B was estimated very close with a 1.32% difference. These results suggested that the methods used by both estimations were considerably different.

The first difference identified was that the design team's estimation did not assume that succeeding subphases will be constructed in sequential order, but rather allowed their initiation prior to full completion of preceding subphases. If the design team had estimated subphases to be executed in sequential order, the result would have been calculated at around 753 working days, and the case study's estimation would be of about 23.4% shorter duration. This project total difference would be more consistent with the differences calculated at a subphase level.

A significant discrepancy was the number of critical path activities considered by each estimation. The case study accounted for 44 more activities than the design team's estimation. Furthermore, activities that drove the critical path were considerably different in both estimations. A review of the construction sequence is recommended to assure accurate results.

The allocation of activity quantities for each subphase shows significant differences between both estimations. For example, the design team's estimation divides retaining wall construction quantities to subphase 1A and 2A almost equally, while Case Study 2's estimation allocates 98% of the activity's quantities to subphase 2A. Such discrepancies may have been the result of misinterpreting project documentation.

The case study's assumed production rates were higher than those used in the design team's analysis. This may have resulted from the design team having access to more information and experience and the case study's limitations in the production-rate level selection process.

Research Findings and Learnings

Production-Rate Differences within Each Source

One research observation is the difference of low, mean, and high production rates considered by each source. To visualize this range, the authors calculated the percentage deviation of the rates in each source from the resource's calculated averages for each work item. The results were then added to calculate the average percentage difference. Table 3 shows the results of this calculation, generally presenting which sources provide higher and lower production-rate data. This information can show how the sources generally affected the *Production Rate Resource*'s calculated averages. At the low level, HYPRIS production rates were 52% lower while all the other sources displayed positive differences.

Although the information in Table 3 may generally indicate the trends of each source's data, these calculations can be misleading as positive values (representing higher rates than the calculated averages) can offset negative values (lower rates than the calculated averages). Percentage variations within the analyzed work items range from 94% lower to 270% higher production rates than the resource's averages, implying much greater differences in both higher and lower production-rate values. Thus, the previous calculation was repeated using the absolute values of the percentage differences. This new calculation, summarized in Table 4, expresses each source's percentage variance from the resource's calculated averages, dismissing if the production rates are higher or lower.

Table 3. Average percentage differences between each source's production rates and the calculated averages

Source	Low (%)	Mean (%)	High (%)
TXCTDS	9	1	−1
HYPRIS	−52	−2	18
OKCTDS	0.3	−13	−14
KYCTDS	9	7	2
FLDOT	7	3	−11
RSMeans	10	3	8

Table 4. Absolute average percentage differences between each source's production rates and the calculated averages

Source	Low (%)	Mean (%)	High (%)	Average (%)
TXCTDS	28	26	27	27
HYPRIS	58	45	46	50
OKCTDS	44	30	36	37
KYCTDS	35	33	31	33
FLDOT	39	34	35	36
RSMeans	66	44	49	53
Average	45	35	37	39

Table 4 shows TXCTDS with the least average variance at 27%, indicating the source with production-rate values closer to the calculated averages. Similarly, Table 4 shows RSMeans with the most average variance at 53%, indicating this source's data deviated most from the calculated averages. Furthermore, the average variation of all the data is expressed at 39%.

Work Item Scope of Work and Definitions Comparisons

Most sources provide work item definitions and descriptions to delineate each work item's scope of work. Generally, most incorporate all related activities within their definitions. For example, TXCTDS and FLDOT literature define the work item Concrete Pavement as "the layout, reinforcing, placing, curing, and jointing of Portland cement concrete pavement." KYCTDS's publication defines the same work item more generally as "all activities required to concrete pave the new or existing road on a project." While the work item definitions are broad, these sources do not include explicit exclusions. However, exclusions could be implied by the content of other work item definitions and descriptions.

HYPRIS contains work item sheets specifically depicting a scope table listing the included and not included activities, providing more detailed information on the work item's related activities.

RSMeans, covering an abundant number of work items and subitems, contains descriptions that detail particularities in equipment, crews, and techniques used. The guide generally specifies that their productivity information includes mobilization, layout, movement of materials, and cleanup. However, subitem descriptions may specify particular exclusions, which may comprise the aforementioned general inclusions.

OKCTDS does not include work item scope information within its publication. Nevertheless, work item descriptions and definitions are available in the Oklahoma DOT's Standard Specifications Book (2009).

Work Items with Little Production-Rate Information

Analysis on the gathered information shows that there are multiple work items important for CTD that are only included in a few publicly available sources. The *Production Rate Resource* contains 20 work items with data provided in two or fewer sources.

There are several vague work items (e.g., major structure demolition, remove old structures) and some work items that are perhaps not expected to drive a given project's critical path (e.g., prime coating, bridge curbs/walks). Other work items' scopes may be covered within other general work items' scopes. Examples of these are rock excavation, which could be considered within the scope of excavation activities (considering rocky material as a factor that reduces productivity), and demolition and removal work items, which can be broadly covered within the duration of the work item preparing right of way.

However, the list includes work items that are of vital importance for CTD, such as initial traffic control, detour, mechanically stabilized warth (MSE) walls, and approach slabs. These may be considered critical activities for determining the contract duration of particular projects, and it is recommended that further data should be gathered for these work items.

Conclusions

The *Production Rate Resource* was developed by gathering data from six publicly available sources, testing these production rates through estimating contract durations on actual highway construction projects, and using the estimation results to improve the resource. The result is an integrated single, easy-to-use reference of production-rate data presented for easy comparison and intended to be used by highway construction contract time estimators.

The final version of the *Production Rate Resource* was assembled as a Microsoft Excel workbook that contains: (1) an introduction tab explaining the purpose and content of the resource, (2) a sources tab detailing the publicly available systems and databases that provided the resource's production-rate data, (3) a summary sheet gathering the most important production-rate data in one single table, and (4) item worksheets detailing the recollected production rates of the 59 work items included in the resource, expressing calculated averages, visual aid graphics, and scope descriptions from the original sources.

Contributions

The *Production Rate Resource* is a single integrated source of heavy construction production rates to assist estimators with production-rate comparison and selection. Estimators can easily use this information in activity-duration calculations for bar chart and CPM estimation procedures. The resource can also be a supplementary reference for production-rate baselines in current CTD systems. Moreover, it can be a valuable resource for future researchers wanting to investigate various activity-level production rates and the factors that affect them. This alone makes it a valuable long-term reference.

This research also provides a recommended process for conducting a contract time estimation using the *Production Rate Resource*. The process focuses on preparing the needed information, conducting the CTD calculations, documenting assumptions, and analyzing results.

Recommendations and Future Topics

After conducting the case studies, the *Production Rate Resource* was improved with the inclusion of a publicly available production-rates source and additional work items. Conducting CTD estimations using the latest version of the resource is recommended for further validation.

The *Production Rate Resource* should also be tested as a reference tool for TXCTDS and other DOT's CTD systems, which are composed of different processes from the conducted case studies. Such tasks would analyze if the tool effectively facilitates estimators' appropriate production-rate selection.

Due to time constraints, it was not possible to compare the time estimates produced with the actual baseline and as-built schedules provided by the construction contractors. However, in the future, it would be helpful to have a comparative analysis of the baseline and as-built schedules with the time estimates produced for assessing the divergences and associated causes and develop a feedback loop for improving future CTD processes.

Acknowledging that production rates may vary over time, the *Production Rate Resource* should be updated with the latest production rates provided by the six data sources. Furthermore, the resource can be improved by incorporating additional production-rate information from other authoritative sources.

Research findings show that, within the resource's data, production rates provided in different sources on average vary 39% from the *Production Rate Resource*'s calculated averages. The authors recommend that this variance should be further analyzed, examining data from other CTD systems and evaluating if these variances are reasonable.

Research findings also show that few of the resource's sources provide production rates for important work items for CTD procedures, such as traffic control, detour, and MSE walls. It is recommended that this finding should be further revised due to these activities' probable impact in the critical paths of highway construction projects.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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