2018

Forensic analysis of DWR data for effective prediction of highway production rates

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Forensic analysis of DWR data for effective prediction of highway production rates

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Construction Engineering and Management)

Program of Study Committee:
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2018

DEDICATION

To my parents without whose support I could not have made it this far in life. To my friends and well-wishers whose valuable suggestions drive me to excel forward in my career.

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GLOSSARY OF TERMS

Definitions were obtained from multiple sources (Hanna 2001; Goodrum and Haas 2002; Chong 2005; Hanna et al. 2005; Aoun 2013; Hanna et al. 2008).

ADT: Arizona of Transportation.

CFR: Code of Federal regulations.

Contract: Legal Agreement between project parties that specifies the scope of work, the payment processes, and general and supplementary conditions.

DOT - Department of Transportation.

DWR data - Daily Work Report data.

Effective Work: Work which is productive, meaning that a value-added activity is taking place. Pouring concrete or installing ducts are examples of effective work.

Efficiency: Relationship between the actual amount of work it takes to create a product (earned hours) and the estimated amount of work expended (estimated hours).

Estimate: The predicted work hours or dollars that should have been spent to complete an activity or project.

Equipment number: The total number of equipment available with the contractor that is allocated to the project.

Equipment used: The total number of equipment used from the total allocated equipment to the project.

FHWA: Federal Highway Authority.

Incentives: Rewards, monetary or otherwise, given to crews for excellent performance or for completing a project or activity in less time than estimated.

Interruptions: When a worker is stopped or prevented from completing an in-progress task. Interruptions disrupt and reduce productivity.

Labor: Physical or mental work compensated by salary or wages.

Louisiana DOTD: Louisiana Department of Transportation and Development.

MDT: Montana Department of Transportation.

NCHRP: National Cooperative Highway Research Program.

Overtime: Work performed on a project that exceeds eight hours a day and 40 hours a week.

PennDOT: Pennsylvania Department of Transportation.

Prefabrication: The process of producing and pre-assembling systems and materials. The prefabricated parts can be produced on-site or off-site.

Productivity: Mathematical relationship between the production units (output) produced in a certain number of work hours (input).

Project duration: The amount of time needed to complete construction on a project. Days from project start (notice to proceed) to project end (substantial completion).

Quality control: The review of project services, construction work, management, and documentation for compliance with contractual and regulatory obligations and accepted industry practices.

R^2: Root mean square.

Scope: The total amount of work and types of activities required to complete a project. The original scope is an agreement between project parties and may not be expanded without compensation.

Shift work: The hours worked by a separate group of workers whose work on a project begins after the first or primary workforce of the same trade has retired for the day.

Site: The area or footprint of ground on which anything is, has been, or will be located.

Task: An individual sub-unit of work necessary for the completion of an activity or project.

Total paid working hours: The sum of the basic hours and paid overtime hours.

Total work hours: The total hours required to complete an activity or construction on a project.

VDOT: Virginia Department of Transportation.

Work Activity: A single, well-defined unit of work.

Work Area: A designated area where an operation of a work item is being performed and is only limited to the observed working phase.

Working hours: The hours worked by employees as part of their standard employment contract before overtime.

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. David Jeong for his guidance, support and feedback throughout the research project and thesis writing. I would also like to thank my committee members, Dr. Charles T. Jahren for his guidance and feedbacks on my research works and Dr.Rahul Parsa for his suggestions on my course work, providing me the valuable skills necessary for undertaking this project and participation on my POS committee.

This project was funded by Montana Department of Transportation and supported by Iowa State University Institute of Transportation. I would like to thank my fellow members on my project, Dr.Tuyen Le for providing me with valuable insights and feedback through the course of the project.

ABSTRACT

Departments of Transportation (DOTs) are collecting a vast amount of digital data to support project-planning, crucial decisions like contract time, and effectively document progress of highway construction activities. Analyzing the digital data in highway construction industry supplements and reinforces managerial and business decisions.

This study uses Daily work report data (DWR data) that are now commonly available in all State DOTs to demonstrate the smart utilization of existing digital data to support and enhance decision-making processes using data analytics and visualization methods. This study aims at providing an estimation model for transportation agencies to quickly estimate production rates based on bid data, DWR data, contractor and equipment data. In addition, the study identified important factors to the production rate of major work items. The study also examined the performance of different categories of contractors. The data used for this study was obtained from Montana DOT. The data was cleaned before being utilized to shortlist thirty-five key controlling activities important to highway construction. The final dataset was used to develop a model that can predict dynamic production rates according to project specific parameters. The scope of the study also includes developing a dynamic production rate estimation tool that would predict production rates depending on project characteristics as well as parameters involving contractors.

This study will enable State DOTs to utilize the existing datasets for contractor evaluation. The study is also expected to enhance professionals' understanding of production rates achieved in the past by contractors. The study demonstrates the importance of data analytics and visualization to obtain more value from the investment made in collecting construction data. Overall, this study serves as a step in making a transition from experience-driven to data-driven decision making in the construction industry.

CHAPTER 1. INTRODUCTION

1.1 Introduction

1.1.1 Contract time

Contract time is the maximum time allowed for completing all required work items specified in the contract documents (FHWA 2002). An accurate forecast of contract time is crucial to contract administration as the predicted duration and associated cost form a basis for budgeting, planning, monitoring and even litigation purposes (Jeong et al. 2008). Providing excessive contract time is expensive because it extends the construction crew's exposure to traffic, prolongs the inconvenience to the public (unnecessary increase of road user costs), hinder local businesses, increase the construction costs and subjects motorists to less than desirable safety conditions for longer periods of time (Chong et al. 2011). Insufficient contract time results in higher bids, overrun of contract time, increased claims, substandard performance, and safety issues. Due to significant importance of contract time determination, Title 23 Code of Federal regulations (CFR) Section 635.121 requires states to have adequate written procedures for the determination of contract time. As a result, most State Departments of Transportations (DOTs) including Montana Department of Transportation (MDT) have a published document describing their procedures to determine a project's contract time. Since a transportation agency maintains numerous ongoing projects under its portfolio, accurate contract time estimation will lead to timely completion of projects, better success rate and efficient use of funds.

1.1.2 Production Rate

Quantity of production accomplished over a specified period is termed as production rate. Realistic production rates are the key in determining reasonable contract times which are neither excessive nor inadequate (Herbsman et al. 1995). Insuring optimum productivity on transportation projects reduces congestion and thus improves economic well-being (Wachs 2011). Conventionally, DOTs use published production rates uniformly across the state. FHWA guidelines also suggest implementation of uniform production rates across the state but this practice it has intrinsic constraints. Production rates vary greatly depending upon the quantity to be produced, type of project, geographical location of the project, budget allocated for the project, seasonal limitations, weather and contractors capacity (Aoun 2013).

Measuring construction productivity is very challenging. In fact, the units of measurement (specially the units of output) depend on what is actually being measured which is different for different construction activities (Goodrum et al. 2009). For example, the production rate of structural steel placement can be expressed in linear feet of steel placed per day which can't be used to measure the production rates of some other activities such as concrete placement or cold milling. The Sitemanager manual used by MDT published the units that are applicable for each work item recorded in the DWR data and the production rates are calculated in units produced per day.

1.2 Background and Motivation

Researchers believe that the construction industry had not been through major technological advances as compared to other industries like manufacturing. Although the construction industry didn't go mainstream in implementing assembly lines and robotics, the techniques, machinery and methods used in this industry became advanced in recent times. Most studies emphasized on the waste of productivity due to different factors and the potential room for improvement to achieve higher production rates (Aoun 2013).

To ensure success of a construction project, the field engineer should make sure that maximum production rates are achieved according to the constraints in different phases of the project. Skitmore et al. (2004) emphasized the need to maximize labor productivity on site by showing that the cost associated with workers constitute about 40% of the construction budget for large projects. For highway projects, studies showed that labor constitutes around 20% of the total construction cost (Construction Labor Research Council 2004).

Managing labor and productivity is of crucial importance for success of a project. That's why labor can be seen as both risk and opportunity (Hanna 2011). In fact, a study (Kellogg et al. 1981) showed that productivity improvement through jobsite efforts can have an impact up to 30% of the project costs. By making sure that labor is being utilized efficiently on site, managers can get rid of the time and cost overruns faced by construction projects (Kaming et al. 1998). To do that, project managers must have a better understanding of the factors that may influence labor productivity (Mojahed and Aghazadeh 2008). This will put them in a better position to be able to control these factors and ensure that resources are being allocated properly. In fact, to improve productivity, it is important for superintendents to know what workers need and under what conditions they would work efficiently (Dai et al. 2009). Although many previous studies focused on the effect of different factors on construction labor productivity, these studies have major limitations that were covered by this research. In fact, these previous researchers studied only the effect of one or some of the factors effecting production rates and didn't account for the complex interactions and interdependence of these factors (Aoun 2013).

Methodology and importance of estimating highway construction time have increased in significance as roadway user costs themselves have become more significant. Having good estimates of production rates used by engineer in the early phase of the project to get reliable total work hours of work which will determine their estimate of the project duration and cost (Hwang and Liu 2010). Daily work report data maintained by MDT is a rich dataset to understand the impact of various parameters on the quantity of work produced per day in a project. Zhai et al. (2009) showed that information technology has been positively impacting construction productivity and will likely continue to do so in the future. In fact, Song and AbouRizk (2008) showed that for the information systems and database technologies to be useful for productivity modeling.

All of this emphasizes the problem statement that this study is solving. MDT does not have a system for capturing production rates from current projects and still uses published production rate charts to determine the contract time of a project. Consequently, the daily work report data is used to understand the different trends in production rates of work items and to accurately predict production rates. This provides MDT engineers with better understanding of the trend in the field and the range in which productivity can vary with different factors. To fulfill that demand, an extensive amount of efforts were made in this study to analyze the influence of each of the project parameters on productivity using DWR data.

1.3 Scope of Research

This research study reviewed the current practices of contract time determination of various DOTs by contacting DOT personnel or procuring documents online. The scope of this project is to: (1) review the current practices from published DOT manuals and develop gap analysis, (2) determining controlling work items and analyzing the factors that have a significant effect on production rates, and especially (3) develop a statistical model along with a MS Excel based production rate estimation tool that can support estimated production rates to be more practical and reliable. A database capturing the statistical summary of production rates achieved on past projects for various influencing factors is also developed to provide engineers with descriptively analyzed data to achieve optimum productivity rates. Using the knowledge gained from current practices, the research aims at updating the production rates of major and minor work items that are critical for highway construction like earthwork, concrete paving and 33 other activities for Montana DOT. DWR data provided by MDT is the primary data source for this research.

1.4 Research Team

The research team includes Dr. David Jeong, Associate professor, and me, Vijay Devaguptapu, a Construction Engineering and Management (ConE) graduate student at Iowa State University. Dr. Tuyen Le, a post doctorate at CCEE department of Iowa state university was involved in theorizing the research work.

1.5 Research Contributions

The objective of this research is to determine the current practices of various state DOTs on their contract time determination procedures and update the production rates used by Montana Department of Transportation using DWR data. The major research contribution of this study to the construction industry in general and MDT in particular is a data-driven technique that professionals can use to obtain more reliable and practical production rate estimates for a specific project taking into account important project characteristics. The findings of this study will provide a means for better planning of resources for highway projects, and allow less experienced personnel to gain confidence as they learn how to consistently estimate reasonable production rates. Guidelines on how to use the tool is also provided in this thesis. This research also includes descriptive analysis of the DWR data consisting of variations in production rates due to different factors. Since the production rates are project specific, this research allows MDT to avoid unnecessarily lengthy duration of highway projects. So, it would minimize the inconvenience to the public and unnecessary increase of road user costs. The research product will also allow MDT to avoid unreasonably short duration for highway projects which typically results in increased exposure of construction crews to safety hazards and substandard performance.

1.6 Thesis Organization

The report summarizes the findings from extensive literature review and case studies of the range of the tools available, results of a nationwide survey of state DOTs' methodologies on production rate estimation. Current practices of State DOTs' contract time determination procedures obtained from DOT engineers and online resources are summarized along with MDTs' current practices. The findings from the literature are discussed in chapter 2. The research methodology used by this study is discussed in chapter 3. Current practices of State DOTs and Key findings from the national survey conducted by (Taylor et al. 2017) are presented in chapter 4 along with review of contract time determination procedure of Montana DOT. Chapter 5 provides an insight on parameters that significantly influence production rates, which are determined by the results of descriptive analysis on DWR data. Chapter 6 provides detailed analysis of some major work items and development of regression models for major work items to develop MDT construction productivity tool. Chapter 7 discusses the guidelines to use the tool as well as certain limitation for the tool and the last chapter discusses the conclusions of the research study.

CHAPTER 2. LITERATURE REVIEW

This chapter discusses several factors that have an effect on production rates and contract time in various state DOTs, general guidelines and methods used for production rate estimation and case studies that cover the range of tools used for determining contract time. FHWA (2002) recommends that in estimating production rates of work items, an accurate database should be established by using normal historical rates of efficient contractors. The most accurate data can be obtained from reviewing project records (i.e., Daily work report data and other construction documents) where the contractor's progress is clearly documented based on work effort, including work crew makeup during a particular time frame (Hildreth 2005).

Conventionally most state DOTs use a rule of thumb and/or a published list of production rates that were developed years ago. Since highway construction is an outdoor construction operation that involves several types of activities that are heavily affected by a number of operational and environmental conditions, common production rate estimation methods such as expert opinion, engineering judgement, and production rate charts have serious limitations. One of the main limitations is that unique project factors and site conditions are very difficult to be considered quantitatively (FHWA 2002).

A detailed review of contract time determination procedures of several states reaffirmed by the findings of NCHRP Synthesis 502, reveals that about 68% DOTs (of the 41 surveyed) use established production rates and generic precedence logic to develop contract time estimates (Taylor et al. 2017). Some of the other commonly practiced methods are template, regression, and CPM based contract time determination. Traditional methods may lead to an erroneous contract time determination due to inaccurate production rate estimates. The paradigm shift is ongoing across DOTs which are moving towards improving their methodology to determine production rate estimates and using an integrated tool that develops project schedule with the critical path acquiring project input.

2.1 Production rate estimation

The production rates of major construction activities, that fall on the critical path in project schedule, play an important role in planning project resources and tracking project progress (Jeong and Woldesenbet 2010). Use of published production rate tables was found in some form across numerous contract time determination manuals. The production rate tables provided by DOTs consisted of highway work items ranging from 20 to over 200 items. PennDOT has only 20 work items yet it is used consistently across Pennsylvania because it goes through adept reviews from multiple stakeholders. Once the production rate estimates are modified to the satisfaction of the attendees, it is then used to determine the project completion date and project duration. The accuracy of the estimated production rates are very crucial for effective contract administration. Studies suggest that the significant factors that influence production rates are weather and seasonal effects, location of a project, traffic impacts, type of project, etc. (Jeong and Woldesenbet 2010).

2.1.1 Factors influencing production rates of major work items

Establishing factors that influence the production rates in a region is critical for improving accuracy in production rate estimates. Numerous production rate estimation and validation studies clearly show that production rates vary widely depending upon project specific factors (Woldesenbet 2011). The common factors which influence production rates are location, route type, weather, project type, operating conditions, etc. When those factors are appropriately incorporated into the production rate estimation process, the contract time determination process will be more accurate and become meaningful for contract administration. An advanced and consistent estimation system which accommodates unique project factors can provide production rate estimates with higher accuracy. Common factors found in the literature are portrayed in Figure 2.1.

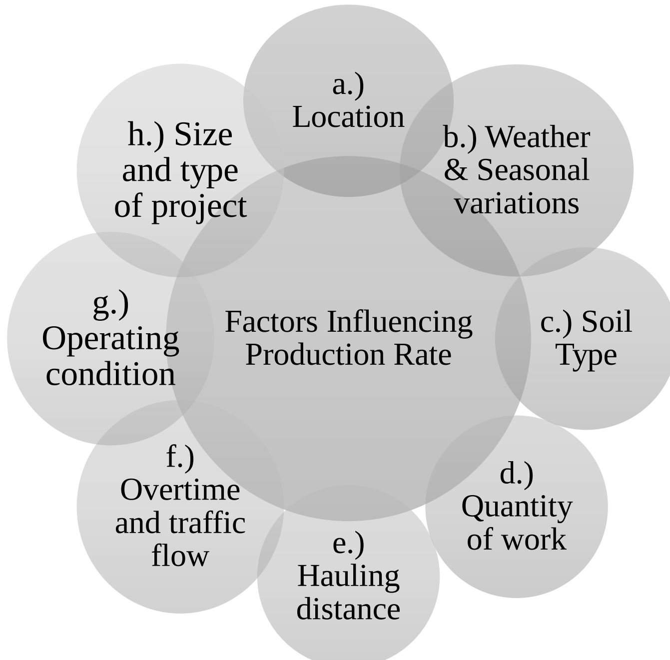


Figure 2.1: Factors that significantly impact production rates

a.) Effect of location on production rate

The location of a project is an important factor that determines the terrain and area type. Rural and urban distinction can be made by classifying location using average daily traffic. Figure 2.2 depicts the difference in production rates between urban and rural areas for six activities (Jeong and Woldesenbet 2010). Some DOTs classify location based on district topography as well as rural and urban classification. Rural areas are not prone to high average daily traffic which often causes disruptions to the activities like excavation in urban areas. The trend shown in Figure 2.2 clearly justifies that rural production rates are higher for certain activities like borrow excavation.

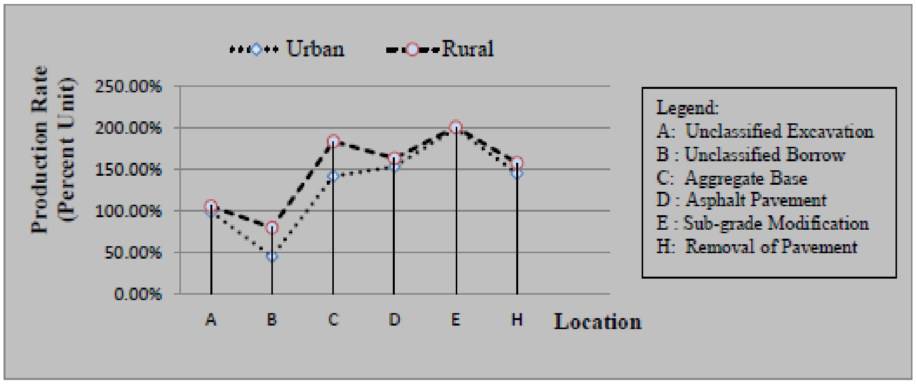


Figure 2.2: Effect of location on production rate.

Figure 2.3 depicts gradual increase in production rates among route types from City Street to state highway, US highway and Interstate. City streets contain a lot of traffic in a relatively congested area which might lead to frequent production delays. Production rate of unclassified highway excavation on an interstate is higher due to ease in management of traffic and availability of space.

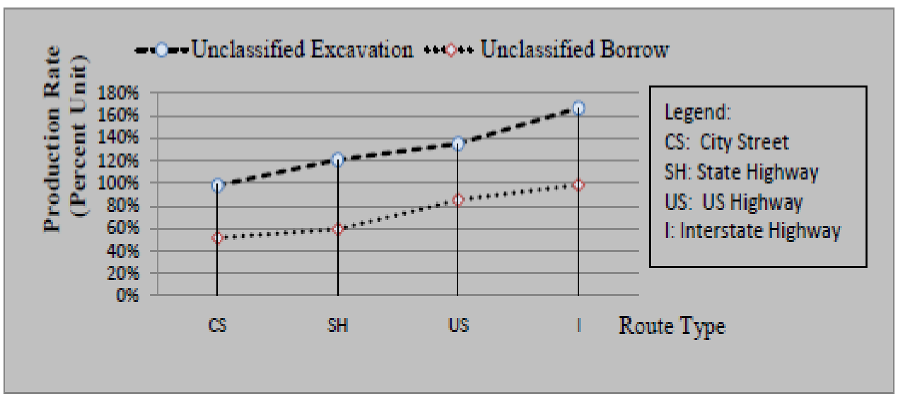


Figure 2.3: Effect of Route Type on production rate

b.) Effect of seasons on production rate

Weather plays an important role in influencing production rate achieved for major work items. Sometimes due to extreme weather conditions, construction activities come to a halt. Rains and snow can hamper the production rates significantly and therefore need to be considered during the contract time estimation process. Additionally, temperature has a significant impact on the production rates. Jiang et al. (2007) determined that highest production rates occurred at air temperature between 70 and 80 Fahrenheit. For example, considering high production rates during summer will produce erroneous estimates as extreme heat also hinders production rate. To accommodate production rate adjustments according to the weather conditions, production rates across four seasons are compared using box plots as shown in Figure 2.4. The visual analysis shows that median production rate in summer and fall is relatively much higher than that of winter and spring (Jeong and Woldesenbet 2010).

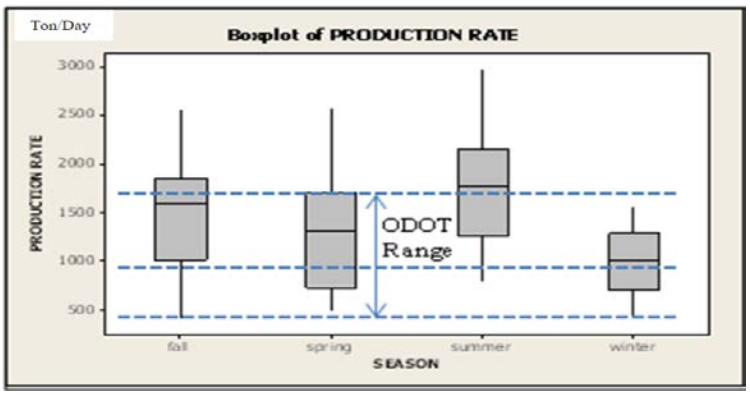


Figure 2.4: Effect of Seasonal on production rate

c.) Effect of soil type on production rate

“The type of soil encountered in a construction job site greatly affects the productivity of highway construction especially earthwork constructions” (Jeong and Woldesenbet 2010). Operating conditions of the soil type determine the production rate adjustment factor required for the job site. The American Standard for Testing Materials uses Unified Soil Classification System based on laboratory determination of particle size characteristics, liquid limit, and plasticity index. This classification system identifies three major soil divisions: coarse grained soils, fine grained soils, and highly organic soils. These three divisions are further subdivided into a total of 15 basic soil groups (Jeong and Woldesenbet 2010). Information regarding the soil type can be used to develop adjustment factors to production rate estimates. Heavy clay or rock soils requires heavy equipment & machineries while sandy soil or clay soils are easier to operate and handle. Understanding the soil types and developing appropriate adjustment factors for each soil type can guide DOT estimators to develop effective production rate estimates.

d.) Effect of quantity of work on production rate

The amount or quantity of work to be accomplished in a construction project has huge impact on production rates of construction activities. Based on the quantity of work, the availability of materials, allocation of resources, construction management and selection of construction means & methods determines the range of highway production rates. As the quantity of work increases, better equipment, resources, and construction methods are utilized to decrease the average cost of construction which in turn increases production rates of construction operations. The effect of quantity of work can be explained by the economies of scale. (Jeong and Woldesenbet 2010). Figure 2.5 shows a scatterplot between production rate and quantity of work for lime treated sub-grade (Connor 2004). The relation between production rates and quantities of work gradually keeps increasing following a log linear curve.

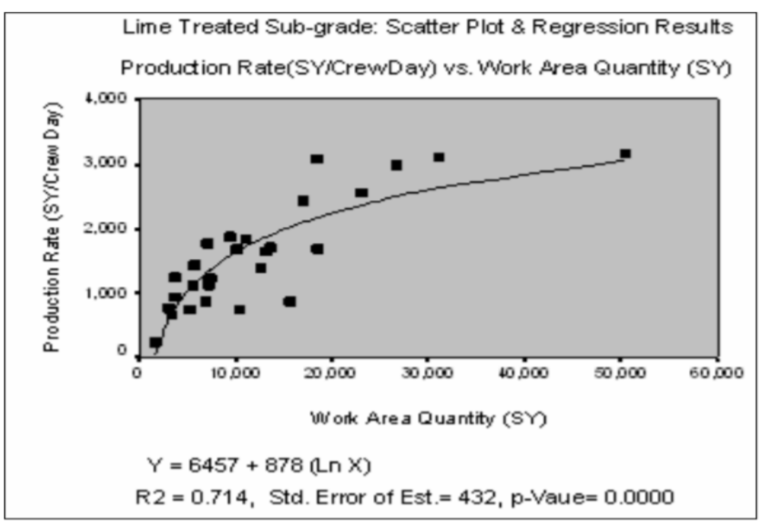


Figure 2.5: Scatterplot of production rate vs quantity of work

e.) Effect of Haul Distance on production rate

The distance to move materials to and from the job site is another critical factor affecting highway construction production rates. Haul distance has higher impact on bulk excavation and pavement construction activities. Considering an earthmoving activity, shorter haul distances (less than 1,000 feet) will result in a reduced cycle time which in turn increases production rate.

f.) Effect of overtime and traffic flow on production rate

Overtime also hampers labor productivity significantly. A decrease in efficiency of 10 to15 percent is observed for scheduled overtime scenarios of fifty working hours and sixty working hours per week when compared with a forty-hour work week (Thomas and Raynar 1997). Disruptions also lead to productivity loss as work is directed to overcome the constraints faced by the project (Halligan 1994). More working days per week are required when there are higher frequency of disruptions. (Thomas and Raynar 1997) Rework, availability of tools, material availability, and equipment availability have a significant impact on performance (Thomas and Raynar 1997). Location of a construction site can affect the production rates with a significant magnitude. Worker motivation (Borcherding 1980; Borcherding and Garner 1981) and the availability of skilled labor (Koehn and Brown 1985) both have a huge impact on construction productivity.

Jiang (2003) studied the effects of traffic flow on the construction productivity of hot mix asphalt pavement. He found that traffic delays increased the cycle time of transporting trucks. Due to this, the construction productivity, in terms of tonnage per hour, decreased. Advancement in technology has led to increase in construction productivity due to increased level of control, amplification of human energy, and information processing (Schexnayder and David 2002). Production rates under ideal conditions have increased 1.58 percent on average per year because of technology advancements. (Bhurisith and Touran 2002) *g.) Effect of operating conditions on production rate*

Operating conditions also contribute significantly to production rates. Studies focusing on excavation activities, identified factors that can be grouped under two categories as operational level and operating conditions. Operational-level factors are related to specific operations (e.g., loading) of an excavation activity (Kannan 1999). Operating conditions include factors, such as site conditions affecting each operation. Losses in productivity are caused by numerous factors such as environmental factors, site factors, management factors, and design factors (Thomas and Yiakoumis 1987). The construction firm or contactor plays vital role in affecting the production rates. Jiang et al. (2007) performed t-test and determined that the production rates differ between major construction firms and have significant impact on highway production rates. A detailed literature review reveals that there is a strong relationship between operating conditions and production rates (Smith, 1999). Lee et al. (2000) reveal that material delivery resources (like delivery trucks) are major factors that constraint the production rates.

h.) Effect of size and type of project on production rate

Another important parameter affecting the production rate is the size of a project. Every highway project is unique in design, size and complexity, but to compare the projects, total construction cost is an appropriate basis. This is because, the construction costs directly impact the size and complexity of the project. There is a direct relation between the total project cost and construction duration (Jiang 2007). Moreover, the construction duration of projects in the rural areas is found to be longer than that of urban areas for a given total construction cost. Factors like accessibility and procurement of labor and materials might be the reason for the extended duration in contract time in rural areas. Type of project has a considerable influence on the production rates as many DOTs design separate templates for the project types used in their state.

Lack of frequent updates to production rate estimates among DOTs is a major drawback leading to inaccurate estimates. Identifying significant factors that influence production rates is the starting point for developing a production rate estimation tool. Next sections discuss the methods available for determining production rate estimates.

2.1.2 Production Rate Estimation Methods

Three methods were found to be most common among current methods used to estimate production rates. a.) Production rate charts and engineering judgement to determine production rates, b.) Use of adjustment factors for work items so that adjusted production rates are estimated as per operating parameters and c.) Statistical methods, where a range of statistical tools are used to analyze the field data, to find patterns and accurately predict production rates.

a.) Production rate chart and engineering judgement

Production rates of controlling work items are determined by estimators based on published tables, past project data and experience. Factors influencing controlling work items must be considered accordingly as mentioned in section 2.1.1. Engineers use their experience to adjust production rates by considering influential factors. The production rates used should be based on the desired level of resource commitment (labor, equipment, etc.) deemed practical given the physical limitations of the project (Kiziltas and Akinci 2009). Rates should be updated regularly to assure they accurately represent the statistical average rate of production in the area. The estimators also consider the construction site related factors like soil condition and hauling information to make final adjustments to the estimated production rates.

b.) Use of systematic adjustment factor

Production rates are calculated by some DOTs using adjustment factors. These DOTs maintain a standard table of production rates. Some main project characteristics like location, traffic, complexity of the project, quantity, soil conditions, etc. are used to adjust the base production rate. These adjustment factors play a crucial role as the production rates to be relevant in soil conditions, topography of the location, average daily traffic in the area, etc. Quantity to be produced also has high impact on production rates for certain work items. Depending on the conditions in the state, DOTs have different adjustment factors for these parameters. The production rates calculation involves use of adjustment factors to make the estimate more project specific as by DOT (Jeong et al. 2008). Method (a) uses engineering judgment to adjust the production rates whereas this method (b) has predetermined adjustment factors which can be implement. Some examples of Ohio DOT and Oklahoma DOT which use this method are provided in section 2.3.

c.) Using statistical methods

"The statistical analysis is an approach in analyzing collected data in determining production rates of highway construction activities. Statistical methods include linear and nonlinear regression analysis, frequency plot, ANOVA, t-tests and multiple regressions modeling which are used to determine and quantify the relationship between production rate and factors influencing production rates as predictor variables in developing a model for highway production rate estimates"(Jeong and Woldesenbet 2010). As discussed in section 2.1.1, numerous factors influence the production rate. With the help of available data from the past projects, tools can be developed which will aid an estimator in attaining accuracy in production rate estimates.

2.2 Contract Time Determination

Contract time determination is a crucial estimate developed by the DOT to set the maximum time allowed to complete a project. An inadequate time estimate and excessive time estimate, both are bound to increase the construction cost and pose safety risks for the public. DOTs inherently use production rate estimates to determine their contract time. There are a lot of other factors that influence the project schedule that should be considered scrupulously during contract time estimation. Some of the main factors that influence contract time in literature are discussed in section 2.2.1.

2.2.1 Factors influencing Contract time

Any parameter which significantly increases the minimum number of days required to complete a project is a factor influencing contract time. Contract time estimates are dependent on factors like type of roadway being constructed, traffic volume (low, medium, high), location (rural or urban), season, phasing allowance, lead time, material availability, etc.

Table 2.1 summarizes the factors that affect contract time reported by DOTs (Taylor et al. 2017). It is indicated that Award time of year, Long-lead time materials, project phasing, maintenance of traffic, permit and other restrictions are most frequently factors. Right-of-way limitations, utility conflicts and community factors are also among the most frequent factors that impact contract time. Project phasing and long-lead time for materials are time sensitive factors and are crucial for establishing contract time.

Phasing is as significant factor that impacts contract time estimates. For example, in Arizona, a unique feature is canal dry-ups. There are a series of irrigation canals that are dry for maintenance at least once per year; some projects have work involving these canals and work must be scheduled to coincide with a dry-up period (ADOT 2015).

Table 2.1: Factors affecting contract time

Factors affecting contract time	**Number of DOTs that claim significance**
Weather	9
Letting/Award Time of Year	11
Long-Lead Time Materials	11
Project Phasing	11
Maintenance of Traffic	11
Seasonal Shutdowns and Seasonal Limitations	9
Permit/Environmental Restrictions	11
Right-of-Way Limitations	10
Utility Conflicts/Limitations	10
Milestones	8
Economies of Scale in Bid Item Quantities for Production Rates	3
Project Size Effect on Production Rates	8
Require Maintenance of Access	2
Community Factors (School Sessions, Fairs, Conventions, Events)	10
Potential Contractor Equipment & Production Capability	6
Multiple Shifts	6
Letting/Award Delays	5

A similar principal applies for winter shutdown periods as well in colder states. Most winter shutdown periods are from mid-November to mid-April. Projects whose lifecycle is less than four to six months shouldn't be let out if their schedule overlaps with winter shutdown or they should be fast-tracked so that the project is completed before mid-November. A project can be fast-tracked by adding working hours to each day or expanding the crew and by working on weekends. Budget must be considered while fast-tracking the project. Effects of maintenance of traffic requirements on scheduling and the sequence of operations must be determined to avoid unnecessary delays in contract time. Curing time, waiting periods between successive paving courses or between concrete placement operations, emergency conditions that require a waiting period should be accommodated in the contract time. Seasonal limitations for certain items and estimated number of adverse days must be appropriately adjusted in the contract time. Utility is a major issue that influences contract time. The estimators must provide ample consideration about the conflicts relating to utilities in the project location. Sufficient time for reviewing false-work plans, shop drawings, post-tensioning plans, mix designs, etc. as well as time for fabrication of structural steel and other specialty items or materials with long-lead requirements should be considered before establishing notice to proceed date.

2.2.2 Contract time determination methods

Contract time determination methods generally fall into the categories of bar charts and critical path techniques.

a.) Conventional method for determining contract time

The following steps are typically used for Contract Time Determination by the State DOTs (NCHRP 1995):

I. Collect and input data
II. Prepare list of activities
III. Use production rates for determining activities duration
IV. Develop logical sequence of activities
V. Make adjustments considering several factors
VI. Review the estimated contract time with experiences industry practitioners
VII. Develop final contract time

b.) Bar charts or Gantt charts

Bar charts or Gantt charts are graphical representations of projects with specific completion dates and activities. Bars or lines are drawn proportional to the planned duration of each activity (FHWA

2010).A brief description of the procedure used to develop a bar chart to determine contract time is as follows (FHWA 2010):

I. The first step in developing a bar chart is to break a project down into separate activities or operations necessary for project completion.
II. Once all the activities necessary to complete a project have been listed, the duration and completion date of each activity needs to be determined based on production rates.
III. With this data established, the bar chart can be prepared. A line or bar is drawn on the chart showing the time when work will be performed for each activity. The resulting diagram will represent when each activity will be undertaken and completed.
IV. With bar charts, the progress of a project may be monitored for each activity by drawing a bar or line below the original scheduled performance to show the actual duration for each activity as it is completed.

Bar charts are advantageous in that they are simple to develop and easy to understand, and they offer a good method of determining contract time. “Some disadvantages are that they do not show the interrelationship and inter-dependency among the various phases of work. Bar charts are difficult to properly evaluate when construction changes occur. Also, controlling items are shown in the same manner as minor items, thus making it more difficult to determine which items actually control the overall time progress of the project. The use of bar charts are not recommended for contract administration and project management of large or complex construction projects” (FHWA 2010).

c.) Critical Path Method (CPM)

“The Critical Path Method (CPM) focuses on the relationship of the critical activities, specifically, those which must be completed before other activities are started. A CPM depicts which tasks of a project will change the completion date if they are not completed on time. The evaluation of critical tasks allows for the determination of the time to complete projects. Because of the size and complexity of most projects, this method is most often applied using a computer software program. Within the CPM software, the ability to use a Program Evaluation Review Technique (PERT) provides a breakdown of each activity to boxes. This enables the user to view the connection of relationships to each activity. CPM software also has the ability to display the contract time in a bar chart view as well” (FHWA 2010).

I. The first step in applying the CPM method is to break a project down into separate work activity.

II. Once all the activities necessary to complete a project have been listed, the relationship of these activities to one another needs to be determined. Every activity has a definite event to mark its relationship with others with respect to completing a task.

III. A diagrammatic representation of the project is developed showing the correct sequence and relationship of activities and events. Each activity is shown as an arrow leading to a node, which indicates the completion of an event or the passage of time. The start of all activities leaving a node depends on the completion of all activities entering a node. Therefore, the event represented by any node is not achieved until all activities leading to the node have been completed. The resulting diagram will be a schematic representation of a project, showing all the relevant activities and events in correct sequence.

IV. An actual time can be set to each activity based on production rates and other appropriate factors. The time to complete each activity is then shown on each arrow to indicate the duration. The completion time of a project is the sum of the longest time path leading to completion of the project.

V. e.) The optimum time and for performing the project can be evaluated by assigning resources i.e. equipment, labor hours, and materials to each activity.

Advantages of using the CPM include an accurate technique for determining contract time and verifying that the project can be constructed as designed and with identified construction sequences (FHWA 2010).

d.). Regression based tool

Jiang et al. (2007) developed a regression-based tool in which a mathematical model is developed where an estimate of contract time was derived from the estimated total construction cost. The derived contract time estimate is further adjusted based on the effect of various factors that affect the production rates. Although their results closely matched the actual construction time, they overlooked several important aspects like quantity and size of work and thus their procedure was too complicated to be implemented in practice.

2.3 DOT Examples

The research team examined practices at other State DOTs through a review of published literature on their methods for determining contract time. State DOTs use various methods for estimating average production rate required for a project. The tools in use at DOTs to determine construction contract time are categorized based on production rate estimation methodology into one of the following categories:

1. DOTs which use static production rates (the system relies solely on production rates for critical activities)
2. DOTs which partially use an automated system (the system uses multiple production rates logic and pre-determined templates)
3. DOTs which use totally integrated systems(the system has an integrated production rate and schedule logic based on bid item quantities).(Taylor et al. 2013)

Some form of archived production rates is found in most of the systems examined in the literature review, but systems included in this category typically provided limited aid in contract time determination. The second category describes the states that had implemented a system using a pre-determined template. These systems could have a pre-determined logic for work scheduling and phasing while using another method for determining work durations (Taylor et al. 2013).

For the most part, partially automated systems had some type of production rates, whether general or specific to highway projects they were used to calculate duration of the activity within the framework. Partially automated system is the least famous among DOTs. Project based templates were used instead of having a generic template. Common templates were project types encountered in their state. Louisiana DOT has the highest number of templates reaching 22. DOT personnel responded saying the substantial number of templates aren't user friendly and they moved back to using static production rates.

An integrated systems might partially use automated systems in combination with static production rates. (Taylor et al. 2013) Some programs found, use Microsoft Access, Microsoft Excel and Microsoft Project where variability in inputs is fairly easy but complex data interaction can be limited, while others use systems developed by professional software developers such as

Primavera and Field Manager which can create much more complex components, but tend to limit user defined inputs that may vary from project to project (Taylor et al. 2013).

2.3.1 TxDOT HyPRIS:

Texas DOTs procedure is relatively informal, but it is consistent statewide. The project designers prepare TxDOT contract time estimates. The designer will calculate the duration of each construction activity by applying production rate to the quantity of the associated bid item. The construction activity and the calculated duration then are placed in a critical-path-method (CPM) schedule. This schedule is documented with either Primavera scheduling software or a simple spreadsheet, depending on the complexity of the project. Once a total number of days is calculated the designer then selects (with the input of the construction engineer) to use either working day charges or calendar day charges. (Connor 2004) The selection of working days will not charge a day of time if weather conditions prevent work from being done. The selection of calendar days will ensure that a day is charged regardless of weather conditions. TxDOT follows a spreadsheet called HyPRIS (Figure 7) that was developed with a TxDOT and CTR research project in 2004 (Chong 2005), which is a Microsoft Visual Basic and Microsoft Excel platform. This system is based on 14 different highway project templates and several factors such as geographic location, traffic conditions, and variance in quantity for adjusting the project duration and the contract time (Chong 2005). The key findings from the research were grouped into four different information elements. The first information element involves information that would be used by the TxDOT to estimate production rates (Connor 2004). Such information includes decile tables, regression plots, results of the regression analyses, and box plots. The second information element contains the glossary of terms that describes some statistical terminologies and terms adopted by the research (Connor 2004). The third information element consists of the descriptions of the individual assessed work items (Connor 2004). The fourth information element includes useful information from the Contract Time Determination System (Connor 2004).

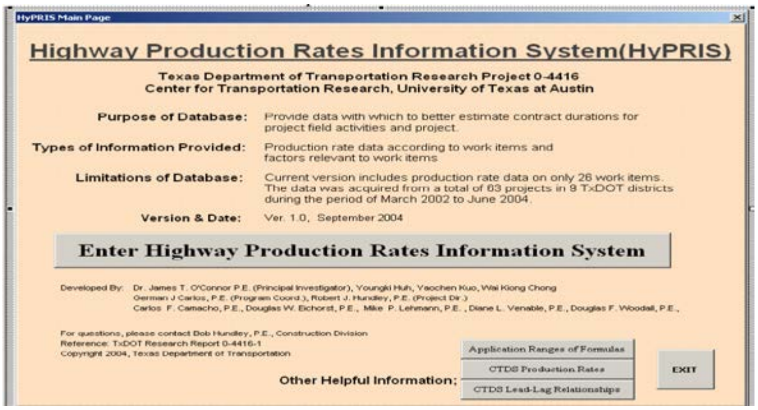


Figure 2.6 a.) HyPRIS main frame

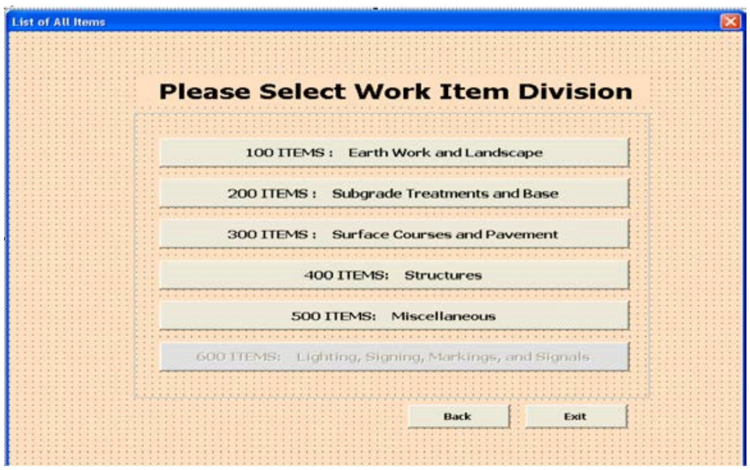


Figure 2.6 b.) Work items division (first-level window)

The Figure 2.6 (Connor 2004) displays the screenshots of the HyPRIS system. From top in Figure 2.6, a.) HyPRIS Main Frame, b.) Work Items Division (first-level window), c.) Work Items Numbers window and d.) Reinforced concrete pipe Work Item Mainframe.

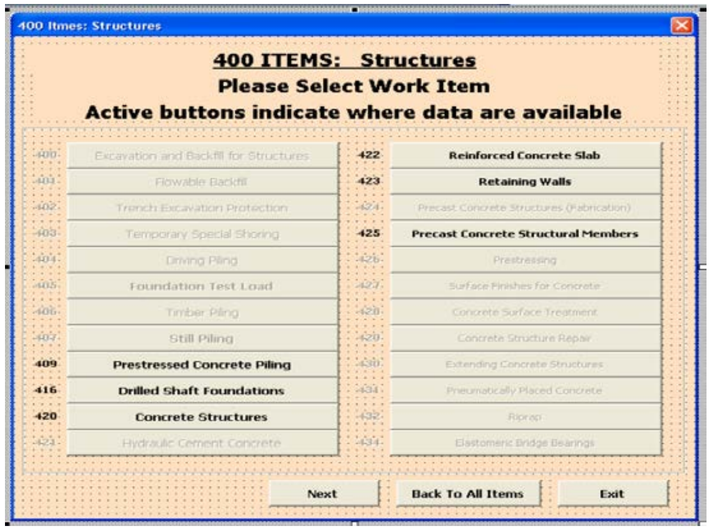


Figure 2.6 c.) Work items numbers window

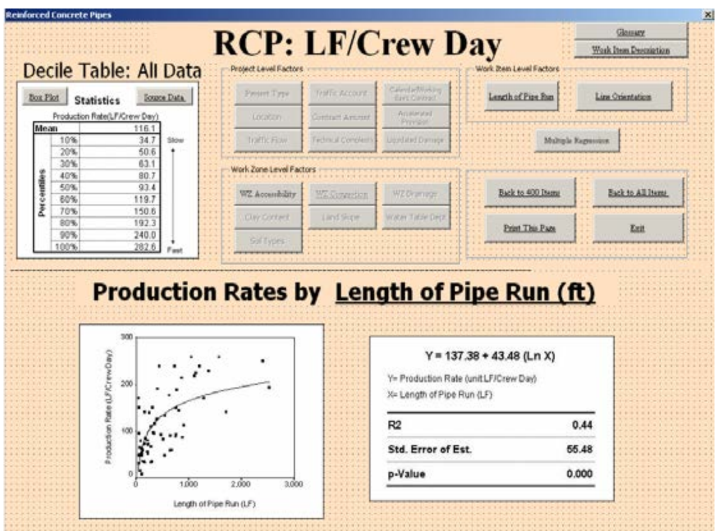


Figure 2.6 d.) Reinforced concrete pipe work item mainframe

Figure 2.6: HyPRIS System screenshots.

"The HyPRIS Main Frame page has five buttons on this window. The largest button links the first window to the three information elements that are grouped in different work items. Three buttons at the bottom provide links to useful CTDS information and guidelines about the usage of formulas in the system. The Exit button constantly appears in most of the windows. This is to provide the users with an option to exit if they would like to stop using the system. The fourth information element contains CTDS lead–lag relationships and production rates" (Connor 2004).

In the first-level window, "five main work item divisions will appear on the first-level window, as shown in Figure 2.6. The users can select from the work item divisions in this window to gain access into the detailed work item numbers. Each work item division contains all the work items under each division. For example, Work Item Number 464 (Reinforced Concrete Pipes) is a sub item in the "400 Items: Structures" division. Once the users enter the 400 Items Division, they will find the second-level windows. All work items are arranged according to the work item numbers, and the descriptions of the work items lie beside the work item numbers as shown in Figure 2.6." (Connor 2004). Once the users identify the work items they want, a click on the work items button will lead them to third-level windows. Texas CTDS used to have 42 work items which came down to 26 work items in HyPRIS system. (Jeong et al. 2008) The engineering judgement was still required for the work items that were not available in the tool.

2.3.2 SCDOT:

South Carolina DOT maintains a list of production rates for 31 major work items for six types of projects encountered in highway letting. The production rates are maintained by the director of constructions office. For each type of project, a selected rate within the production range is considered default production rate as shown in Figure 2.7. Depending on site and project conditions the selected range can be adjusted to better represent the production expected on the particular project. To set completion dates for a typical SCDOT project, the quantities of the critical path items are taken and divided by the production rates. This calculation gives the number of working days for each critical path item. The sum of all the days for each item gives the total number of working days to complete the project. Depending on the type of project several charts are maintained that list the amount of working days in each month. Starting with the anticipated start of construction dates, the completion date is out until the available amount of working days exceeds the total amount of working days calculated. The month that this occurs becomes our completion date. Once the date is set other factors such as utility or material delays are considered to determine if additional time will be added to the calculated completion date. Once the review is completed the completion date is included in SCDOTs advertisement and contract documents.

Work Item	UNIT	PRODUCTION RANGE		large primary	small primary	Rehab	large bridge	small bridge	secondary
		LOW	HIGH	RATE	RATE	RATE	RATE	RATE	RATE
Clearing and Grubbing	Mile	0.1	0.3	0.23	0.17	0.17	0.12	0.12	0.12
Removal of Existing Pavement	SY	100	1000	578	578	578	116	116	578
Removal of Existing Asphalt Pavement	SY	300	3000	1732	1732	1732	1732	1732	1732
Unclassified Excavation	CY	1200	5000	3465	1155	1155	578	578	578
Borrow Excavation	CY	300	5000	3465	346	174	346	346	346
Earth Type Base Course	SY	2400	7200	5775	5544	5544	5544	5544	5544
Graded Aggregate Base Cr. - (4"- 6")	SY	1250	3000	2310	2310	2310	1155	1155	1155
Graded Aggregate Base Cr. - (8" & above)	SY	750	5000	2888	1848	1848	867	867	867
Bituminous Surfacing	SY	2500	7500	5775	5775	5775	5775	5775	5775

Figure 2.7: Production rate table for some work items used by SCDOT

2.3.3 Louisiana DOTD:

Researchers developed production rates and 22 critical path templates for various types of projects in all 9 maintenance districts of Louisiana. The software proved difficult to maintain as new operating systems came along, so for the last several years DOT engineers have been using standard production rate tables, which tend to yield an approximate construction time value which, field personnel may change during review. The production rate table used is exhaustive with 221 work activities covering a wide array of projects. Due to the complications of template-based scheduling, some DOTs use regression-based equations to estimate their contract durations. KYTC found that regression-based models were accurate under certain project specific conditions. The production rates used should be based on the desired level of resource commitment (labor, equipment, etc.) deemed practical given the physical limitations of the project. Rates should be updated regularly to assure they accurately represent the statistical average rate of production in the area.

2.3.4 Ohio DOT:

Ohio DOT uses Construction Duration Determination Tool ver01 to determine contract time. There are several tabs in the spreadsheet that contain instructions, bar chart, adjustment factors, items of work, monthly data and completion date. Production rates of 163 work items are documented by the DOT. Numerous factors influencing production rate are adjusted. Each work type has a low value and high value. The factor is incorporated to determine the adjusted production rate as per project requirement. Adjustment factor is utilized as shown in Figure 2.8 (a). The five significant factors influencing production rate are location, traffic, complexity, soil conditions and bid quantity. The production rate and the total number of working days are determined by giving the work activity and the bid quantity as input according to the construction schedule in the tool (Figure 2.8 (b)). The excel tool provides drop down lists for the user to select project specific parameters. For example, the user selecting a city with light traffic, medium complexity and fair soil conditions, an adjusted production rate will drop by 52.5% from the base production rate. The total number of working days is determined by providing the critical path activity logic in the contract time determination worksheet. The tool calculates the completion date with the help of total number of working days and the notice to proceed date as provided by the estimator (Figure 2.8 (d)).

Location		Traffic		Complexity		Soil Conditions		Quantity	
Rural	1.00	Light	1.00	Low	1.00	Good	1.00	Large	1.00
Small City	0.85	Moderate	0.88	Medium	0.85	Fair	0.85	Medium	0.88
Large City	0.75	Heavy	0.70	High	0.70	Poor	0.65	Small	0.75

Figure 2.8 a.) Adjustment Factors used by Ohio DOT

ID No.	Description	Base Production Rate	Units	Adjustment Factors										Adjusted Production Rate	Units
				Location		Traffic		Complexity		Soil Conditions		Quantity			
1	Excavation - Excavation (Topsoil)	1,000.0	Units	Small City	0.85	Light	1.00	Medium	0.85	Good	1.00	Medium	0.88	636	Units
2	Drainage - Concrete Box Culverts	15.0	cubic yard	Small City	0.85	Light	1.00	Low	1.00	Good	1.00	Medium	0.88	11	cubic yard
3	Aggregate - Gravel or Crushed Stone	1,200.0	cubic yard	Small City	0.85	Light	1.00	Low	1.00	Good	1.00	Medium	0.88	898	cubic yard
4	Bridge - Concrete Structures	25.0	cubic yard	Small City	0.85	Light	1.00	Low	1.00	Good	1.00	Medium	0.88	19	cubic yard
5	Paving - Pavement Rem/Rep Reinforced	100.0	ton	Small City	0.85	Light	1.00	Low	1.00	Good	1.00	Medium	0.88	75	ton
6	Drainage - Curb & Gutter	1,200.0	cubic yard	Small City	0.85	Light	1.00	Low	1.00	Good	1.00	Medium	0.88	898	cubic yard
7	Miscellaneous - Chain Link Fence	500.0	square yard	Small City	0.85	Light	1.00	Low	1.00	Good	1.00	Medium	0.88	374	square yard

Figure 2.8 b.) Production rate calculation of OhioDOT

ID No.	Description	Contract Quantity	Units	Base Production Rate	Units	Adjusted Production Rate	Units	Working Day Duration	Preceeding Activity		Start Day	Finish Day
									ID	Percent Complete		
1	Excavation - Excavation (Topsoil)	6500.00	cubic yard	1000	cubic yard	635.8	cubic yard	11			1	11
2	Drainage - Concrete Box Culverts	108.00	cubic yard	15	cubic yard	11.2	cubic yard	10			4	13
3	Aggregate - Gravel or Crushed Stone Base Course	6000.00	ton	1200	ton	897.6	ton	7			6	12
4	Bridge - Concrete Structures	250.00	cubic yard	25	cubic yard	18.7	cubic yard	14			8	21
5	Paving - Pavement Rem/Rep Reinforced Concrete	750.00	square yard	100	square yard	74.8	square yard	11			12	22
6	Drainage - Curb & Gutter	3000.00	foot	1200	foot	897.6	foot	4			14	17
7	Miscellaneous - Chain Link Fence	2000.00	foot	500	foot	374.0	foot	6			17	22

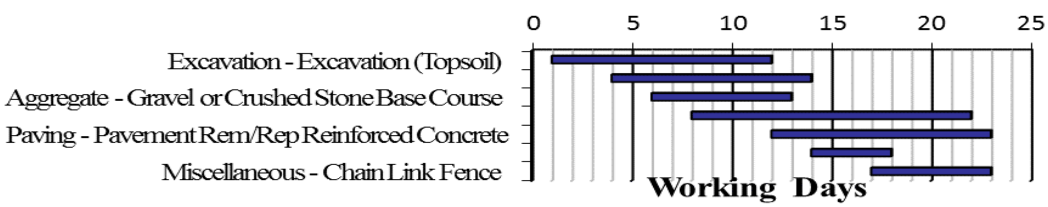


Figure 2.8 c.) Contract time determination worksheet of OhioDOT

ENTER TOTAL WORKING DAYS	22			
ENTER MONTH START	**CUMMULATIVE WORK DAYS (WITH WEATHER DAYS)**	**CUMMULATIVE CALANDER DAYS (WITH WEATHER DAYS)**		
January-18	14	31		**PROJECTED FINISH MONTH**
Feb-18	26	59	**Weather Sensitive Months and Work Types**	
Mar-18	41	90	**November**	asphalt (polymer modified)
Apr-18	56	120	**December**	asphalt, traffic markings, concrete sealing, bridge painting
May-18	73	151	**January**	asphalt, concrete pavement, earthwork, traffic markings, concrete sealing, bridge painting
Jun-18	89	181	**February**	asphalt, concrete pavement, earthwork, traffic markings, concrete sealing, bridge painting
Jul-18	106	212	**March**	asphalt, concrete pavement,traffic markings, concrete sealing, bridge painting
Aug-18	125	243	**April**	asphalt, traffic markings, concrete sealing, bridge painting
Sep-18	139	273	Work Types during these months will push completion date	
Oct-18	156	304	**Incidental Work**	
Nov-18	171	334	Add one month for projects that contain significant incidental work not entered into bar chart	

Figure 2.8 d.) Completion Day calculation of OhioDOT

2.3.5 Kentucky Transportation Cabinet:

KYTC adopted regression-based modeling, to estimate contract time, for this system. Mathematical equations that closely align with the trends of significant variables in historical data base are developed. The first step for estimating a project's contract time begins with determining its classification according to the project's construction estimate. Upon opening the Kentucky Contract Time Determination System, a MS Excel based tool, the user is asked to select the size of the construction project in terms of dollar value as seen in Figure 2.9 (a). Projects of less than $1 Million are referred to as small projects while those over $1 Million are referred to as large projects.

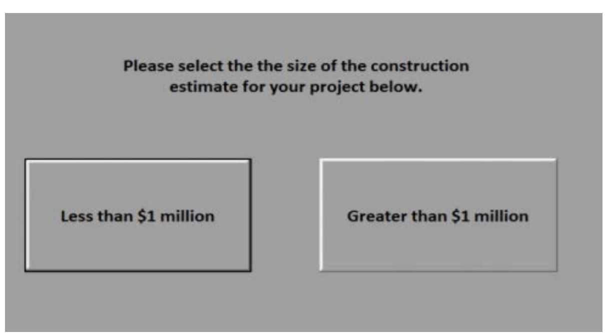


Figure 2.9 a.) Opening screen of KYTC tool

The contract time tool for small projects is essentially one regression equation using ten major project types and the project budget for estimating contract time. After input values are entered, the system will have estimated the mean and upper and lower ranges for the number of calendar days for the applicable project as shown in Figure 2.9 (b). The season estimator provides an estimate of the number of seasons for the project.

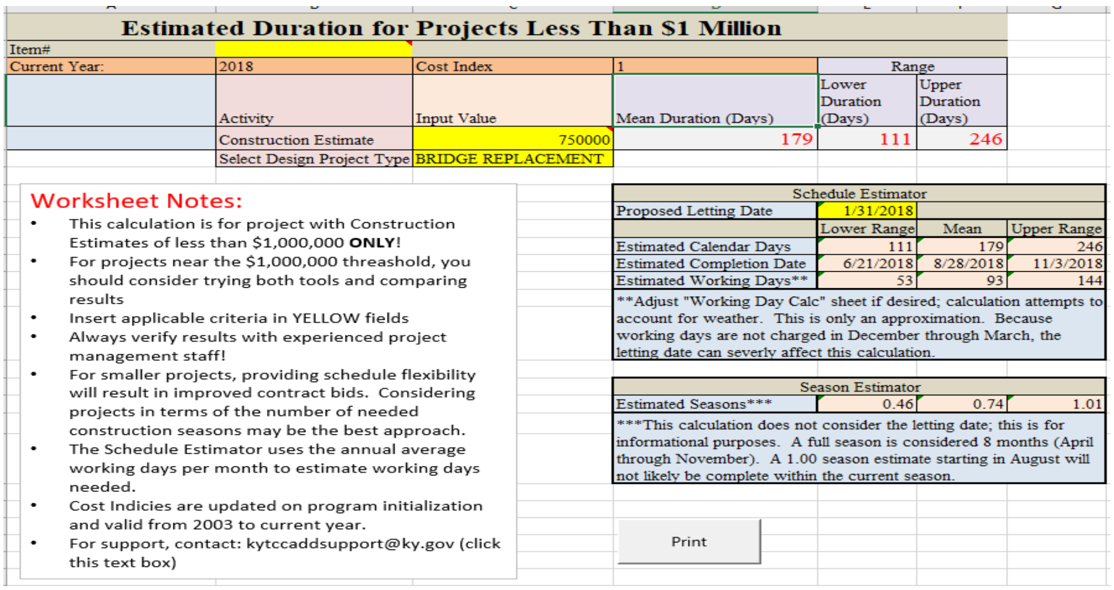


Figure 2.9 b.) Small bridge replacement project estimate in KYTC tool

The completion date is calculated by adding the calendar days determined by the system to the letting date. Additionally, approximately one month is added to this duration to account for the time transpiring between the letting date and the awarded notice to proceed. The "Estimated Working Days" are calculated using anticipated working days in the months of April through November according to historical temperatures, rainfall, and typical contractor schedules. For large projects, the KYTC tool provides five project types to select from namely open access, limited access, new route, bridge rehabilitation and bridge replacement as shown in Figure 2.9 (c). These projects undertaken by KYTC mostly fall under these five project types. The completion day calculation for each of these project types also follow a similar approach to that of a small project.

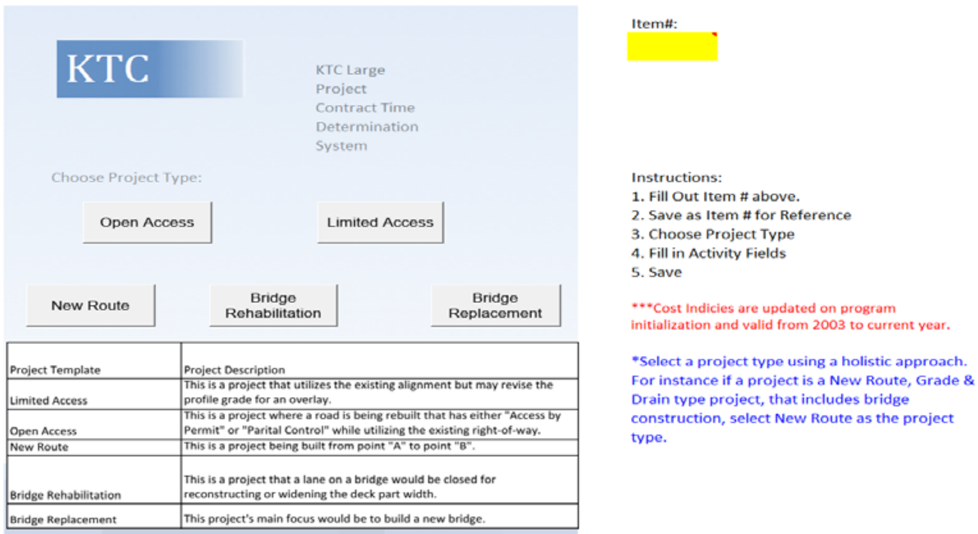
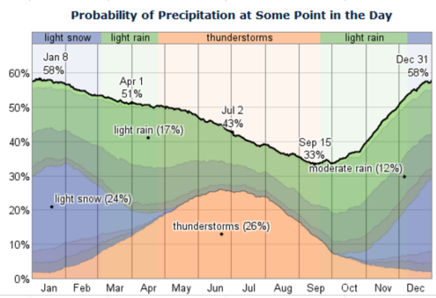


Figure 2.9 c.) KYTC tool title page for large projects

The table and information for working day calculations can be seen in Figure 2.9 (d). Adjusting the figures in the beige fields will adjust the number of working days in the months from April through November. Adjusted working days are calculated using the rainfall and temperature data. For each month, percentage of constrain caused by temperature and rainfall is used to calculate the adjusted working days. Once a contract time estimate is determined, careful consideration is given to its significance. The range provided by the tool is used by the estimator to determine the appropriate contract time for specific projects.

Kentucky Adjusted Working Days								
Month	Calendar Days	Working Days Per Week	Start Working Days	Adjusted Working Days (AWD)	Spec & Weather Adjusted Working Days	Rainfall Issues	Temp Issues	Adverse Days
January	31	5	22	11	0	20%	30%	11
February	28	5	20	10	0	25%	23%	9.6
March	31	5	22	13	0	33%	8%	9.02
April	30	5	21	15	15	30%	0%	6.3
May	31	6	27	19	19	28%	0%	7.56
June	30	6	26	19	19	25%	0%	6.5
July	31	6	27	20	20	23%	0%	6.21
August	31	6	27	20	20	23%	0%	6.21
Septembe	30	6	26	19	19	25%	0%	6.5
October	31	5	22	17	17	25%	0%	5.5
Novembe:	30	5	21	15	15	25%	5%	6.3
Decembe:	31	5	22	12	0	23%	25%	10.56

**Criteria: Moderate or greater rainfall/snow, temperatures less than 32 degrees (Source: weatherspark.com)



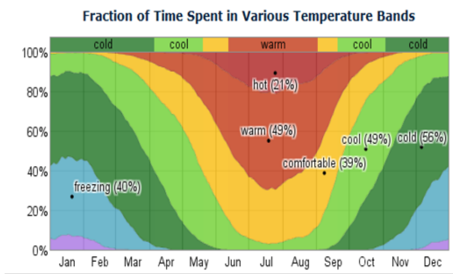


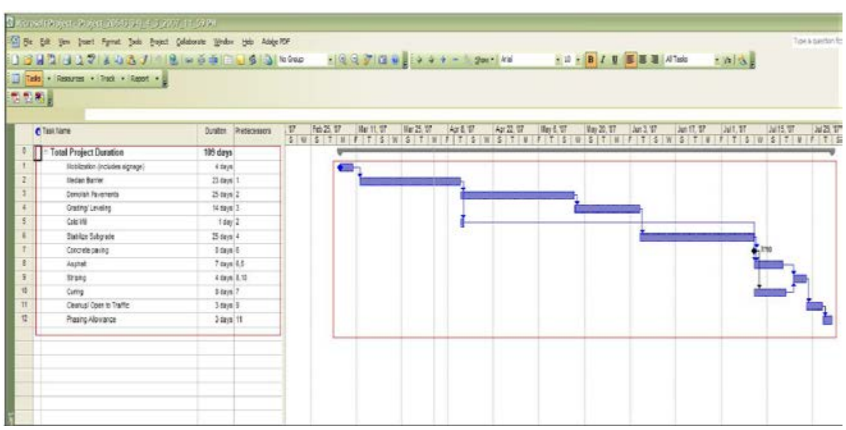
Figure 2.9 d.) Working day calculation of KYTC tool

2.3.6 Oklahoma DOT:

Researchers identified significant variables like weather, soil type and number of lanes as the factors affecting production rates of controlling highway activities (Jeong and Woldesenbet 2010). Oklahoma DOT follows a procedure involving an integrated automated scheduling. This procedure uses a custom developed User Interface and a Microsoft Access database (Jeong et al. 2008). “The database consists of default project type templates and production rates that is then linked with Microsoft Project to create a project schedule. Each controlling activity’s productivity was analyzed using recently completed highway projects. Experienced engineers as well the project scheduling coordinators assisted in determining the default average production rates as well as the ranges for all the selected controlling activities” (Jeong et al. 2008). All the controlling activities have a range of production rates that have a minimum value, an average value and a maximum value (Jeong et al. 2008). “In all the templates, each controlling activity is represented using the average production rate which the user needs to adjust to incorporate actual site characteristics and constraints" (Jeong et al. 2008). The benefit of this procedure is that the workflow is automated for the user, but there are opportunities for adjustments. Figure 2.10 (b) shows the use of Microsoft Project creating a bar-chart schedule of the project from the user input. Design and Construction staff refine the developed schedule to set the project's contract time. Figure 2.10 (a) displays a screenshot of production rates for some of the controlling (Jeong et al. 2008).

S.N	Controlling Activities	Unit	Min Rate	Avg Rate	Max Rate
1	**Mobilization**	days	2	4	5
2	**Traffic Control & Detours**		-	-	-
	Signs	days	20	30	40
	Striping	Lf	5000	10000	18000
	Barrier wall	Lf	625	1045	1336
	Pavements for detours	tons	400	862	1600
3	**Clearing and Grubbing**	days	1.5	4	6.2
4	**Removals**		-	-	-
	Pavements (Asp/Conc)	Sy	1200	1900	2600
	Excavate/ Borrow Bridge Structure	Sy	80	620	1600
	Cold Mill pavement	Day	-	-	1
5	**Grading - Top soil, excavation & embankment**		-	-	-
	Unclassified Roadway Excavation/ borrow	Cy	1800	2825	7000
6	**Sub Grade operations**		-	-	-
	Soil Stabilization works (Lime or Fly Ash)	Sy	1900	2500	4600
7	**Drainage Structures**		-	-	-
	Storm Drainage Piping	Lf	50	110	190
	Manholes	EA	-	1	1.5
	RCB's (Extend/ install 4'x2', 3'x3', etc)	Lf	25	60	95
8	**Retaining Walls**				
	Excavation & backfill	cy/day	200	350	500
	Rebar	tn/day	2.5	3	4
	Formwork	sfca/day	1700	2200	2400
	Conc pouring + cure	cy/day	75	80	90

a.) Production rates chart for some controlling activities in OKDOT.



b.) Total project duration and CPM network diagram from the tool in OKDOT.
Figure 2.10 OKDOT CTDS

CHAPTER 3. RESEARCH METHODOLOGY

The research methodology that was followed for this study is represented in Figure 3.1 below. This chapter provides a description of research work during each phase of the study. The study is divided into various phases based on chronological order. The research started with a through literature review and is followed by data collection stage where state DOTs were contacted regarding their contract time determination procedures. Current practices of production rate estimation and contract time determination procedures were reviewed, and a gap analysis was conducted. The data collection stage provided the necessary input required for statistical analysis. The current practices were used to determine which statistical analysis would be appropriate for production rate estimation and a construction productivity tool was developed using the results of the analysis.

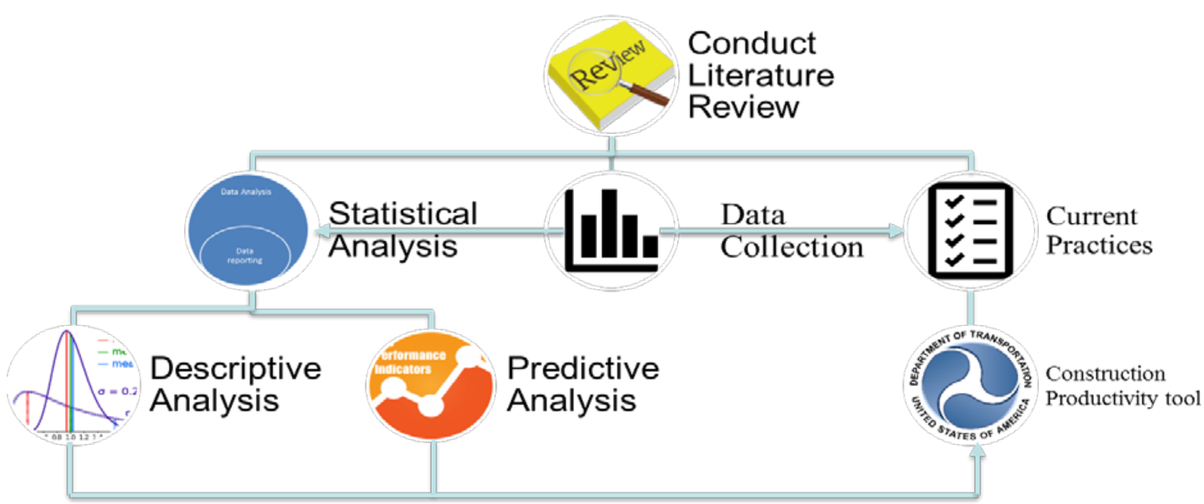


Figure 3.1: Research Methodology

3.1 Literature Review

As mentioned in chapter 2, this research started by an intensive literature review that was conducted to find the potential factors that may affect productivity of construction projects as well the different techniques used in previous studies to determine production rates and contract time. Chapter 4 also consists of a review of state DOT's contract time determination manuals and of the Federation Highway Administration (FHWA) to determine what construction activities they consider useful and significant in estimating contract time, the production rates utilized, and the methodology used in determining the reported production rates. These construction activities were contrasted to the ones currently listed by MDT and recommendations were made as to what MDT should adopt. Moreover, information regarding the current practices of Montana DOT, which are documented in the contract time determination manual(MDT 2008) is studied extensively to get a broader understanding on the DWR data. The different methodologies used by MDT designers to determine production rates were also compared to that of other DOTs.

3.2 Data Collection

This phase focused on collecting the necessary data for this study. It consisted mainly of determining the target population from various DOTs to obtain their current practices, searching DOT websites and collecting the data. This data is incorporated with the historical work report data to conduct meaningful analysis.

3.2.1 Gathering published data from DOTs

The first task in this phase was to gather published manuals of contract time determination and production rate charts from various DOTs. Given the scope of our research project, 46 state DOTs were contacted regarding their documentation in highway construction contract time determination procedures for projects in their respective states and to obtain published production rates or production rates they are achieving on highway projects.

3.3.2 DWR Data and other sources

MDT engineers had provided the research team with raw historical work report data which consisted of information pertaining to various aspects of highway construction as described in chapter 5. MDT data obtained from online sources regarding the maintenance district boundaries and urban and rural is thoroughly studied to determine if these parameters have any impact on the production rates achieved on a project. Based upon review of data, the research team decided to focus on 13 parameters for the most frequent work items in the historical data as well as major work items available in state DOT manuals. Most of these parameters are available for each work item. Moreover, some of the activities that were part of this study such as cement treated base (CTB) or pulverizing CTB have little project data points available and effective analysis on established factors has its limitations.

Specialty contractors are the vendors that worked on only one project type for MDT. Projects completed by these contractors were identified from the historical DWR data to analyze weather there is significant influence on production rates as compared to other projects.

Table 3.1: States contacted regarding current practices of contract time determination

States contacted	States responded	States with documented procedures	States that do not release procedures
46	30	26	3

3.3 Descriptive Statistical Analysis

In this phase, descriptive statistics or summary statistics is used to analyze the data. Quantitative research uses vast amounts of data. Descriptive statistics is the term given to the analysis of data that helps describe, show or summarize data in a meaningful way. Descriptive statistics do not, however, allow us to make conclusions beyond the data we have analyzed or reach conclusions regarding any hypotheses we might have made. Raw data is hard to visualize what the data was showing, especially in the case of DWR data. Descriptive statistics therefore enables us to present the data in a more meaningful way, which allows forensic interpretation of the data. Typically, there are two general types of statistic that are used to describe data:

- **Measures of central tendency:** These are ways of describing the central position of a frequency distribution for a group of data. We can describe this central position using several statistics, including the mode, median, and mean.
- **Measures of spread:** These are ways of summarizing a group of data by describing how spread out the scores are. Measures of spread help us to summarize how spread out production rates are for selected parameters. To describe this spread, a number of statistics are available to us, including the range, quartiles, absolute deviation, variance and standard deviation.

Examples of descriptive statistics methods used in this study include tabulated description (i.e., tables), graphical description (i.e., graphs and charts) and statistical commentary (i.e., a discussion of the results). These measures are used to summarize seasonal variations, district level comparisons, urban and rural production rates as well the production rate comparison between contractors.

3.4 Predictive Statistical Analysis

This phase consists of choosing appropriate analysis methods for the desired outputs and developing a statistical predictive model using the JMP Pro statistical software application.

In the analysis, the independent variables are the factors that affect production rates. Those variables that have the least effect on productivity are removed from the model. The analysis considers only factors that have some or significant effect on the dependent variable. The dependent variable of the predictive model is production rate that is estimating based on the 13 parameters (independent variables) previously determined. For equipment variables, imputation was done by mean for each project.

Multiple regressions are classified mainly by the method used to add independent variables into the prediction model. Simultaneous multiple regression adds all variables into the model at the same time. In contrast, using sequential multiple regression will permit the input of these variables in the order of preference. Using stepwise linear regression, the contribution of each of the independent variables in explaining the variance in the dependent variable and the order of statistical importance of these independent variables is given priority. It is important to note that these different types of regressions will generate the same regression equation if the same inputs are used (same independent variables and same dependent variables).

The second task that was done in this phase is the selection of the appropriate statistical methodology. In this study, the model involves exploring relationships between more than two variables that regression analysis is very useful. To assess factors which influence production rate, stepwise linear regression model is used through this study. A multiple linear regression model comprises two components,

$$Y_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki} + \varepsilon_i$$

Where a single response measurement Y is related to a single predictor X for each observation. Error term ε_i is included to specify how the responses vary around their mean values. There are five primary assumptions fitting a regression model that dependent variable Y which is the production rate in the study has linear relationship with independent variables Xs, and errors are normally distributed with un-correlation and homoscedasticity. Moreover, all the Xs considered are independent.

Since there was an extensive list of factors that affect construction productivity for various work items, a stepwise linear regression approach considering all the independent variables (parameters) was considered. However, as previous studies have shown, not all parameters have an impact on each work item. That's why it is extremely important to identify the main parameters that affect the productivity of each activity and to account for these specific parameters when predicting productivity rates for future projects. To obtain these desired outputs, the research team used stepwise regression which is designed to find the most critical set of independent variables that affect each dependent variable the most.

Independent variables are added to the equation one at a time and the critical variables are selected by finding the combination of variables that maximize R^2. This regression will keep adding variables to the model until the highest adjusted R^2 statistically possible by adding any of the variables that are not in the equation yet or until all of the variables are included (Chatterjee and Hadi 2006). We can say that the independent variables will only be included in the equation if they have some statistical impact on the analysis. This gives strength to the stepwise regression model, which now only contains independent variables that have a significant effect on the production rates.

Stepwise linear regression for each activity are summarized and shown later in this report in Appendix B for the different activities. After getting the best selection of independent variables for each of the dependent variables, a final multiple linear regression model was generated and its residual standard error was obtained. Consequently, for each dependent variable, the model includes only the independent variables that were selected.

3.5 MDT Construction Productivity Tool

This phase involves developing a production rate estimation tool and providing the MDT engineers with guidelines on how to use it and how to update it in the future.

3.5.1 Development of Tool

Identifying the factors that significantly impact productivity by relating them to the actual productivity achieved on site obtained from analyzing the historical data, provided a rich dataset consisting of major work items to develop MDT construction productivity tool. This tool can be used to accurately determine 35 appropriate production rates. In fact, it allows MDT engineers to precisely select the productivity rates applicable to their project based upon the identified criteria.

3.5.2 User Guidelines and Limitations of Tool

Given the importance of having a good estimate of contract time, tool provides the users with a production rate estimates that is more adoptable than what is currently used by the MDT today but also with some guidelines on how this tool should be used as well as a description of the circumstances under which this tool can be used to avoid misleading rates and bad estimates.

3.6 Summary of Results

This section consists of summarized information obtained in the previous tasks into a tabular format. It includes a narrative on the use and limitations of use of data determined in this study for estimating production rates. An overview of the database and guideline for using the tool are provided.

CHAPTER 4. CURRENT PRACTICES OF STATE DOTs

This chapter discusses current practices used by State DOTs in Contract time determination procedures. Due to the interrelatedness of production rate estimation procedures and contract time determination, this chapter puts focus on the review of various contract time determination procedures used by State DOTs obtained from DOT personnel and websites. This chapter also discusses key findings from the NCHRP Synthesis 502.

4.1 Current Practices of State DOTs in Contract Time Determination

In this section, the documented procedures and current practices of State DOTs regarding contract time determination are discussed. The research team has contacted 46 state DOT personnel, out of which 30 DOTs responded to the request, regarding their contract time determination procedures and Production rate estimates for controlling activities. The states which responded, are divided into three categories (Figure 4.1) below. Figure 4.1 also represents the states for which data wasn't available in green.

- DOTs that do not share their contract time determination guidelines (blue) - 2 DOTs
- DOTs without documented contract time determination guidelines (orange) - 3 DOTs
- DOTs with documented contract time determination guidelines (red) – 25 DOTs

Some state DOTs (Kansas and Arkansas) maintain production rates used for estimation of contract time out of the public domain. This category of DOTs do not share the production rate estimates or the contract time determination procedures. Maine, Colorado and Vermont do not have documented procedures for determining contract time. Maine DOT has not established any procedures as most of their projects fall in the range of $1-3 Million and contract time determination is relatively straight forward. Colorado project engineers use their experience and knowledge to determine contract time prior to advertising. Majority of the DOTs that did not have formal procedures for determining contract time have mentioned that resident engineers are responsible for estimating contract time using their expert judgement.

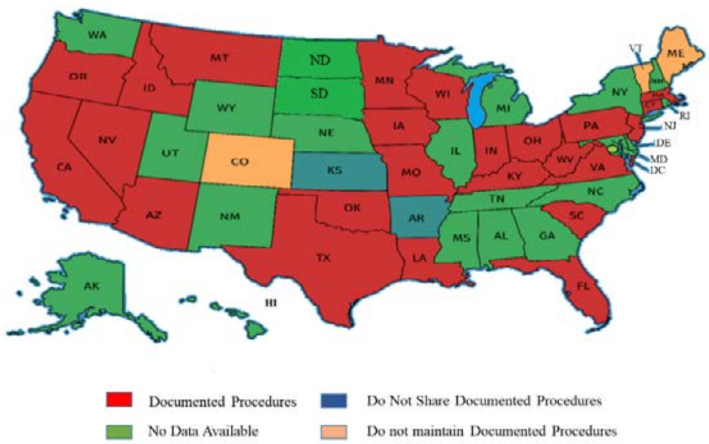


Figure 4.1: Representation of DOTs Contract time determination procedures

PennDOT has only 20 work items yet it is used consistently because it goes through multiple reviews from different divisions. Once the project schedule is complete, it is reviewed in a meeting by stakeholders. The major stakeholders include a.) Utility unit; b.) Environmental unit; c.) Construction Unit; d.)Right of way unit; e.) Traffic unit; f.) Project manager; g.) Central office. Once the schedule has been modified to the satisfaction of the attendees, it is then used to determine the project completion date and project duration. Revision of the project schedule by all the major stakeholders may improve the accuracy of project schedule.

The success of Contract time determination hinges on the accuracy of production rates and a thorough understanding of job parameters and limitations. Some of the important aspects regarding Contract time determination across various DOTs are

- Production rates are used to help develop a bar chart for a construction project. A Bar chart must be filed anticipating phasing, lag and delays of various activities. It represents expectation from the site activity.
- Lead-time (if required) for work items must be included in the estimation of contract time. Phasing is considered crucial by some DOTs. The most commonly cited factor that affected the setting of contract time was project phasing followed by maintenance of traffic and the time of letting. DOTs require minimum amount of materials to be stock piled and reviewed prior to the start of related phase of work. This would keep the supply intact without leading to delays in production.
- Many DOTs have winter shutdown periods. This is an important aspect to be considered while setting the contract time. Most winter shutdown periods are from mid-November to mid-April. Projects whose lifecycle is less than four to six months shouldn't be let out if their schedule overlaps with winter shutdown or they should be fast-tracked so that the project is completed before mid-November. Budget constraints must be considered a project for fast-tracking.
- A comparison of practices of various state DOTs for developing schedules are represented in Figure 4.2 (a).

4.1.1 Scheduling methods

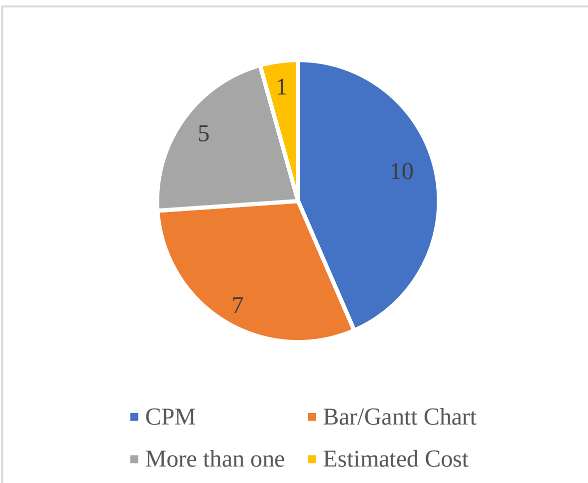
There is a significant variance between the scheduling methods used among various state DOTs (Figure 3.2 a). CPM is the most common methodology followed by Bar/Gantt Charts. Bar charts offer advantages of wide familiarity and ease of understanding. However, they fail to show interrelationship and inter-dependency among various work items and evaluation becomes difficult when change orders are eminent (Taylor et al. 2017). Thus, bar charts are not recommended for large or complex projects. This is where CPM proves to be beneficial. It addresses the flaws in the bar chart method but requires knowledge and skill to be implemented successfully(Taylor et al. 2017). Since both these methods have intrinsic limitations, 7 out of 23 states recommend both these methodologies depending upon the complexity of the project (Taylor et al. 2017).

Virginia DOT implements Estimated Cost method for scheduling, but its implementation is limited to projects that are repetitive and linear in nature. The Estimated Cost Method of contract time determination utilizes a comparison of dollar value to time (VDOT 2007). Based on historical information, tables illustrating project cost versus project time are developed for different project types, traffic volume, and geographic location. Examples of such project types include new construction, reconstruction, overlay and widening projects, pavement repair, and bridge construction. Contract time is essentially determined based solely on the amount of the engineer's estimate (VDOT 2007). For non-complex projects and projects affecting small volumes of traffic, this procedure may be appropriate. The estimated cost method is not recommended for use on projects where completion time is a major factor. Virginia DOT uses this method on non-complex projects (VDOT 2007).

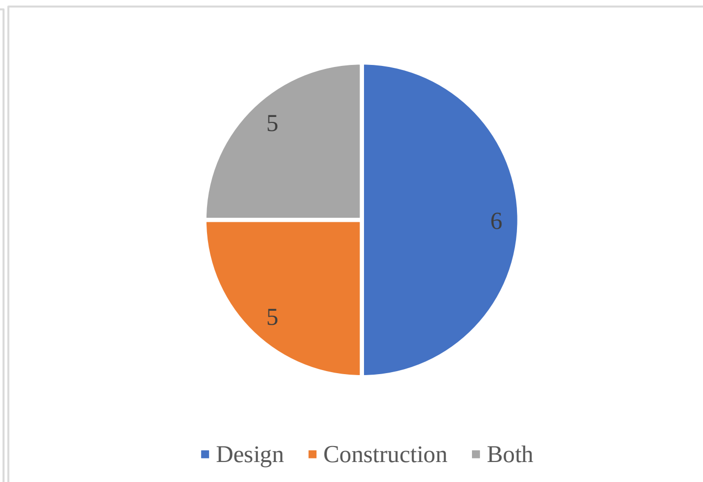
4.1.2 Department responsible for CTD

In terms of departments handling the contract time determination, the current practices are equally divided between design division and construction division among state DOTs (Figure 4.2 b). Out of the data collected from 30 DOTs, only 12 clearly define which department handles the CTDS. Primarily, 50% of these 12 state DOTs reveal that a designer handles CTDS while 25% state that construction department is in-charge and in the remaining 25% state DOTs, the CTDS is handled by both construction and design department. The current practices in this context are unknown for

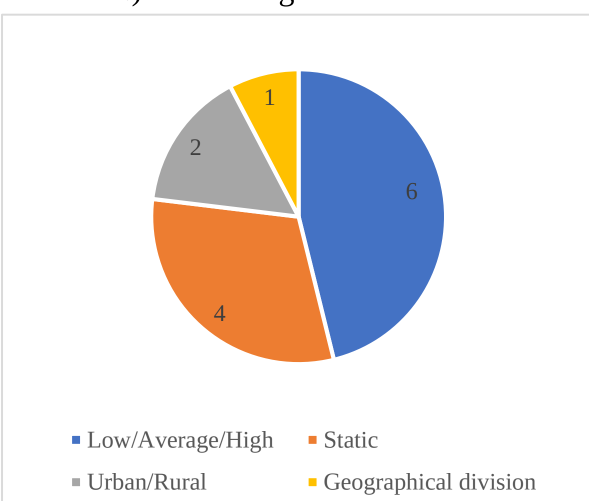
11 states. Secondly, (Taylor et. al 2017) report that design division handles the contract time estimation amongst the 28 state DOTs that have a formal documented procedure. However, the findings from NCHRP Synthesis 502 indicate that the contract time estimates are more accurate when developed by the construction division rather than the design division.



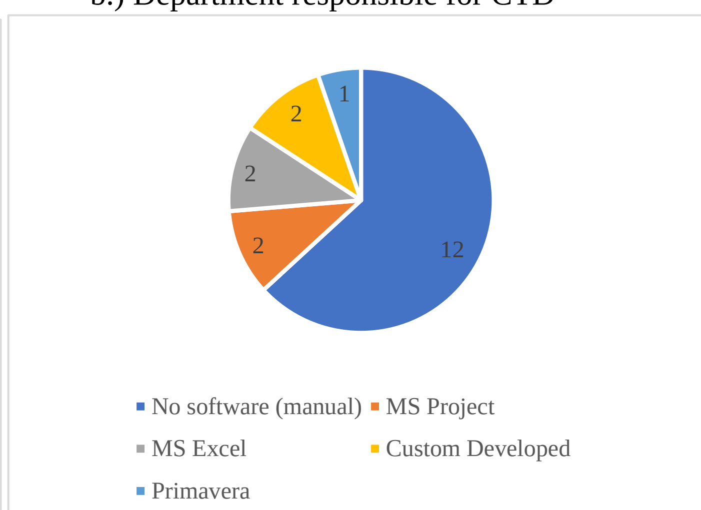
a.) Scheduling methods followed



b.) Department responsible for CTD



c.) Classification in Production Rates



d.) Type of software used for CTD

Figures 4.2: Pie charts for classification among DOTs

The DOTs should maintain a system where the accuracy of contract time is determined after each project and lessons learned must be applied on the future projects. In practice, highway construction projects are more scrutinized for budget performances while less feedback is provided on project duration estimates leading to a lack of feedback and coordination between the design and construction divisions. NCHRP Synthesis 502 stresses on the improvement of the feedback loop between these two divisions to improve the existing contract time estimation techniques.

4.1.3 Classification in Production Rate

This classification provides the different types of production rate charts maintained by state DOTs as shown in Figure 4.2 (c). Four of the thirteen DOTs maintain static production rates which are standard across all projects and must be adjusted as per judgement of the estimator. Six DOTs maintain three values of production rates for each work item (low, average and high). This procedure provides the estimator with the range of possible values for production rates. Urban and rural classification is used by two DOTs and only one DOT uses geographical division. Geographical division is useful where there is high variance in topography of the state.

4.1.4 Type of software used

Table 4.1 provides information regarding different software prevalent across State DOTs used for contract time determination. Template based CTD system typically uses templates for different project type and with the given user input the contract time is calculated as followed by Kentucky transportation cabinet (KYTC). Examples of each of these methods can in found in section 2.3. KYTC also uses regression based equations for its different project types to accurately estimate the contract time. Many DOTs that use standard production rate charts usually prefer bar chart-based system to determine the contract time for a project. This categorization of various CTDS provides the states with the opportunity to select the appropriate tool that fits their requirement.

Table 4.1: Type of software used for CTD

Category	State DOTs
Template Based	Massachusetts, Kentucky, Oklahoma, Texas
Regression Based	Kentucky, Indiana, Ohio
CPM Based	California, Colorado, Florida, Indiana, Iowa, Missouri, New Jersey, Oklahoma, Washington, West Virginia, Wisconsin
Bar/Gantt Chart Based	Arizona, Arkansas, Connecticut, Florida, Hawaii, Idaho, Minnesota, Montana, Virginia, West Virginia, Wisconsin

4.2 Key influential factors across DOTs

NCHRP 502 Synthesis Report published key factors influencing contract time and production rate estimation. The survey contacted 29 state DOTs to analyze and shortlist influential factors that affect states contract time determination procedures (Taylor et al. 2017). The survey results published by Taylor et al. are incorporated into this study to understand best practices and shortlist the influential factors across state DOTs. This section provides a brief description of the NCHRP 502 synthesis report survey results that are related to contract time estimation methods, accuracy of contract time and production rate estimation tools and their ease of utilization.

The majority of contract time estimation methods (63%) in use by state DOTs are custom developed, state-specific systems that utilize generic job logic and production rates (Taylor et al. 2017). 7 DOTs indicate that the error in estimated contract time is more than 50% while 10 DOTs are unsure regarding the accuracy (Taylor et al. 2017). High percentages of inaccuracy in contract time estimation leads to schedule delays. If incentives/disincentives are used in the contract, high percentages of inaccuracy in contract time estimates could adversely affect the optimum utilization of funds available to the transportation agency.

Among the 29 DOTs contacted by this study, 60% use CPM-using project specific logic while only 26.7% use CPM-using static logic.(Taylor et al. 2017) Historic project durations are considered by 66.7% of the DOTs (Taylor et al. 2017). A number of State DOTs using Daily work report data to establish appropriate production rates. While 66.7% of DOTs use static production rates that aren't frequently updated, three DOTs (Kentucky, Indiana, Ohio) use regression based templates for production rate estimations and indicated that the regression method was far more accurate and easier to use (Taylor et al. 2017). 60% of the respondents claimed that they used engineer's estimates and four respondents considered contractor input before finalizing the production rates for major work activities. Construction personnel feedback is also suggested to make the estimates more pragmatic.

Five DOTs reported that contract duration for 62.5% of their projects are overset while only two DOTs reported that 25% of their projects contract duration is underset (Taylor et al. 2017). The study also reveals that 50% of the projects require a change in contract duration. These responses confirm the need to improve existing procedures of contract time determination. Table 4.2 describes the ease of production rate/contract time estimation tools used by transportation agencies. Only 5 DOTs claimed that the tool being used was effective while 50% of respondents claimed that tools were dependent on construction experience. It is necessary for a DOT to maintain a system that is easy to use. If the system is sophisticated, the engineers will revert back to using standard production rate tables.

Only two DOTs stated that their contract time estimation tool reduced claims for additional time and considered the system moderately accurate (Taylor et al. 2017). Agencies do not prefer complicated tools to estimate production rates as they are not user friendly.

Table 4.2: Ease of production rate/contract time estimation tools(Taylor et al. 2017)

Description	**Percent**	**Responses**
Simple	78.6%	11
Sophisticated	21.4%	3
Labor Intensive	28.6%	4
Program Assisted/Automated	42.9%	6

Calculated by hand	50.0%	7
Construction Experience Dependent	50.0%	7
Effective	35.7%	5
Reduces Claims for Additional Time	14.3%	2
Is an Asset to Managing Agency Personnel	7.1%	1

Table 4.3 summarizes the responses by DOTs for scope for improvement in their current contract time determination procedures or tools (Taylor et al. 2017). According to the study, increased feedback between agency divisions is considered top priority for 58.6% of DOTs which is trailed by improved accuracy and increased automation in the system (Taylor et al. 2017). Only 7.1% of DOTs claimed that there was no improvement required in their contract time determining procedure.

Table 4.3: Areas of Improvement in contract time determination procedures (Taylor et al. 2017)

Value	**Percent**
Improved Accuracy	37.9%
Improved Usability	20.7%
Increased Automation	34.5%
Adaptability to Multiple Delivery Methods	34.5%
Increased Feedback/Communication Between Agency Divisions	58.6%
No Improvement Needed	6.9%
Other - please specify	20.7%

4.3 Current Practices of Montana DOT

In this section, the current practices of MDT are reviewed. Analyzing MDT contract time determination procedures provides the research team with influential factors that affect production rates and contract time in Montana. MDT utilizes documented production rates for major work activities to establish contract time. A project consultant is responsible for taking lead on creating and maintaining contract time, during the design phase or at least prior to the Plan in Hand (PIH) review. During the PIH review, the production rates are adjusted if deemed unsatisfactory. If additional time is required to develop the schedule, or if the project is too complex to finalize at the time of PIH, the decision will be made at the Plan-in-Hand to schedule a Sequencing Coordination Meeting to establish a contract time. (MDT 2008). The general process that is followed to make the initial estimate of contract time in MDT represented in Figure 4.3.

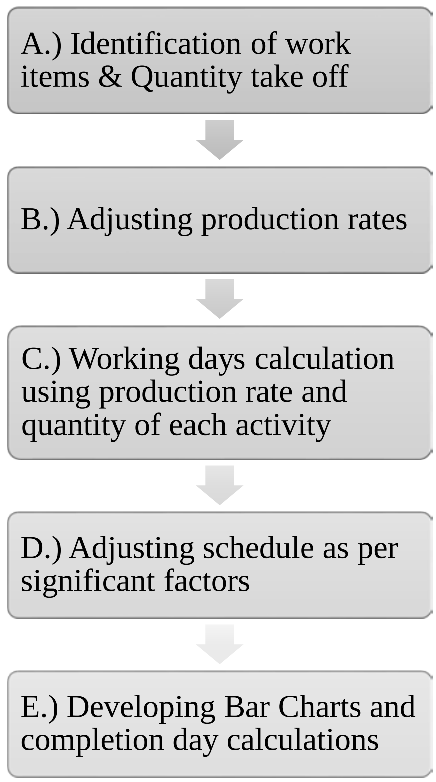


Figure 4.3: Contract time determination process of MDT

a.) A list of major construction activities that will take place on the project is developed by reviewing the plans. MDT maintains a list of 31 major work items that impact the critical path of a project. Small items or those items that will be performed in conjunction with other work items are considered incidental to the contract time. The quantities are a good indicator for the amount of work that needs to be performed. (MDT 2008) b.) Determining the duration of activities using the standard production rates may be modified based on known project specific information and documented (MDT 2008). Factors that are considered for affecting the production rates include regional differences (grading in mountainous terrain will be slower than on the prairie), construction in restricted areas (urban, limited R/W) may require more time, the need and availability of specialized construction equipment and greater traffic volumes.

c.) Total duration calculated for each critical path activity will be the total number of working days. Timing restrictions like environmental commitments, commercial limitations (tourist season, fairs, and other local events), irrigation season, weather/seasonal factors (spring runoff) are considered along with limitations on specific activities that have method specifications, sequenced construction for specific items and specific segments of the project, particularly for developed/urban areas (MDT 2008).

d.) Utilities relocations done as part of or in conjunction with the contract and providing access and maintaining traffic can also affect production rates. (MDT 2008) The predictive method for bridge contract time estimation is problematic for deck overlays and other types of rehabilitation projects where a lot depends on the expertise and ingenuity of the contractor. MDT has documented construction sequencing and published production rate for major activities in bridge construction. All the significant factors which effect the project schedule are accommodated before developing the bar charts.

e.) The bar chart is developed using the number of days calculated for controlling work items on the critical path as shown in Figure 4.4 (MDT 2008). The chart will show the resulting working days. For calendar day or completion date contracts, the days must be converted from a five-day work week to a six or seven-day work week, depending on the requirements of the contract. For rural projects, a 10% contingency factor and for urban projects, a 20% contingency factor is added to the contract time.(MDT 2008)

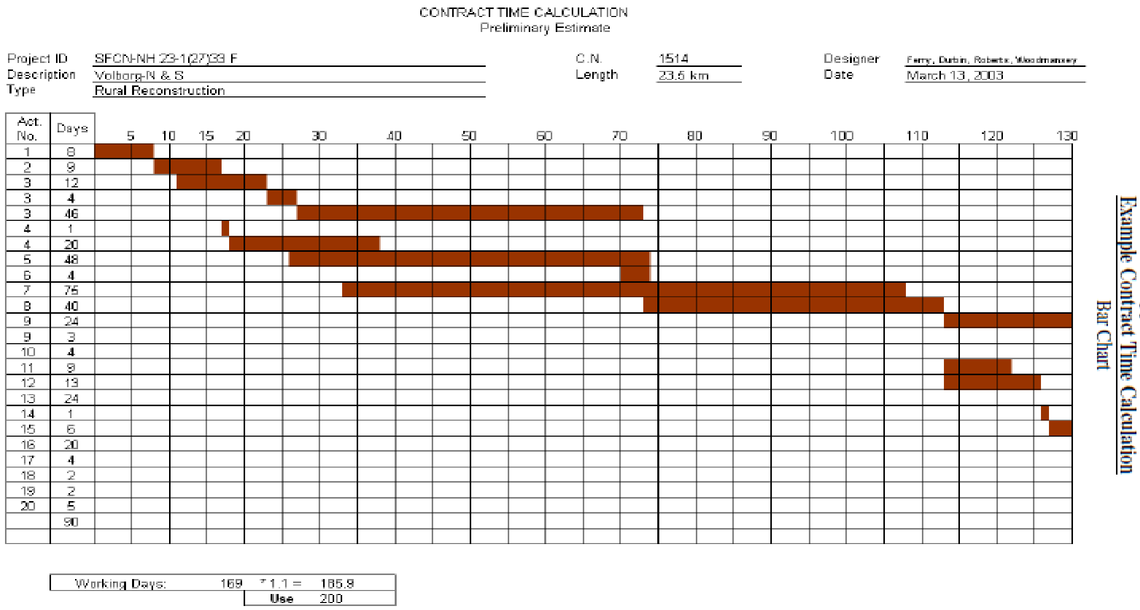


Figure 4.4: Sample barchart developed for rural reconstruction by MDT

Analysis of current practices and review of NCHRP 502 Synthesis report led to shortlisting factors that are significantly crucial for production rate estimation. The research team considered quantity of work to be produced, district is considered to accommodate topographical differences in the state of Montana, season of work, if the project is in a urban or rural location, budget of the project and contractor characteristics on past project are used to develop statistical models to predict production rates. These statistical models are discussed in detail in chapter 5 and chapter 6.

CHAPTER 5. DESCRIPTIVE ANALYSIS OF DWR DATA

This chapter discusses a descriptive analysis of various parameters available in the historical daily work report data and bid data of Montana DOT. This chapter provides insights about which parameters significantly influence production rates. This chapter also presents the determination of major work activities for highway construction based on their high frequency in the raw data, as well as discusses a comparison between them with those items published in the documented contract time determination manual (MDT 2008).

5.1 Data Description

The information from bid data and daily work report data were consolidated to develop a central database. Data obtained from MDT include is 10 years of historical daily work report data of MDT and their associated bid data. The variables considered from the DWR data for analysis of production rates are shown in Figure 5.1. The item level data consists of unique contract ID and project number, item code and description which uniquely describes the type of construction activity taking place on the field, vendor ID and name, the daily work report date which provides the date on which quantities of work have been recorded. The contractor and equipment data provide information regarding the number of supervisors present, workers on the field, total worked hours, equipment availability and usage information. Bid data of MDT is used to map the total project cost with the DWR data. The budget category is defined as projects below $ 2 million and above $2 million. This basis is determined based on the median value of the project budget available from the data.

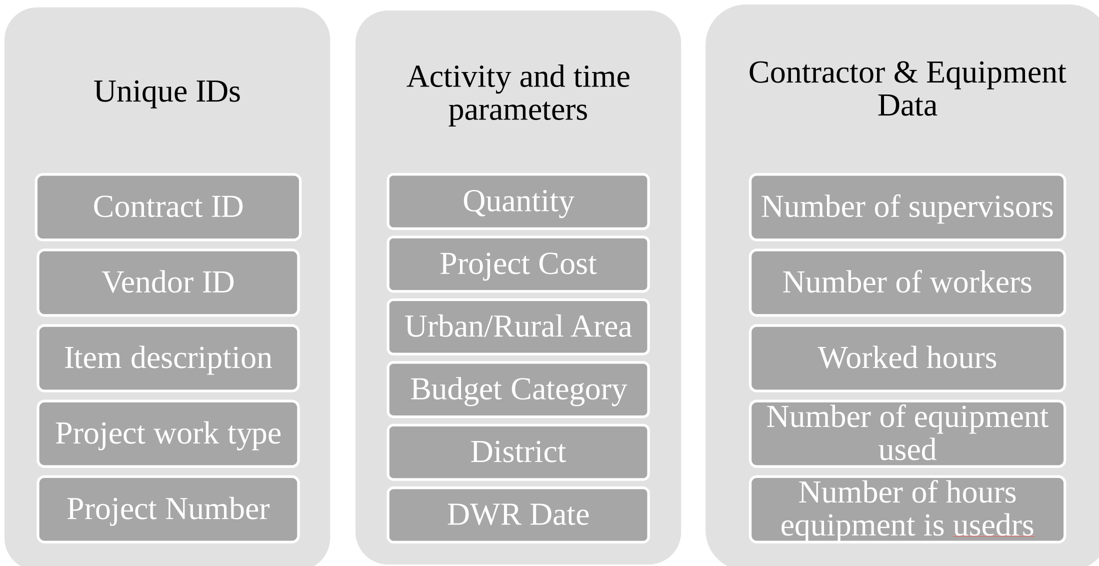


Figure 5.1: Key variables selected from DWR data

Montana is categorized into five maintenance districts (Figure 5.2) District 1 – Missoula, District 2 – Butte, District 3 - Great Falls, District 4 – Glendive and District 5 – Billings. Using Tableau software, Latitude and longitude coordinates from MDT bid data are used determine contractor presence in single/multiple districts. Maintenance district has profound impact on production rates as Montana has a varying topography (mountainous and plains).

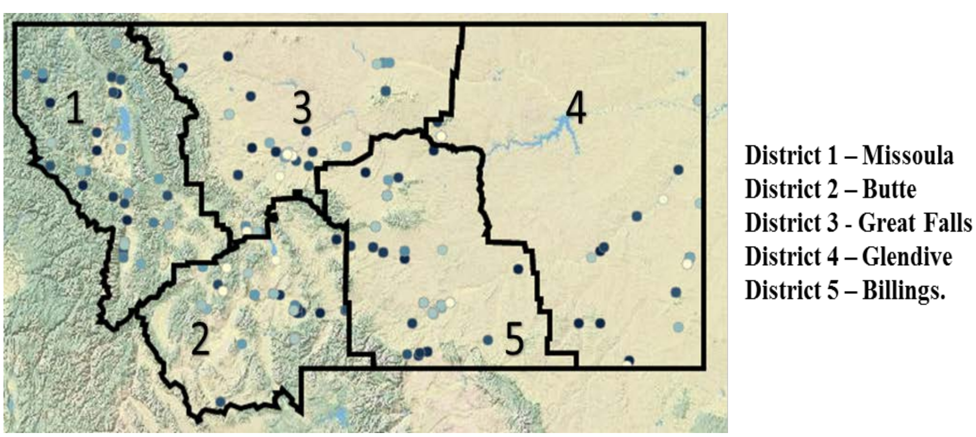


Figure 5.2: Topographical Map representing District boundaries and project locations in Montana.

Production rates are historically higher in a plain region than a mountainous terrain as it is challenging to maintain ideal production rates on mountain terrain. A location indicator has been established to differentiate between rural and urban projects in Montana. The major urban regions in Montana are identified using public data available on the web. This information is used to map the all projects available in the DWR dataset to extracted projects that are in urban areas. The descriptive analysis conducted using this data is discussed in section 5.2.

5.2 Descriptive Statistical Analysis

This section discusses the findings of descriptive analysis on parameters, such as seasonal variations of production rates, production rate comparison among various project types, and variations in production rates among different districts, urban and rural areas in Montana. The comparisons and analysis discussed in this section are listed below:

- Seasonal variation of production rates
- Variation in production rates across project types
- District level comparison of production rates
- Urban and rural production rate comparison
- Production rate comparison among contractors
- Adverse day calculation

Before the descriptive analysis were conducted, raw DWR data needs to be cleaned. Production rates are obtained when the total quantities of a work item produced in the projects are divided by the total number of unique DWR days recorded for the activity. The raw data consists of many null values in its quantities. To overcome this problem, the research team has calculated production rates using the dataset with and without the null values. The average production rate is calculated for each controlling work item.

$$\text{Average Production Rate} = \frac{\text{Total quantity of material produced}}{\text{Unique DWR dates when the particular activity is recorded}}$$

This study is focused only on major work items which account for a large portion of the total work of a highway project. The Montana DOT has static production rates for 31 controlling activities. DWR item level data is used to determine most frequently occurring activities across various project types. After careful evaluation of the documented controlling activities of MDT and most frequent activities from DWR data, a list of 35 activities have been shortlisted as controlling activities. Table 5.1 shows the shortlisted controlling work items along with average production rates calculated from DWR data. The table shows that the published production rates are comparable to that of average production rates across Montana. To extract insightful information from the DWR data, production rates are calculated for each project for the shortlisted 35 controlling work items. A central database is created which consists of data merged from DWR data, bid data and other parameters described in section 5.1. The central database is used to conduct descriptive analysis on production rate estimation for major work activities.

For initial calculation of production rates, each activity has been considered separately. Average production rates of each of these activities is determined by dividing the total quantity produced across all projects undertaken by MDT and unique DWR dates when the quantities are recorded on site. Unique DWR dates are considered to avoid double-counting when the same activity is conducted on multiple locations or when an activity is recorded multiple times in a day. Descriptive analysis of the data is conducted to check whether the input variables are significant. Some of the analysis conducted shows comparison between production rates of different seasonal, variations within the districts of MDT and between urban and rural areas.

Table 5.1: Production rates of controlling work items

SN	Item description	Production rates from DWR data	Units	Production rates from Manual	Unit
AA	CRUSHED AGGREGATE COURSE-MEDIUM	2621	CUYD	2600	yd3/day
AB	CRUSHED AGGREGATE COURSE -LARGE	4041	M3	3000	m3/day
AC	EXCAVATION-UNCLASSIFIED	21048	M3		
AD	EXCAVATION-UNCLASS BORROW	8480	M3	4500	m3/day
AE	COLD MILLING	29294	SQYD	35000	yd2/day
AF	BEDDING MATERIAL	86	M3		
AG	RUMBLE STRIPS	9	KM	8	Lane KM/day
AH	COVER - TYPE 1	51395	M2		
AI	COVER - TYPE 2	15440	M2		
AJ	TRAFFIC CONTROL DEVICES CB	3113	UNIT		
Ak	Temp PAVEMENT MARKINGS	4	MILE		
Al	CURB AND GUTTER	253	M	300	m/day
AM	FENCE-CHAIN LINK	1405	LNFT	600	ft/day
AN	SIDEWALK	263	M2	250	m2/day
AO	GUARDRAIL STEEL	430	LNFT	750	ft/day
AP	Seeding	11	ACRE	12	acre
AQ	SODDING	513	SQYD	3500	yd2/day
AR	PCCP	4134	SQYD	2000	yd2/day
AS	Muck Exc.	2846	CUYD	650	yd3/day
AT	Top Soil Excavation	3492	CUYD	4000	yd3/day
AU	MOBILIZATION	1	LS	2	days min
AV	Street Exc.	1492	M3	500	m3/day
AW	CTB Pulverized	9045	SQYD		
AX	CTB	2170	M3	1000	m3/day
AY	Culvert RCB	32	LNFT	30	ft/day
AZ	Drinage Pipe	132	LNFT		
BA	Cold Recycled Plant Mix	22126	SQYD	2	lane mi/day
BB	PMS -PLANT MIX BIT SURF	2444	MT	3300	tons/day
BC	Epoxy	6801	GAL	4	days
BD	Words and Symbols	36	GAL	2	days
BE	CONCRETE PAVEMENT GRINDING	3031	SQYD	3500	yd2/day
BF	TEMPORARY EROSION CONTROL	2089	LS		
BG	EMULS ASPHALT CRS-2P	233	TON		
BE	EXPANSION JOINT	59	LNFT		
BF	Riprap	243	CUYD		

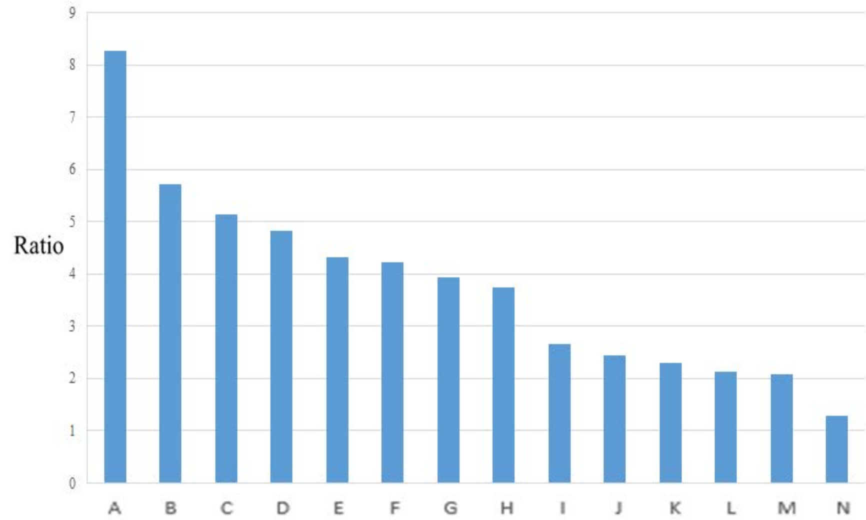
5.2.1 Seasonal variation of production rates

An analysis is conducted on production rate variation in the construction and winter season. The degree of variation in production rate between a construction season and winter season is represented as the ratio below.

$$\text{Ratio} = \frac{\text{Production rates achieved in construction season}}{\text{Production rates achieved in Winter season}}$$

Figure 5.3 illustrates the ratio of production rates achieved in construction season to that of winter season for top fourteen most frequent controlling activities of MDT. As shown in the Figure, seasonal variation is an important factor to be considered while estimating production rates.

In specific, production rates in summer and fall season are much higher than the production rates achieved in the winter period for most of the work items. The figure also clearly shows a huge drop of production rates during winter for many activities such as mobilization, bedding material, etc. Mobilization falls at the start of construction phase when equipment and personnel are set up on the project site for construction phase and typically takes one or two days for completion. The dataset does contains less number of projects for mobilization in winter season and these projects recorded low production rates as compared to a large dataset available for construction season. Unclassified excavation, riprap production, mobilization and crushed aggregate course are the main activities that have more than twice the production rate in construction season than in winters. Cold milling is the process of removal of existing bituminous layer using power-operated cold milling machine. Cold milling has similar production rates across all seasons as it mainly depends on the usage of equipment. This characteristics will be included in the production rate estimation model with appropriate adjustments to attain realistic production rates according to the letting season.



Legend	Work Item Description
A	MOBILIZATION
B	BEDDING MATERIAL
C	RIPRAP-CLASS 2 RANDOM
D	TOPSOIL-SALVAGING AND PLACING
E	TEMPORARY EROSION CONTROL - LS
F	TRAFFIC CONTROL DEVICES CB
G	REMOVE PIPE CULVERTS
H	RIPRAP-CLASS 1 RANDOM
I	EXCAVATION-UNCLASSIFIED
J	DRAINAGE PIPE 450 MM
K	CRUSHED AGGREGATE COURSE
L	GUARD RAIL-STEEL
M	DRAINAGE PIPE 24 IN
N	COLD MILLING

Figure 5.3: Ratio of production rates between construction and winter season

5.2.2 Variation in production rates across project types

The section contains an analysis conducted to observe the differences between production rates achieved for work item in different project types. The DWR data consists of 45 project types but on 11 of these project types contribute to impact on controlling work items. After shortlisting these 11 project types, the production rates achieved by 8 work items along with their inter quartile ranges were calculated. It is observed that production rate of a work item is dependent on the project work type. Figure 5.7 below illustrates the mean production rates achieved in unclassified excavation and it is seen higher production rates are achieved for new construction and major rehabilitation. Certain project types have specific work items that are crucial for timely completion of the project and these work items vary among project types. For resurfacing projects is crucial to have high production rate for traffic control devices as these projects are to be constructed on highways that are already in use and delay in installing these devices can increase road user risk. It is also observed that project types with added capacity tend to have lower production rates as seen in the case of much excavation for reconstruction projects. Additional scope for work items involving heavy machinery tends to decrease production rates that can be achieved.

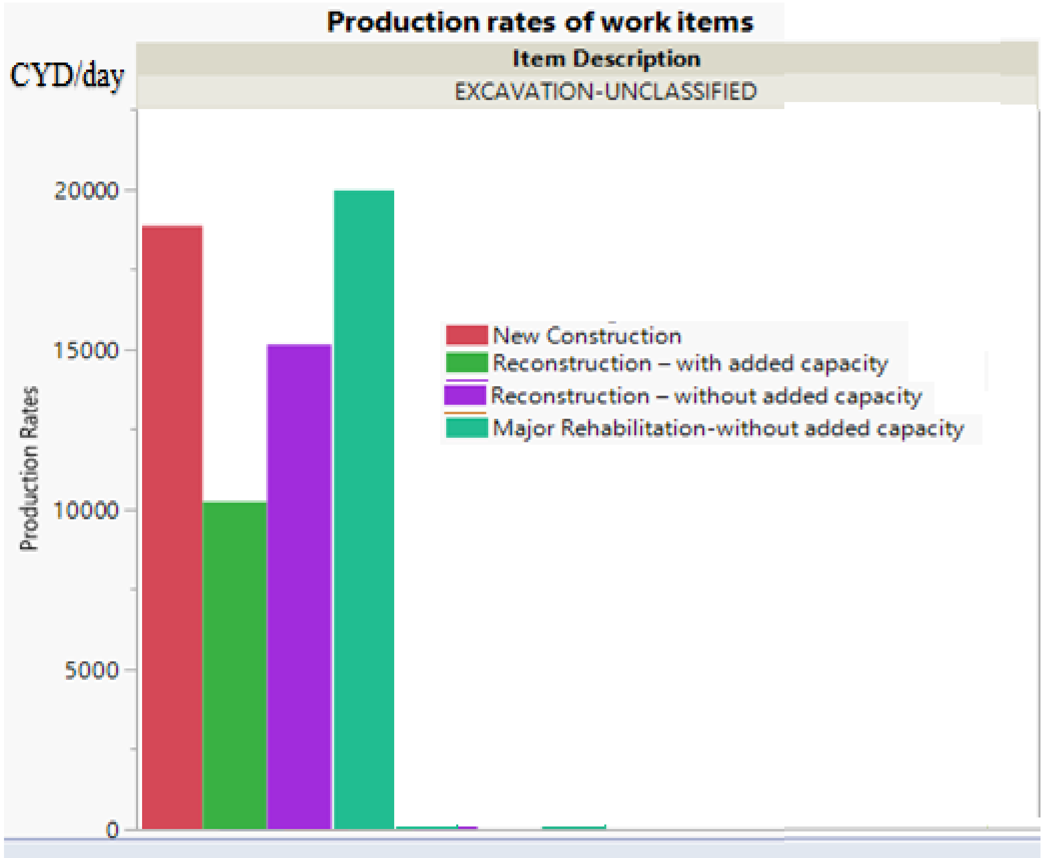


Figure 5.7: Production rate comparison of various project types

5.2.3 District level comparison of production rates

Production rates for controlling work items were calculated for each district and are compared with the average production rate of these activities across Montana. Maintenance district's Boundary location data was obtained from MDT GIS data portal. ArcGIS software is used to create a map (Figure 5.2) which provides project locations based on district boundaries.

The ratio of production rate achieved by a district for a work item and the average production rate of the work item across Montana is calculated. This ratio allows us to analyze the performance of production rates in a district for controlling work items. A bar graph as shown in Figure 5.4 is developed. The ratio is represented on the horizontal axis. Each bar indicates a work item as described in Table 5.1. Production rates of work items are aligned in the same row for visual comparison. The figure is ordered by highest production rates achieved in districts for unclassified excavation.

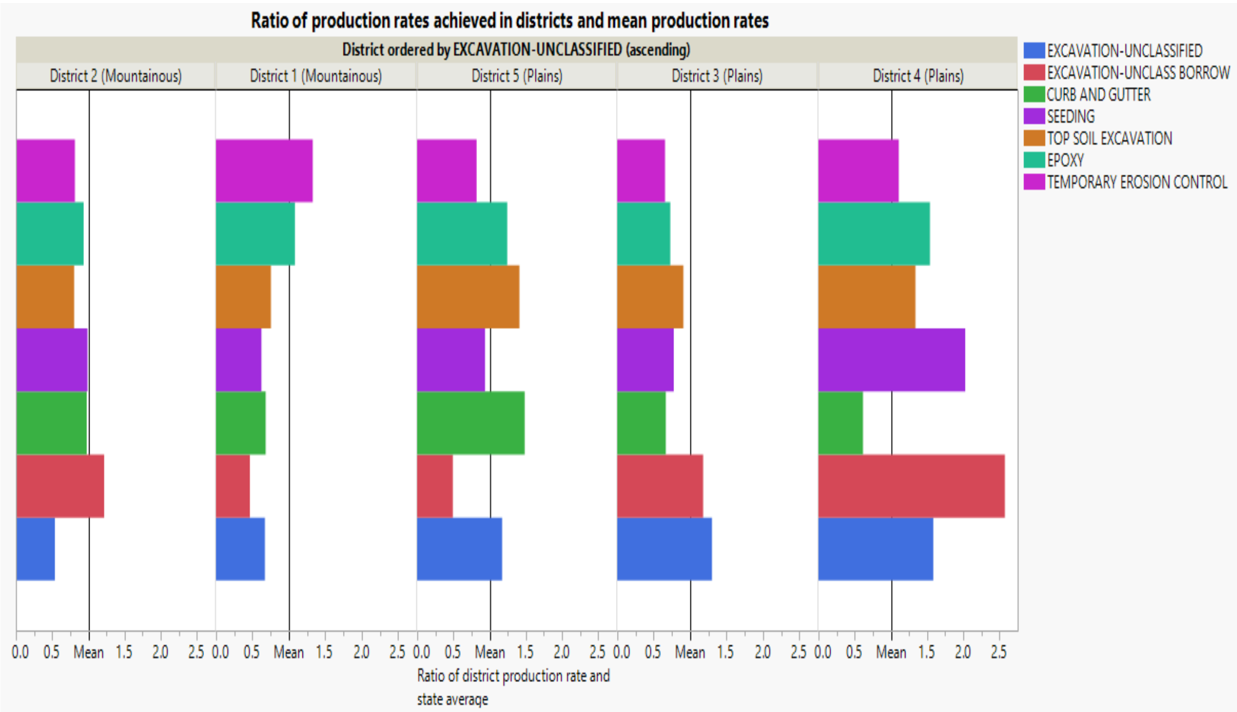


Figure 5.4: Bar graph of production rates of districts.

The average production rate of Montana is taken as 1 for all work items. The districts where the ratio is greater than 1 signifies better performance. The underperforming districts have ratios less than 1 for work items. This methodology allows us to calculate the total number of underperforming work items in each district. Table 5.2 show the total number of underperforming work items for each district.

Table 5.2: Districts with low production rate work items.

District	Number of work items below average production rate (out of 35)	% of work items under average
District 5	16	50%
District 1	17	--
District 4	15	-
District 3	18	-
District 2	20	70%

As observed in Figure 5.4 most of the work items for districts 2 and 3 fall below the average production rate. The production rates of districts 5, 1 and 4 are deemed better as they perform significantly better than average production rates for certain activities such as excavation, culvert installation, rumble strips, drainage pipe etc. The ranking of different districts is given according to the number of work items that fall below average production rates. Districts 5, 1 and 4 have higher ranking than Districts 3 and 2. District 4 is given lower priority among top performing states as the projects in the district do not contain all the work activities undertaken in other districts. Transportation of material and personnel takes longer duration in mountainous terrain than on a plain terrain. Lower production rates in districts 1 and 2 for certain work items might be due to the presence of mountainous terrain.

5.2.4 Urban and Rural production rate comparison

Among the 625 projects available in the DWR data, the total construction cost of a significant number of projects is less than $2 million. This led to creation of a budget category to analyze its effects on production rates. The projects were divided based on total project amount into two categories:

a.) Projects budget less than $ 2 Million

b.) Projects budget greater than $ 2 Million.

Production rates are calculated for urban and rural areas for all controlling activities after categorizing them into their respective budget category.

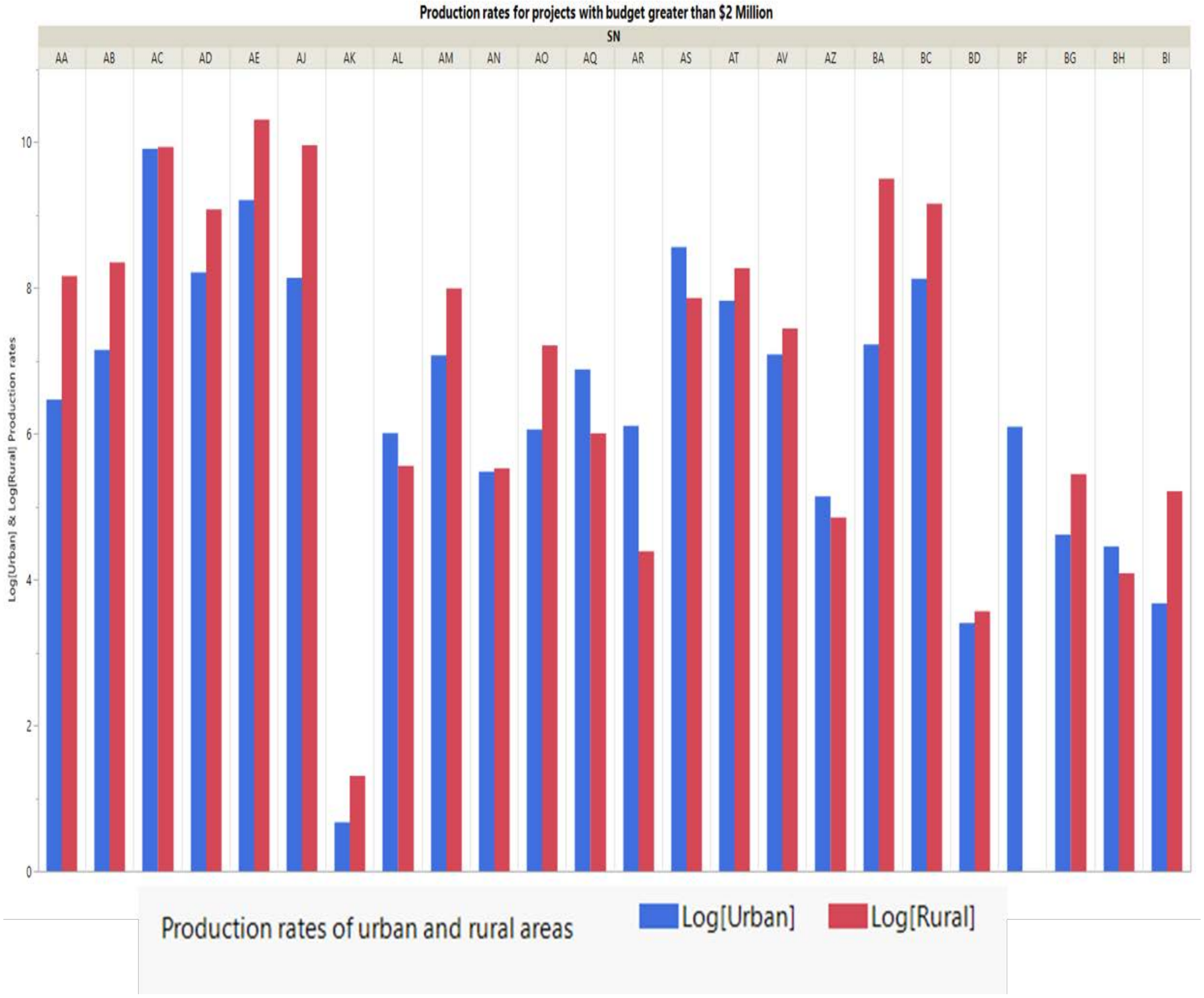


Figure 5.5 (a): Rural and urban production rate comparison for project budget greater than $2 Million

It is observed that for 25 controlling work items, the production rates in rural areas is higher than urban areas for projects with budget greater than $2 million as shown in Figure 5.5(a). The activities for which urban production rates are higher are riprap, temporary erosion control, epoxy, street excavation and sodding for medium size projects. This can be attributed to the ease of transportation and availability of materials. Similarly, it is observed that for 23 controlling work items, the production rates in rural areas is higher than urban areas for projects with budget less than $2 million as shown in Figure 5.5(b). This analysis gives better understanding on why the predicted production rates are lower for some activities in urban areas than rural areas as described in the chapter 6. Figure 5.5 illustrates production rates of major activities in rural and urban areas based on their budget category.

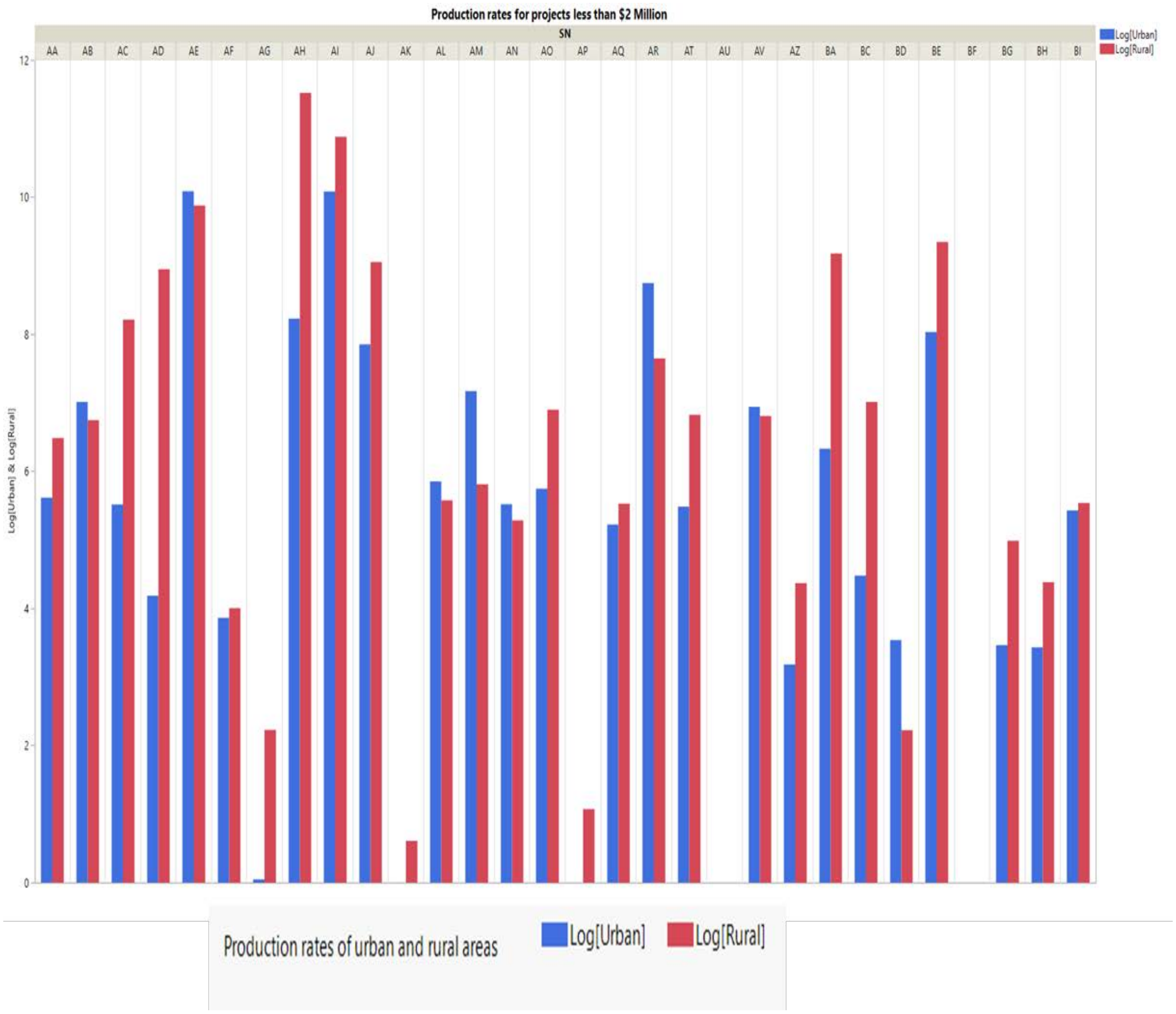


Figure 5.5 (b): Rural and urban production rate comparison for project budget less than $2 Million

In Figure 5.6 below, urban and rural production rate comparison for bedding material is shown for projects which are larger than $ 2million as an example. It's clear that the median production rate value is almost 33% greater than that of the urban production rate.

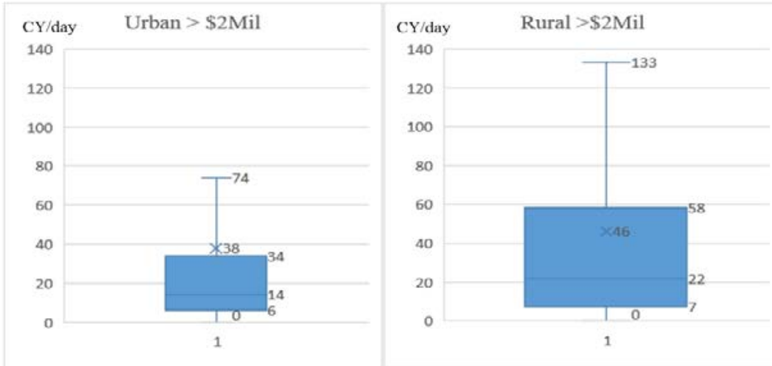


Figure 5.6: Box plot comparison of bedding material production rates for urban and rural areas

Table 5.3 shows production rate comparison of 11 work items between urban and rural areas for projects larger than $ 2 million. The urban production rates are greater than its rural counterpart for only eight work items in this category. This analysis provides confidence in using urban rural divide as a significant factor while developing regression models for work items.

Table 5.3: Ratio between urban and rural production rates

Item Description	Area	Production rate for projects greater than $2 Million	Ratio (Urban to Rural)
CRUSHED AGGREGATE COURSE Medium	Urban	646	0.18
	Rural	3518	
CRUSHED AGGREGATE COURSE Large	Urban	1275	0.30
	Rural	4234	
EXCAVATION-UNCLASSIFIED	Urban	20165	0.98
	Rural	20613	
EXCAVATION-UNCLASS BORROW	Urban	3702	0.42
	Rural	8769	
COLD MILLING	Urban	9984	0.33
	Rural	30081	
BEDDING MATERIAL	Urban	79	0.81
	Rural	97	
RUMBLE STRIPS	Urban	15	1.61
	Rural	10	
COVER - TYPE 1	Urban	67266	0.56
	Rural	120645	
COVER - TYPE 2	Urban	78512	0.94
	Rural	83851	
TRAFFIC CONTROL DEVICES CB	Urban	3435	0.16
	Rural	21192	
PAVEMENT MARKINGS	Urban	2	0.53
	Rural	4	

5.2.5 Production rate comparison among contractors

Production rates of 377 contractors who worked on past project for MDT were calculated for controlling work items from the DWR data. These production rates are color coded for ease of identification if they are higher, lower or similar to that of production rates published in MDT contract time determination manual (MDT 2008). This data would provide the MDT engineer in identifying the contractors who are capable of required production rates for a project. Since the production rates achieved by a contractor may be different depending on the work item, estimators should use judgement to observe if the contractor achieved expected production rates on work items crucial for the type of work being performed. Table 5.4 shows production rates achieved by 25 contractors for seven major work items. The color coding legend is as follows:

Tier 1 contractors
Tier 2 contractors
Tier 3 contractors

The file containing the production rates achieved by all contractors is shared with MDT to provide input to the engineer to evaluate past production rates of contractor before awarding the project. The percentage of contractors falling in each category is also developed. It is observed that for crushed aggregate course the 13% of contractors belong to tier 1, 11% of contractors belong to tier 2 and 75% of the contractors fall in tier 3 category.

Table 5.4: Production rates achieved by contractors on past projects.

VEND_ID	VEND_FULL_NM	CRUSHED AGGREGATE COURSE	EXCAVATION-UNCLASSIFIED	EXCAVATION-UNCLASS BORROW	COLD MILLING	BEDDING MATERIAL	PCCP	FENCE-CHAIN LINK
2785	J & S CONSTRUCTION INC	235						
3744	M.A. DEATLEY CONSTRUCTION, INC.	7516	17201	2695		83		
6259	KNIFE RIVER CORPORATION - MSLA	502			9778	40	119	
2096	SK CONSTRUCTION, INC.	3187	30642	22627		45		
2054	SLETTEN CONSTRUCTION COMPANY	409			116	17		
2094	PRINCE, INC.	2193			10799	0		
2364	JCT CONSTRUCTION, LLC	164						
6297	CENTURY COMPANIES, INC.	239			9431			135
6272	KNIFE RIVER CORPORATION - BLGS	313	4556		10819	34		
6805	(OBS)RIVERSIDE SAND & GRAVEL INC	1122	2901	2213	3913	53		94
6900	FOOTHILLS CONTRACTING INC	1051	7049			61		
6689	PAVEMENT MAINTENANCE SOLUTIONS, INC.	142						
4343	HELENA SAND & GRAVEL, INC.	1164			2535		2681	987
3058	BULLOCK CONTRACTING LLC	1052	5148		911	105		
6271	KNIFE RIVER CORPORATION - BELG	1425	1877	3013	2536	56		4723
2061	WICKENS CONSTRUCTION, INC.	3763	19174			65		
2059	UNITED MATERIALS OF GREAT FALLS, INC.	323			3669		19	1
6095	FRANZ CONSTRUCTION INC	731						
2097	SCHELLINGER CONSTRUCTION CO., INC.	2444	7150		43880	67		
2242	PUMCO INC	1111	25881		1097			
2050	RIVERSIDE CONTRACTING, INC. - MSLA	2366	23247	6769	19819	89	11536	
6129	A. M. WELLES, INC.	2569	996	4922	149			
2087	NELCON, INC.	3335	6209		10015	44		
2053	SHUMAKER TRUCKING & EXCAVATING CONTRACTORS, INC.	3112						
6124	MONTANA MATERIALS INC DBA LS JENSEN CONSTRUCTION & READY MIX	150	4375	4605	28775	53		40

5.2.6 Adverse day calculation using DWR data

DWR data provides information regarding chargeable days when work is completed and non-chargeable days when work is stopped due to adverse weather. Adverse weather is a major factor that affects productivity on the field. The research team used DWR data to determine the number of days work stopped due to snow, winds, intermittent showers and rains in every month. Percentage of adverse weather occurrence and possible working days for each month was calculated. This data is used to determine the number of possible adverse days by multiplying the cumulative adverse percentage with possible working days. Table 5.5 below shows the calculated number of adverse days expected in each month. Schedulers can use this data to allot additional time for adverse weather while setting contract time.

Table 5.5: Adverse day calculation for each month in Montana using DWR data

Month	Days	Possible Working days	Snow	Cloudy and Windy	Intermittent Showers	Rain	Possible Adverse days
January	31	22	53%	71%	3%	4%	14
February	28	20	13%	14%	3%	1%	4
March	31	22	26%	92%	34%	26%	12
April	30	21	24%	86%	31%	24%	11
May	31	22	4%	86%	47%	62%	15
June	30	21	1%	72%	61%	61%	13
July	31	22	0%	35%	29%	17%	4
August	31	22	0%	39%	34%	26%	6
September	30	21	2%	40%	27%	27%	6
October	31	22	8%	71%	33%	25%	8
November	30	21	25%	50%	6%	4%	7
December	31	22	10%	19%	1%	1%	3

CHAPTER 6. PREDICTIVE ANALYSIS OF DWR DATA

This chapter discusses the various factors affecting production rates and statistical results obtained from the production rate analysis of work items significant for highway construction. Moreover, this chapter also comprises of contractor evaluation which evaluates the contractors who worked for MDT on past projects based on the production rates achieved of two major activities.

6.1 Sample Size and Usable data

The study obtained the historical bid data and DWR data from in an excel format which was imported into a central database. Parameters like the location of the project in urban or rural regions which were also obtained from online databases are also included in the central database. The database consists of 625 projects over a period of ten years from 2008 to 2017. MDT has developed a list of 5,645 unique item codes published in specification manual (MDT 2006). Each item code represents a unique construction activity on a highway project. For example, item code "301020340" represents Crushed Aggregate Course. The total number of work items for which quantities and other parameters recorded on one day (DWR date) is more than 500,000. Based on current practices of other DOTs production rate calculations as well as the most frequent items available in the DWR dataset, a comprehensive list of 35 work items were selected for analysis.

Highway projects are divided into 45 categories by Montana DOT (MDT 2015) and not all project types have similar work items. So, the sample size depends on the number of projects undertaken for the 35 work items rage. The samples size ranges from only 4 projects in the case of CTB pulverized to 544 projects where mobilization and traffic control devices are deployed.

Contractor and equipment database was provided by MDT and the number of supervisors, workers, equipment availability, working and equipment usage hours are matched with the respective projects by using the vendor ID and project number. Since these are two separate datasets equipment data was not available for all the vendors that worked with MDT. These variables are calculated by taking the total number of supervisors/workers/equipment and diving them the total number of unique DWR days they were recorded. The average supervisor, worker and equipment data for each project was obtained.

Projects were then mapped in tableau software to determine the project location using latitude and longitudinal coordinates. The location of urban regions of Montana were superimposed on project location map and the projects falling in the urban regions of Montana were extracted to create a separate area variable (urban/rural) in the central database.

The contractual total amount of all the projects were compared and based on the inter quartile range and median, the projects were divided into two categories i.e., projects that are less than $2 million in value and projects greater than $2 million in value. This classification provided a logistical variable for analysis of production rates to check if budget of a project had significant impact on the production rate of work items. This variable is also incorporated in the central database as budget category.

The total quantity of work for each work item in a project was obtained by summation of all quantities produced on each DWR date. These quantities were then divided by the total number of unique DWR dates recorded for a project to obtain production rates of work items that were achieved on each project.

The DWR database also consisted of number of null values in quantities produced on some DWR dates. To avoid skewed results, production rates were calculated separately both using and without using these null values.

6.2 Data Characteristics

While organizing the central database, looking at the different types of construction of the available database, it is evident that majority of the project types that are crucial for highway contracts are available in the dataset. In fact, as shown in figure 6.1 below, most of the projects undertaken by

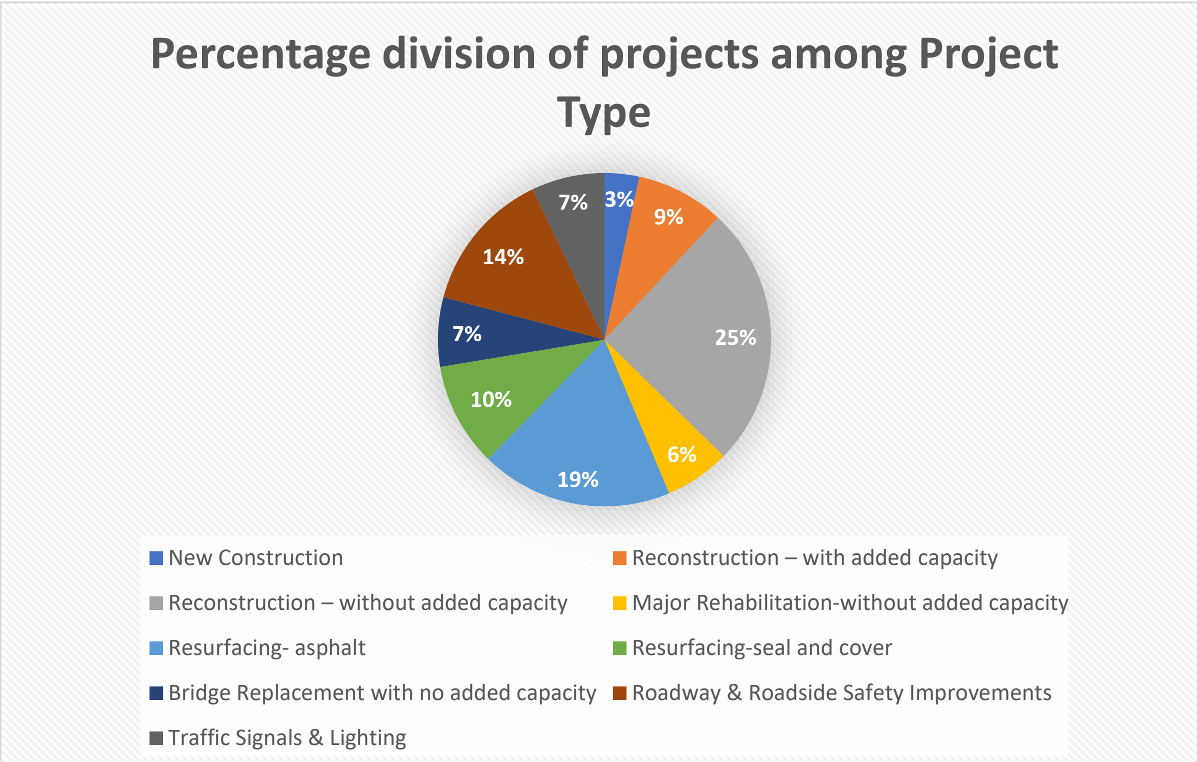


Figure 6.1: Percentage division of project types in the dataset

MDT were reconstruction (with and without added capacity) projects accounting to 34%. Resurfacing projects account for 29 % of the sample size and rehabilitation and new construction projects were 6% and 3 % respectively. Road and roadside safety improvement projects were 14% of the sample size.

Among the projects that were undertaken by MDT in the dataset 13.6% of the projects (85 in number) were in the urban areas while 86.4 %(540 in number) of the projects were undertaken in the rural areas of Montana. These results show that majority of the projects undertaken by Montana are in the rural areas. For better understanding of how the location of project had an impact on the production rates achieved on past projects, the district locations of the project were compared to find majority of the projects were undertaken in district 5 (33%), district 4 contributed to 27% of the projects in the dataset and district 3 about 20% of the projects as shown in Figure 6.2. Districts 1 and 2 contribute to 7% and 13% respectively and the dataset for these district to predict production rates is quiet small in comparison to other districts.

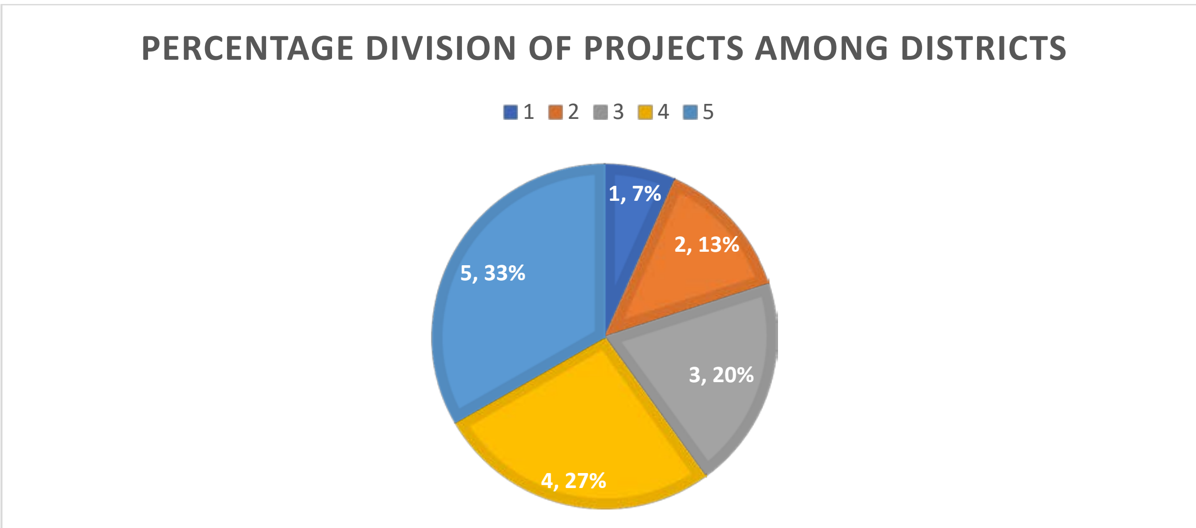


Figure 6.2: Percentage of projects undertaken in a district in Montana

Reviewing the size of projects based on the total budget allocated to the project, it is found that number of projects with budget more than $2 Million were 262(42%) while the number of projects with budget less than $2 Million were 363(58%).

6.3 Effect of Different factors on Production rates

The central database is used to determine which independent variables have significant effect on production rates of work items. For this analysis, as shown in Figure 5.1, activity and time parameters and contractor parameters are used. JMP Pro. Statistical software is used to run the analysis using standard least squares to determine the effects of various factors. This section focuses on the effects of factors on major work items such as Crushed aggregate course, unclassified excavation, Culvert, Cold milling, Top soil excavation and PCCP. These activities are selected as they cover major work items published in MDT production rate table (Appendix A). Studies show that performing construction on a commercial corridor with high traffic flows and having to maintain access to business and residents reduces production rates. Long stretch of highway resurfacing, concrete bridge deck overlays as well as shoulder and approach slab replacement are required to have higher production rates to avoid delays and reduce safety risk for the public (Aoun 2013). The factors considered for the analysis from the central database cover most of the major variables that have influence over production rates.

Table 6.14 below indicates the factors selected for each activity and the adjusted R-squared value associated for the regression model developed for the work item. Sections below explain detailed discussion for several top major work items.

Table 6.14: Effects of different factors on major work items in highway construction

SN	Item description	Total quantity	Project Worktype Code	Area	Maintenance District	Contract total amount	Budget Category	Supervisor	Number of Workers	Worked Hours	Equipment Available	Equipment Used	Usage Hours	Rsquare
AA	CRUSHED AGGREGATE COURSE-MEDIUM	X						X		X				0.84
AB	CRUSHED AGGREGATE COURSE -LARGE	X						X		X				0.79
AC	EXCAVATION-UNCLASSIFIED	X	X		X									0.80
AD	EXCAVATION-UNCLASS BORROW	X			X				X					0.96
AE	COLD MILLING	X								X				0.30
AF	BEDDING MATERIAL													0.40
AG	RUMBLE STRIPS	X												0.80
AH	COVER - TYPE 1	X			X									0.75
AI	COVER - TYPE 2	X			X									0.81
AJ	TRAFFIC CONTROL DEVICES CB	X	X	X										0.38
AK	TEMP PAVEMENT MARKINGS	X			X									0.30
AL	CURB AND GUTTER	X		X	X			X						0.97
AM	FENCE-CHAIN LINK	X		X				X	X	X		X		0.96
AN	SIDEWALK	X	X	X	X		X				X			0.49
AO	GUARDRAIL STEEL	X	X											0.88
AP	SEEDING	X				X				X				0.82
AQ	SODDING	X			X									0.78
AR	PCCP	X												0.70
AS	MUCK EXCAVATION	X	X		X		X	X		X				0.97
AT	TOP SOIL EXCAVATION	X												0.72
AU	MOBILIZATION	X				X	X					X		0.36
AV	STREET EXCAVATION	X			X		X				X	X	X	0.92
AW	CTB PULVARIZED													
AX	CTB													
AY	CULVERT RCB	X										X		0.95
AZ	DRAINAGE PIPE	X	X	X			X						X	0.64
BA	COLD RECYCLED PLANT MIX													
BB	PMS -PLANT MIX BIT SURF	X												0.49
BC	EPOXY	X	X											0.60
BD	WORDS & SYMBOLS	X												0.87
BE	CONCRETE PAVEMENT GRINDING													
BF	TEMPORARY EROSION CONTROL	X				X								0.78
BG	EMULS ASPHALT CRS-2P	X			X									0.46
BH	EXPANSION JOINT	X	X	X	X		X							0.82
BI	RIPRAP	X			X		X	X						0.83

6.3.1 Effects of factors on Crushed Aggregate Course:

For the analysis of the Crushed Aggregate course from the central database, the most important factors that have an effect on production rate were identified to be the following: total quantity of item to be produced for the project (Total quantity), total budget of the contract (Contract total amount) and maintenance districts. As shown in Table 6.1 below, the factors with P values under 0.10 have significant effect on production rates. Other contractor and equipment factors like number of equipment available, hours of equipment usage and hours of work do not have any significant effect on the production rates of crushed aggregate course.

This analysis of crushed course aggregates, the total number of projects available in daily work report are 67. The Log Worth of significant factors is provided in the table below. The R^2 obtained for this analysis is 0.84. Figure 6.3 shows a profiler developed for the nominal regression model used for this analysis which predicts the production rate that can be produced (PR) when the contract amount which is more than \$ 2 Million, for a project located in district 4 and the total quantity to be produced is 26500m^3. The predicted production rate is calculated to be 3370m^3/day which is an increase of 370m^3/day over average production rate.

Table 6.1: Effects of different factors on Crushed aggregate course production rate

Source	LogWorth		PValue
Total quantity	14.815		0.00000
CONTRCT_TTL_AMT	2.487		0.00326
District	1.227		0.05929
USED_HRS	0.586		0.25914
NBR_USED	0.372		0.42431
WRKD_HRS	0.282		0.52279

Measure	Value
Number of Projects	67
Number of factors	3
RSquare	0.8579

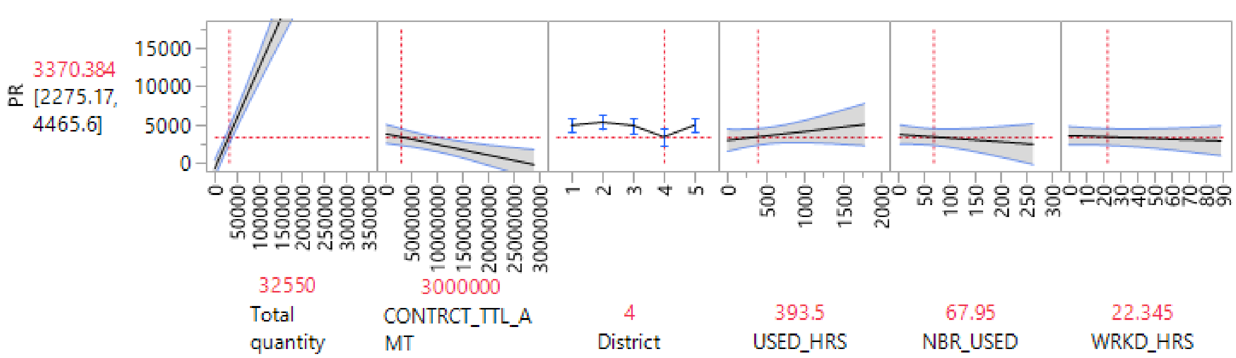


Figure 6.3: Profilers for crushed aggregate course to predict production rate.

The regression model developed for this work item is as shown in the below equation:

$$\text{Production rate of crushed aggregate course} = 1108.70 + 0.13 * Total\ quantity + Match(\ District\ 1 = -13.0594140705028, 2 = 390.98, 3 = -31.5699766108194, 4 = -1529.71, 5 = 0) + -0.000139540809872609 * CONTRCT\_TTL\_AMT - 7.7836 * WRKD\_HRS - 4.85695594914564 * NBR\_USED + 1.157965 *: USED\_HRS$$

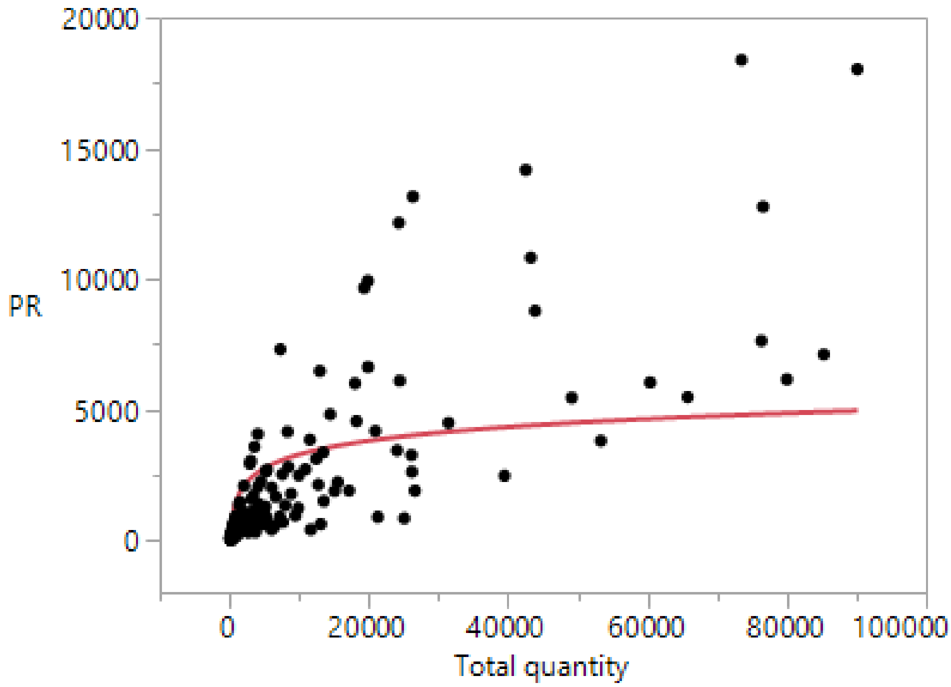


Figure 6.4 (a): Relation between production rate and quantity

The relationship between production rate and the quantity to be produced on the field is very significant in the regression model. Figure 6.4 (a) illustrates a graph describing the relationship between production rate and quantity. It can be observed that till 30,000 cubic yards of quantity to be produced, the production rate increases linearly and then becomes asymptote when production rate reaches 5000 cubic yards per day.

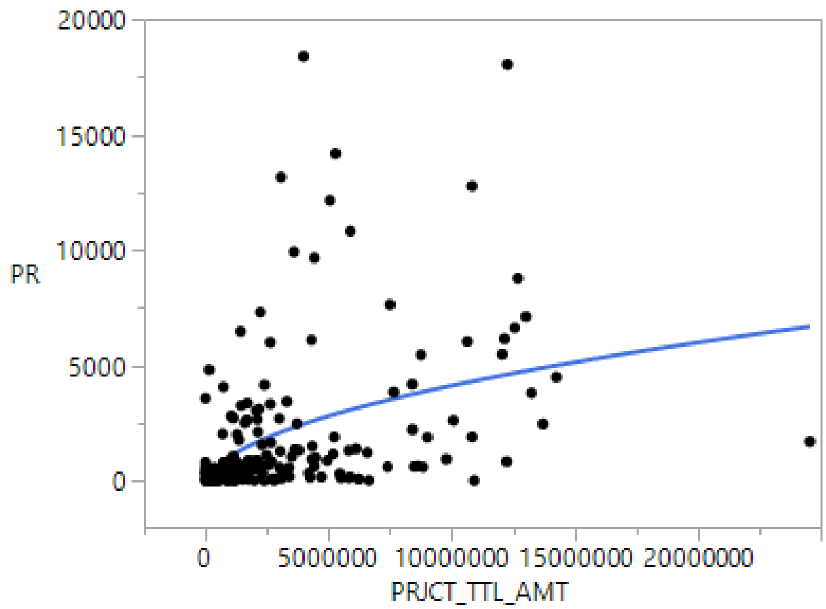


Figure 6.4 (b): Relation between production rate and Project budget

Figure 6.4 (b) illustrates the relationship between production rate and project budget. It can be observed production rate stabilized around 6000 cubic yards per day. Since quantity and project total amount are most significant influencing factors on production rate, the cap on the predicted production rate in the regression model is taken as 6000 cubic yards per day.

It is found that increase in quantities and contract amount have a direct relation with production rates of crushed course aggregate whereas district four (Glendive) produces the highest production rates among all the districts. This may be attributed to the topography of Montana where districts 3, 4 and 5 are relatively plain compared to mountain regions found in districts 1 & 2. Table 6.2 shown below provides the mean production rates achieved in past projects in various districts of Montana. The average production rate of Montana is also provided.

Table 6.2: Mean production rates in districts of Montana for Crushed Aggregate Course

				District 1	District 2	District 3	District 4	District 5
SN	Item description	Units	Mean	Mean	Mean	Mean	Mean	Mean
AA	CRUSHED AGGREGATE COURSE-MEDIUM	CUYD	3154	2276	2500	3900	3773	4215
AB	CRUSHED AGGREGATE COURSE -LARGE	M3	1557	836	2310	1328	1826	1890

6.3.2 Effects of factors on Unclassified Excavation:

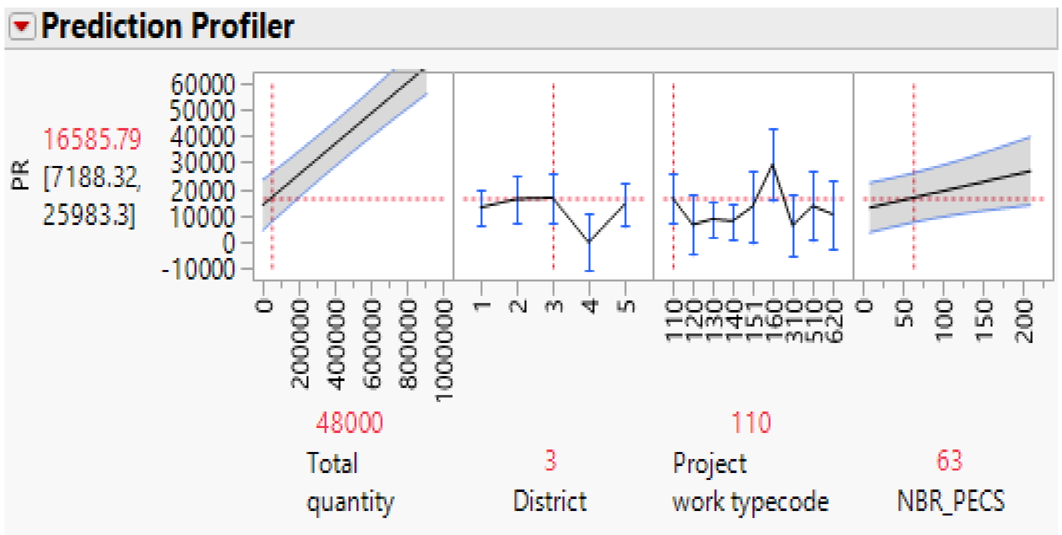
For the analysis of the unclassified excavation from the central database, the factors that have an effect on production rates were identified to be the following: total quantity of item to be produced for the project (Total quantity), the type of the project, for example new construction or rehabilitation projects (considered in Figure 6.4), number of equipment available with the contractor and maintenance districts. Total quantity and equipment available are continuous variables whereas project work type and district location of the project are nominal variables. As shown in Table 6.3 below, the factors with P values under 0.05 have significant effect on production rates. Other contractor and equipment factors like number of supervisors, number of hours of equipment usage and hours of work do not have any significant effect on the production rates of unclassified excavation.

This analysis of unclassified excavation, the total number of projects available in daily work report are 53. The Log Worth of each of these factors is provided in the table below. The R^2 obtained for this analysis is 0.89. Figure 6.4 shows a profiler developed for the nominal regression model used for this analysis which predicts the production rate that can be produced (PR) when the type of project is New construction (Figure 6.5 (a)) and Minor Rehabilitation Project (Figure 6.5 (b)), for a project located in district 3 and the total quantity to be produced is 48000m^3. The predicted production rate is calculated to be 16586m^3/day and 29287m^3/day for the same parameters which is an increase of 12000m^3/day when calculating for specifically these factors.

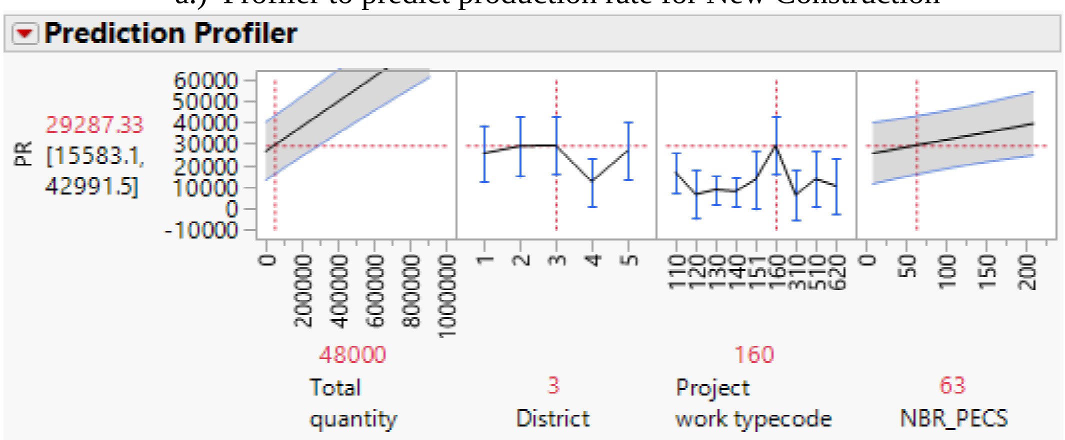
Table 6.3: Effects of different factors on Unclassified Excavation production rate

Source	LogWorth		PValue
Total quantity	10.031		0.00000
District	2.662		0.00218
NBR_PECS	1.752		0.01769
Project work type	1.401		0.03976

Measure	Value
Number of Projects	53
Number of factors	4
RSquare	0.8895219



a.) Profiler to predict production rate for New Construction



b.) Profiler to predict production rate for Minor Rehabilitation

Figure 6.5: Profilers for unclassified excavation to predict production rate

The regression model developed for this work item is as shown in the below equation:

$$\text{Production rate of unclassified excavation} = 734.05 + 0.0578 * Total\ quantity + Match(\ District1 = -1188.89, 2 = 2091.33, 3 = 2508.63, 4 = -14428.70, 5 = 0) + Match(\ Project\ work\ typecode\ 110 = 6215.72, 120 = -4016.69, 130 = -1844.24, 140 = -2611.69, 151 = 3003.37, 160 = 18917.26, 310 = -4281.71, 510 = 3239.73, 620 = 0) + 69.095 *: NBR\_PECS$$

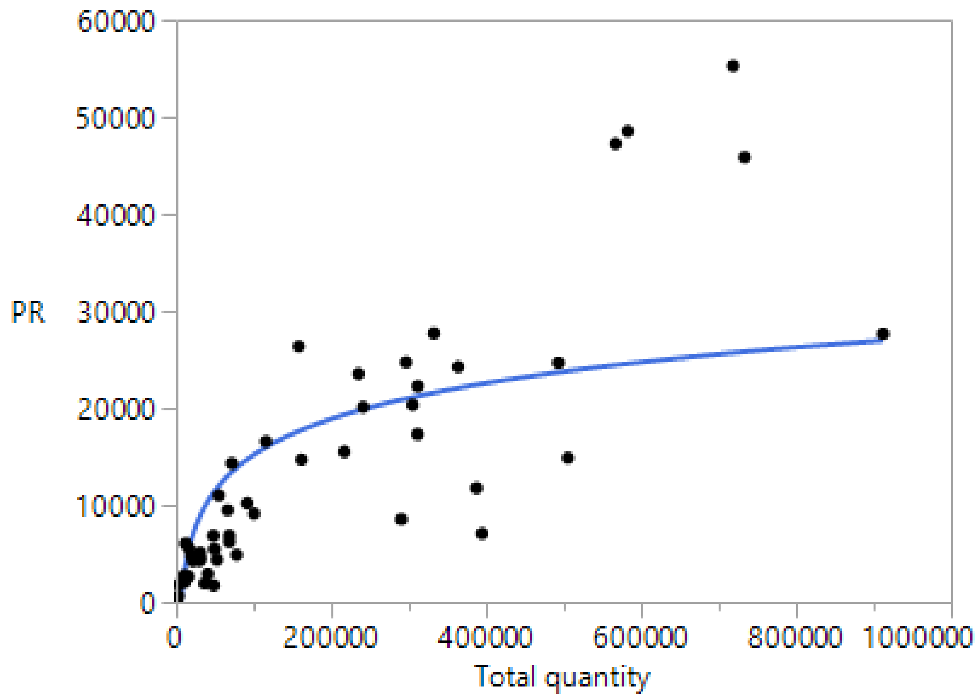


Figure 6.6: Relation between production rate and quantity

The relationship between production rate and the quantity to be produced on the field is very significant in the regression model. Figure 6.6 illustrates a graph describing the relationship between production rate and quantity as a log linear relationship where production rate increases drastically with quantity increase till 200,000 cubic yards of excavation. The production rate tends to stabilize making an asymptote at 30,000 cubic yards a day. High values of production rates are only possible in the model because there is no restriction the number of equipment that can be used.

It is found that increase in quantities and available equipment have a direct relation with production rates of unclassified excavation as per the profiler shown in Figure 6.4. District three (Great Falls) produces the highest production rates among all the districts. Table 6.4 shown below provides the mean production rates achieved in past projects in various districts of Montana. The average production rate of Montana is also provided.

Table 6.4: Mean production rates in districts of Montana for Unclassified Excavation

				District 1	District 2	District 3	District 4	District 5
SN	Item description	Units	Mean	Mean	Mean	Mean	Mean	Mean
AC	EXCAVATION-UNCLASSIFIED	M3	13085	8777	7032	17009	20736	15333

6.3.3 Effects of factors on Culvert:

For the analysis of work item culvert from the central database, factors that have an effect on production rates were identified to be the following: total quantity of item to be produced for the project (Total quantity) as shown in Table 6.5. Total quantity is a continuous variable. As shown in Table 6.5 below, the factors with P values under 0.05 have significant effect on production rates. Other contractor and equipment factors like number of equipment used and hours of work do not have any significant effect on the production rates of unclassified excavation.

This analysis of culvert, the total number of projects available in daily work report are 20. The Log Worth of each of these factors is provided in the table below. The R^2 obtained for this analysis is 0.95. Figure 6.7 shows a profiler developed for the nominal regression model used for this analysis which predicts the production rate that can be produced (PR) when the total quantity to be produced is 125 linear feet. The predicted production rate is calculated to be 60 linear feet/day.

Table 6.5: Effects of different factors on Culvert production rate

Source	LogWorth		PValue
Total quantity	2.891		0.00129
NBR_USED	0.423		0.03773

Measure	Value
Number of Projects	20
Number of Factors	4
BIC	44.532145
AICc	64.748505
Rsquare	0.9509299

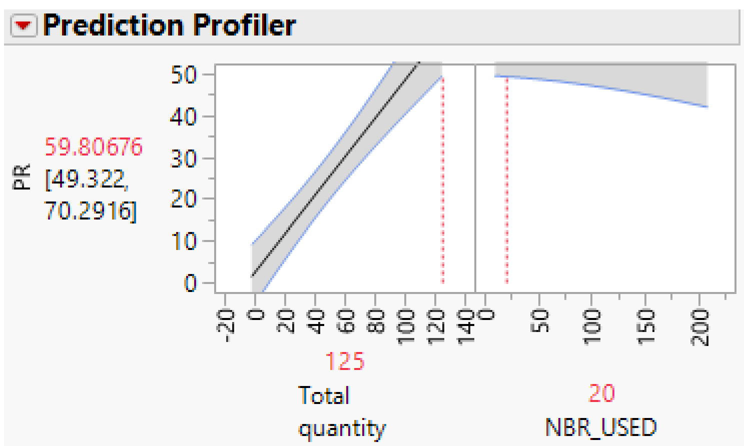


Figure 6.7 Profiler for Culvert to predict production rate

The regression model developed for this work item is as shown in the below equation:

Production rate of culvert = $2.68 + 0.46107 * Total\ quantity + (-0.0255) * NBR\_USED$

It is found that increase in quantities is directly proportional to production rates achieved for reinforced concrete culvert per the profiler shown in Figure 6.7. District five (Billings) produces the highest production rates among all the districts. Table 6.6 shown below provides the mean production rates achieved in past projects in various districts of Montana as well as mean production rates for projects with budget less than \$2 Million and more than \$2 Million. It is observed that when the contract budget is higher, past projects have achieved higher mean production rates. The average production rate of Montana is also provided.

Table 6.6: Mean production rates in districts of Montana for Unclassified Excavation

				District 1	District 2	District 3	District 4	District 5	Less than $2 Mil	More than $2 Mill
SN	Item description	Units	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
AY	CULVERT RCB	LNFT	43	47	46	22	25	88	41	55

6.3.4 Effects of factors on Cold Milling:

For the analysis of work item cold milling from the central database, factors that have an effect on production rates were identified to be the following: total quantity of item to be produced for the project (Total quantity), total hours of work done by workers. As shown in Table 6.7 below, the factors with P values under 0.05 have significant effect on production rates. Other contractor and equipment factors like number of workers or total worked hours do not have any significant effect on the production rates of cold milling.

This analysis of cold milling, the total number of projects available in daily work report are 20. The Log Worth of each of these factors is provided in the table below. The R^2 obtained for this analysis is 0.30. Figure 6.8 shows a profiler developed for the nominal regression model used for this analysis which predicts the production rate that can be produced (PR) when the total quantity to be produced is 120500 square yards. The predicted production rate is calculated to be 26860yd^2/day.

Table 6.7: Effects of different factors on Culvert production rate

Source	LogWorth		PValue
Total quantity	6.399		0.00000
WRKD_HRS	3.931		0.00012
District	0.446		0.35780

Measure	Value
Number of Projects	275
Number of factors	2
RSquare	0.2988876

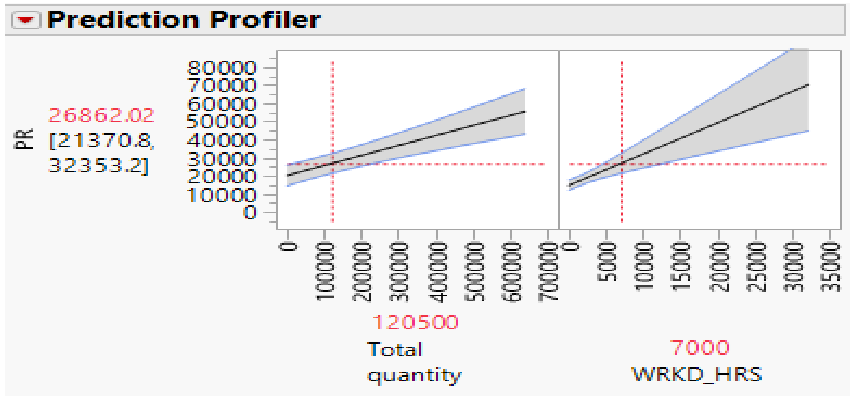


Figure 6.8 Profiler for Cold Milling to predict production rate

The regression model developed for this work item is as shown in the below equation:

$$\text{Production rate of cold milling} = 8193.25 + 0.055 * \mathit{Total\ quantity} + 1.7196 * \mathit{WRKD\_HRS}$$

It is found that increase in quantities is directly proportional to production rates achieved for cold milling according to the profiler shown in Figure 6.8. District two (Butte) produces the highest production rates among all the districts. Table 6.8 shown below provides the mean production rates achieved in past projects in various districts of Montana as well as mean production rates for projects with budget less than $2 Million and more than $2 Million. It is observed that when the contract budget is higher, past projects have achieved higher mean production rates. The average production rate of Montana is also provided. It's noted that mean production rates achieved by past projects are lower than the documented production rate of Montana which is 35,000 square yards per day.

Table 6.8: Mean production rates in districts of Montana for Cold Milling

				District 1	District 2	District 3	District 4	District 5	Less than $2 Mil	More than $2 Mill
SN	Item description	Units	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
AE	COLD MILLING	SQYD	17800	14110	20780	11364	15930	16263	14215	19950

6.3.5 Effects of factors on Top Soil Excavation:

For the analysis of work item Top soil excavation from the central database, factors that have an effect on production rates were identified to be the following: total quantity of item to be produced for the project (Total quantity), number of equipment available and the pieces used on the field and the supervisors present on site as shown in Table 6.9. All significant factors are continuous variables. Table 6.7 below depicts the factors with P values under 0.05 which have significant effect on production rates. Factors like location and budget do not play show a significant effect on the production rates of topsoil excavation but the mean of projects below $2 million in total is relatively lower than the projects with higher budget allocation.

This analysis of top soil excavation, the total number of projects available in daily work report are 233. The Log Worth of each of these factors is provided in the table below. The R^2 obtained for this analysis is 0.75. Figure 6.9 shows a profiler developed for the nominal regression model used for this analysis which predicts the production rate that can be produced (PR) when the total quantity to be produced is 18,350 yd^3. The predicted production rate is calculated to be 3007 yd^3/day. This rate is almost 1000 yd^3/day higher than the production rates of medium sized top soil excavation work published by Montana (MDT 2008).

Table 6.9: Effects of different factors on Culvert production rate

Source	**LogWorth**		**PValue**
Total quantity	36.519		0.00000
NBR_USED	2.789		0.00163
NBR_PECS	2.455		0.00350
NBR_SUPRVSR	2.090		0.00813

Measure	**Value**
Number of Projects	233
Number of Factors	4
Rsquare	0.7528991

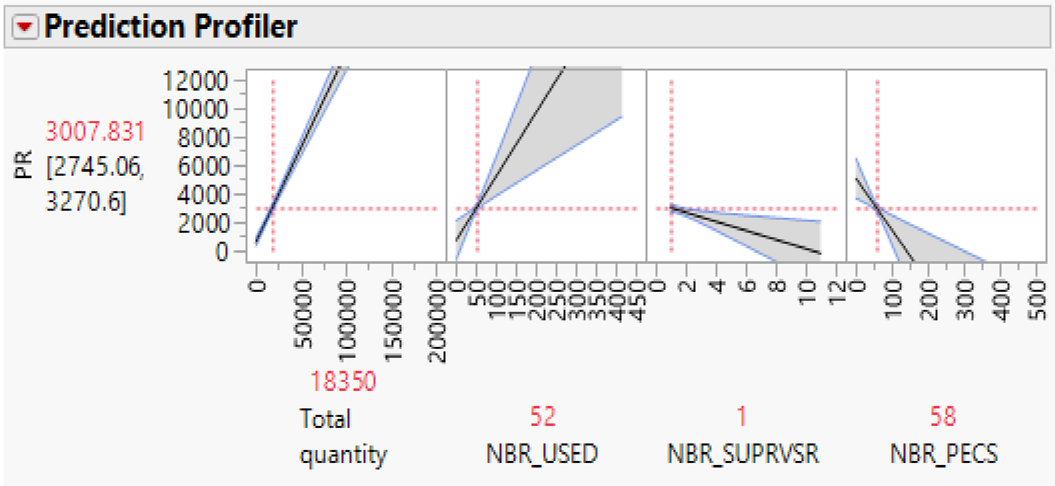


Figure 6.9 Profiler for top soil excavation to predict production rate

The regression model developed for this work item is as shown in the below equation:

$$\text{Production rate of top soil excavation} = 316.289 + 0.12898 * Total\ quantity + 3.247 * NBR\_USED$$

It is found that increase in quantities is directly proportional to production rates achieved for top soil excavation according to the profiler shown in Figure 6.9. District four (Glendive) produces the highest production rates among all the districts. Table 6.10 shown below provides the mean production rates achieved in past projects in various districts of Montana as well as mean production rates for projects with budget less than $2 Million and more than $2 Million. It is observed that when the contract budget is higher, past projects have achieved higher mean production rates. The average production rate of Montana for this work item is also provided. District five has very low production rate for this work item as the total number of project data points available were low.

Table 6.10: Mean production rates in districts of Montana for Top Soil Excavation

				District 1	District 2	District 3	District 4	District 5	Less than $2 Mil	More than $2 Mill
SN	Item description	Units	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
AT	TOP SOIL EXCAVATION	CUYD	1881	1419	1512	1706	2520	483	874	2660

6.3.6 Effects of factors on Drainage Pipe:

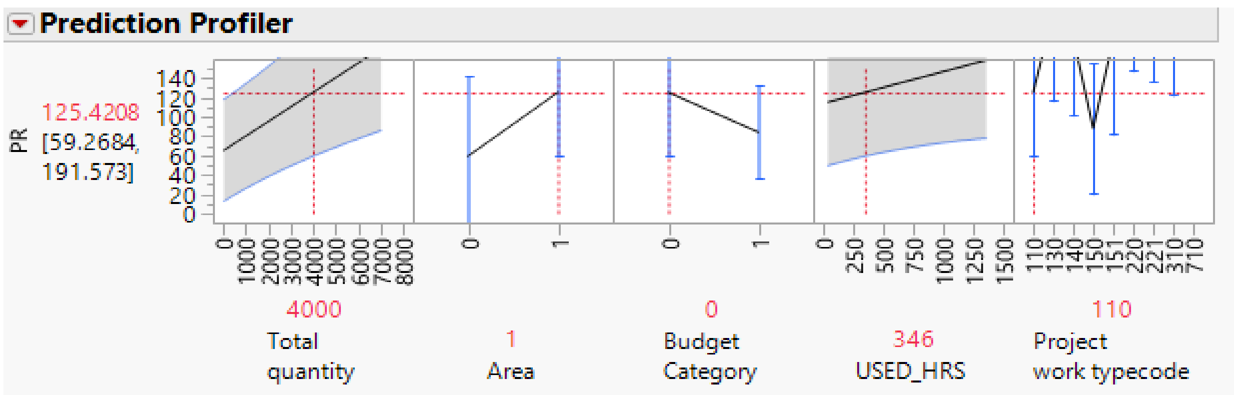
For the analysis of work item Drainage pipe from the central database, factors that have an effect on production rates were identified to be the following: total quantity of item to be produced for the project (Total quantity) and usage time of the equipment which are continuous variables. Significant factors which are nominal variables are area, budget category and the type of project. Table 6.11 below depicts the factors with P values under 0.10 which have significant effect on production rates. Factors like District do not play show a significant effect on the production rates of drainage pipe but the mean of projects above $2 million in total is relatively lower than the projects with lower budget allocation.

This analysis of drainage pipe, the total number of projects available in daily work report are 140. The Log Worth of each of these factors is provided in the table below. The R^2 obtained for this analysis is 0.64. Figure 6.10(a) shows a profiler developed for the nominal regression model used for this analysis which predicts the production rate that can be produced (PR) when the total quantity to be produced is 4000 feet for a new construction project. The predicted production rate is calculated to be 125 LNFT/day. This rate is very dependent on the type of project being considered. The difference in production rates calculated by this model increases to 240 LNFT/day when considering a bridge replacement project with added capacity as shown in Figure 6.10(b). The R^2 for this model is relatively low and quantities should be practical for the model to predict more accurate production rates.

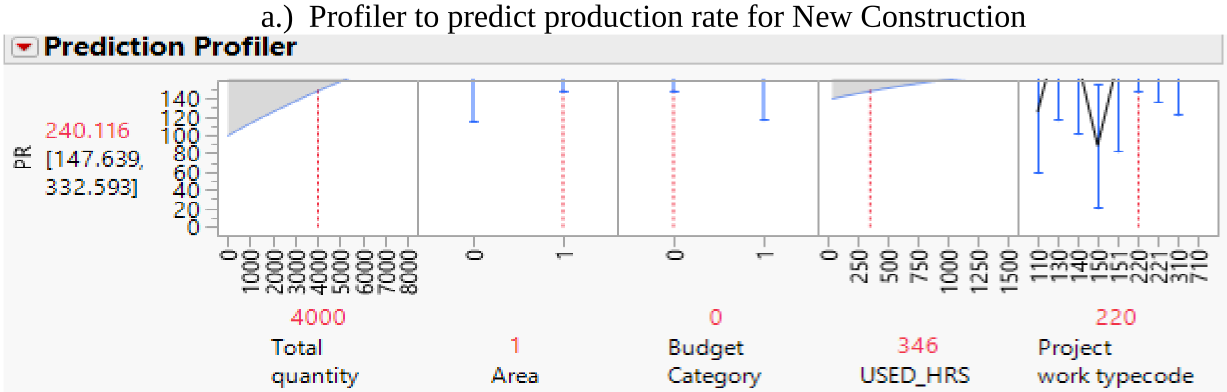
Table 6.11: Effects of different factors on Drainage pipe production rate

Source	LogWorth		PValue
Total quantity	2.538		0.00290
Project work type	1.855		0.01397
Budget Category	1.318		0.04808
Area	1.311		0.04891
USED_HRS	0.978		0.09528

Measure	Value
Number of Projects	140
Number of Factors	4
Rsquare	0.6359068



a.) Profiler to predict production rate for New Construction



b.) Profiler to predict production rate for Bridge Replacement

Figure 6.10 Profilers for Drainage Pipe to predict production rate

The regression model developed for this work item is as shown in the below equation:

$$\text{Production rate of Drainage pipe} = 179.868 + 0.0151 * Total\ quantity + Match\ (Area\ 0 = -65.969, 1 = 0) + Match\ (Budget\ Category\ 0 = 41.1364707180842, 1 = 0) + 0.0329 * USED\_HRS + Match\ (Project\ work\ typecode\ 110 = -167.43, 130 = -84.24, 140 = -110.61, 150 = -204.60, 151 = -113.057, 220 = -52.74, 221 = -46.52, 310 = -74.01, 710 = 0)$$

District two produces the highest production rates among all the districts but there isn't much difference in production rates across the districts as shown in Table 6.12. The mean production rates achieved in past projects in various districts of Montana as well as mean production rates for projects with budget less than $2 Million and more than $2 Million are shown in table 6.10. It is observed that when the contract budget is higher, past projects have achieved lower mean production rates. Figure 6.8(a) also shows the profiler where inter quartile range of projects with higher budgets is lower compared to that of projects with budgets less than $2 million. The average production rate of Montana for this work item is also provided.

Table 6.12: Mean production rates in districts of Montana for Top Soil Excavation

				District 1	District 2	District 3	District 4	District 5	Less than $2 Mil	More than $2 Mill
SN	Item description	Units	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
AZ	DRAINAGE PIPE	LNFT	78	69	89	67	78	68	77	71

6.3.7 Effects of factors on PCCP:

For the analysis of work item PCCP (Portland Cement Concrete Pavement) from the central database, factors that have an effect on production rates were identified to be the following: total quantity of item to be produced for the project (Total quantity) which is a continuous variable. Table 6.13 below depicts the factors with P values under 0.05 which have significant effect on production rates. Factors like location and budget do not play show a significant effect on the production rates of PCCP. The mean of projects below $2 million in total is 4561 yd^2/day but not many projects were available in the data with higher budget allocation. Hence, budget category could not be used as a decisive factor for influencing production rates.

This analysis of PCCP, the total number of projects available in daily work report are 15. The Log Worth of each of these factors is provided in the table below. The R^2 obtained for this analysis is 0.71.

Table 6.13: Effects of different factors on PCCP production rate

Source	LogWorth		PValue
Total quantity	4.069		0.00009

Measure	Value
Number of projects	15
Number of factors	1
Rsquare	0.7074011

The regression model developed for this work item is as shown in the below equation:

$$\text{Production rate of PCCP} = 141.399 + 0.1982 * Total\ quantity$$

While evaluating the effect of each factor on production rates project size, project duration, accelerated project schedule, project type, night time paving, materials delivery, project constraints relating to utilities or permits, and quantity of the material to be produced have a significant effect on their production rates. These results are very similar to what was found for the different analysis presented in this chapter. Moreover, as shown in Table 6.14, project location (urban or rural), budget allocated for the project have a significant effect while contractor data pertaining to number of supervisors on the field, equipment availability, labor availability on the project and the time spent on equipment usage have some effect on the production rates. The extent to which each factor effects the productivity of construction work items was obtained through implementing stepwise linear regressions in JMP Pro. The results obtained in this analysis are included in Appendix B.

Moreover, production rate of curb and gutter is effected by the increase in supervisors, quantity and is dependent on the area (urban/rural) in which the project is located. Furthermore, productivity of sidewalks majorly depends on the availability of equipment and project type. It was found that production rate of major work items is also effected by whether they are produced in large amounts and the equipment available for disposal. Production rate of PCCP is controlled by staging and it will decrease if the project is in an urban location. The extent to which each factor effects production rates of construction activities was obtained using stepwise linear regression.

6.4 Production rates of major work items

During the data mining phase of this study, inter quartile ranges were derived from the daily work report data for each work item. Table 6.15 below represents all the major construction activities that were considered in this research and a summary of their respective productivity rates as obtained from the analysis. Missing information regarding project data for activities were filled by calculating averages of the data available. The production rates are usually calculated for 8 hour work shifts.

The mean production rate is the average production rate of all the projects that are in the historic data for that work item. The production rates are calculated by dividing the quantity with the total number of days it took to finish the activity. The upper 95% confidence limit and lower a 95 % confidence limit does not mean that there is a 95 % probability that the interval contains the true mean. The interval computed from a given sample either contains the true mean or it does not. Instead, the level of confidence is associated with the method of calculating the interval. The confidence coefficient is simply the proportion of samples of a given size that may be expected to contain the true mean.

Table 6.15: Quartile production rates of work items from DWR data

SN	Item description	Units	Mean	Upper 95% Mean	Lower 95% Mean	Q1	Median	Q3
AA	CRUSHED AGGREGATE COURSE-MEDIUM	CUYD	3154	3888	2420	1039	2113	4328
AB	CRUSHED AGGREGATE COURSE -LARGE	M3	1557	1915	1200	98	440	1459
AC	EXCAVATION-UNCLASSIFIED	M3	13085	16737	9494	4255	7050	20210
AD	EXCAVATION-UNCLASS BORROW	M3	8095	12895	3300	851	4170	8801
AE	COLD MILLING	SQYD	17800	21053	14544	2133	8603	20957
AF	BEDDING MATERIAL	M3	83	100	66	44	64	113
AG	RUMBLE STRIPS	KM	9	13	6	3	7	13
AH	COVER - TYPE 1	M2	56115	69334	42896	21687	45419	74750
AI	COVER - TYPE 2	M2	16578	22831	10324	8019	11960	28779
AJ	TRAFFIC CONTROL DEVICES CB	UNIT	3150	3308	2988	1972	2960	4035
Ak	TEMP PAVEMENT MARKINGS	MILE	3	3	2	1	2	3
Al	CURB AND GUTTER	M	253	349	156	136	175	275
AM	FENCE-CHAIN LINK	LNFT	538	846	230	93	251	587
AN	SIDEWALK	M2	245	303	187	65	131	294
AO	GUARDRAIL STEEL	LNFT	817	1212	422	113	376	946
AP	SEEDING	ACRE	8	9	6	1	3	10
AQ	SODDING	SQYD	534	767	300	51	260	801
AR	PCCP	SQYD	3419	5934	905	119	2407	4491
AS	MUCK EXCAVATION	CUYD	2440	3371	1508	415	1442	4357
AT	TOP SOIL EXCAVATION	CUYD	1881	2200	1364	210	897	2535
AU	MOBILIZATION	LS	1	1	1		1	
AV	STREET EXCAVATION	M3	1072	1576	570	236	545	1348
AW	CTB PULVARIZED	SQYD	10200			20670	5272	4670
AX	CTB	M3	4036	6723	1349	1167	2726	5045
AY	CULVERT RCB	LNFT	43			2	7	42
AZ	DRAINAGE PIPE	LNFT	78	88	68	31	68	107
BA	COLD RECYCLED PLANT MIX	SQYD	45555			10572	13689	112403
BB	PMS -PLANT MIX BIT SURF	MT	2816	4847	784	244	1694	3309
BC	EPOXY	GAL	1458	1812	1105	84	309	681
BD	WORDS & SYMBOLS	GAL	17	21	13	3	7	17
BE	CONCRETE PAVEMENT GRINDING	SQYD	3904	7702	1050	961	2014	7702
BF	TEMPORARY EROSION CONTROL	LS	909	1194	624	86	338	1039
BG	EMULS ASPHALT CRS-2P	TON	132	152	113	27	94	178
BH	EXPANSION JOINT	LNFT	73	104	43	34	56	81
BI	RIPRAP	CUYD	201	259	143	22	96	229

That is, for a 95 % confidence interval, if many samples are collected and the confidence interval computed, in the long run about 95 % of these samples would contain the true mean within the limits. The quartile production rates provide us with the percentile of the projects that have production rates below a particular quartile. For example, Q1 means 25% of the projects available in DWR data have recorded production rates lower than that of the value at Q1. Median provides the production rate value at which 50% of the projects have lower production rates as available in DWR data. Similarly, Q3 provides the value at which 75% of the projects have lower production rate than the designated value.

These values provide the engineer who is determining production rates for an activity with a holistic idea on the historic production rates achieved for a construction activity. Making adjustments based on this data would add more value to the estimate as these are directly derived from the production rates achieved on the field.

6.5 Contractor Evaluation

Contactor's expertise and performance can determine the project success. Contractor performance can be defined by the level and quality of projects delivered to clients. While clients do not have a clear understanding related to contractor selection and they struggle to make appropriate decisions in selecting best fit for the project. It has been a common practice however, to select the lowest bidder among competing contractors to perform the job which might experience inefficient management of construction project and result in low performance and productivity. (Doloi, 2011) (M. R. Lee, 2014)

Currently, there are some research papers on evaluating and measuring contractor performance either based on scores, key performance indicators, etc. Innovation of the performance records system (PRS) for public construction contractors, which was established in Taiwan in 2010. The system provides performance records pertaining to the project management contractor, the supervision contractor, and the construction contractor who have taken part in public construction in the last 5 years (Chang, 2016). Similar computer-based scoring system for measuring environmental performance committed by a contractor through calculating the contractor`s environmental performance score (EPS) which the level of EPS can be used as a simple indicator for measuring and communicating the level of a contractor`s environmental performance. (Shen, 2005) In addition, another model created in Australia employing the structural equation modelling technique and adapting 29 technical attributes across five confirmatory factors could potentially contribute to the development of a company's procedures and enhance existing knowledge of contractor prequalification practices. (Doloi, 2011) Moreover, benchmarking can provide an objective analysis of how an organization is performing. Utilization of data envelopment analysis (DEA) which has been recognized as a robust tool that is used for evaluating the performance of organizations to benchmark safety performance of construction contractors. (El-Mashaleh, 2010) The key to developing effective benchmarking is to obtain measures that can provide truthful and significant measurement. It is generally believed that past performance is the best predictor of future performance. A simple system or method of evaluating contractors is essential. If the system is too complex or difficult for evaluators to carry out, it will not achieve its goals (Straight, 1999)LR technique is able to model the relationship between clients' evaluation preferences (i.e., LIA of each evaluation criterion) and contractor performance to achieve satisfactory accuracy in contractor performance prediction. The findings also show that the LR model can deal relatively easily with a mixture of qualitative and quantitative independent variables to demonstrate the dichotomous outcome, whereas other multivariate statistics have difficulty with predicted values or group memberships, which are constrained to binary results (Wong, 2004). While determining the contract completion time for a project, it is most important to determine if a contractor is able to achieve the desired production rates. If the contractor can't maintain the desired production rates the project will have cost and schedule overruns. For this reason, this research focuses on using

DWR data to develop a method to evaluate the capability of contractors to maintain their production rates. Two major construction activities are selected for this analysis (1) crushed aggregate course and (2) portland cement concrete pavement. These activities are selected based on the importance in the critical path of highway construction projects as any delay would directly impact the schedule of the project. Crushed Aggregate Course is producing and placing one or more courses of aggregate surfacing on a prepared surface or producing and stockpiling aggregate surfacing and Portland cement concrete pavement is the construction of PCCP on a prepared subgrade or base course (STANDARD SPECIFICATIONS FOR ROAD AND BRIDGE CONSTRUCTION, 2006).

The calculated production rates for each project are compared with the documented production rates of the MDT to categorize the contractors into:

a) Tier 1 contractors: Calculated Production rate > 1.5 times documented production rates
b) Tier 2 contractors: 0.8 times Documented Production rates < Calculated Production rate < 1.5 times documented production rates
c) Tier 3 contractors: Calculated Production rate < 0.8 times Documented Production rates

This categorization has been used in the data under the contractor indicator column forming a logistical variable where each tier is represented by numbers 1, 2 and 3. Each category of contractors was analyzed separately, and simulation was run using @Risk to gather data on the production rates possible for each tier of these contractors in future projects.

6.5.1 Comparing Production rates of contractor categories

The production rates of contractors are considered two tiers at a time for this analysis to observe the variation in production rates possible by each of these categories. Research hypothesis for this analysis was that there might be a clear distinction between possible production rates of different tiers. Monte Carlo simulations are used to simulate the production rates achieved by each tire.

a.) Simulation between all categories of contractors for Crushed Aggregate Course

This analysis used @Risk software for performing Monte Carlo simulation on the production rates for tier 1, tier 2 and tier 3 contractors to observe, if any distinction existed between high performing contractors and low performing contractors. Figure 6.11 shows the production rate simulation curves for these tiers. The red curve is tier 1 high performing contractor category, blue curve is tier 2 contractors while the green curve is tier 3 or low performing contractor category. From the simulation results, it is visible that tier 3 contractors have lower production rates as compared to Tier 1 contractors. The mean production rate of tier 3 contractors is 415 yd^3/day whereas the mean production rate for tier 1 contractors is 8,409 yd^3/day. The difference in average production rates achieved for these contractors is clearly observed in the graph shown in Figure 6.11. Number of data points (Projects) for each contractor are 13 and 17 for tier 1 and tier 3 contractors respectively. Out of the 17 projects by tier 3 contractors, only 11 projects had low production rates recorded. Out of the 11 projects, 5 projects were in urban areas and data regarding two projects is unknown. This also suggests that contractors who predominantly work in urban areas tend to have lower production rates. All the projects taken up by tier 1 contractor belong to rural region. This suggests that location has a significant impact on contractors' productivity. Following sections discuss the distinction between tier 2 and tier 3 contractors.

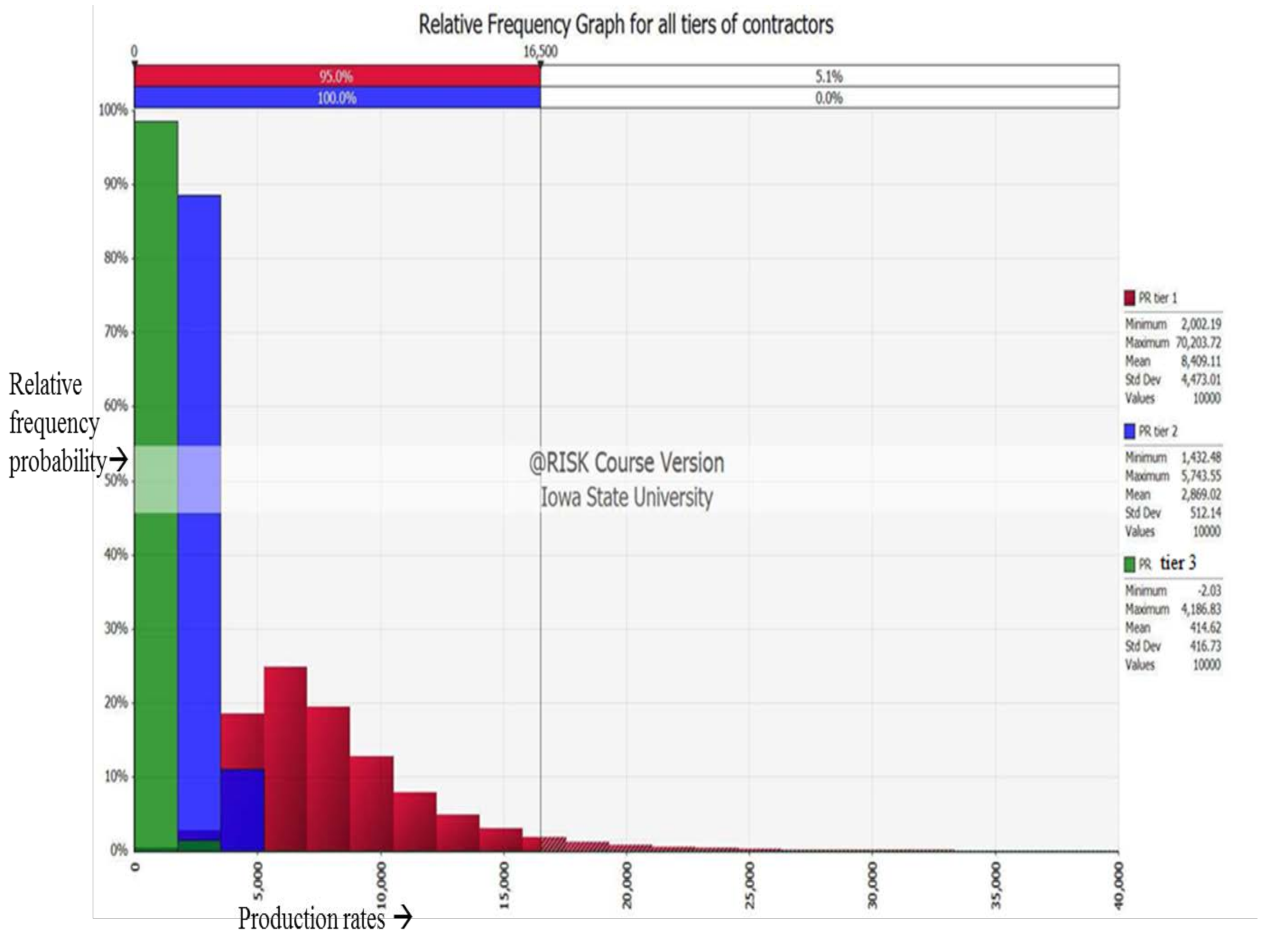
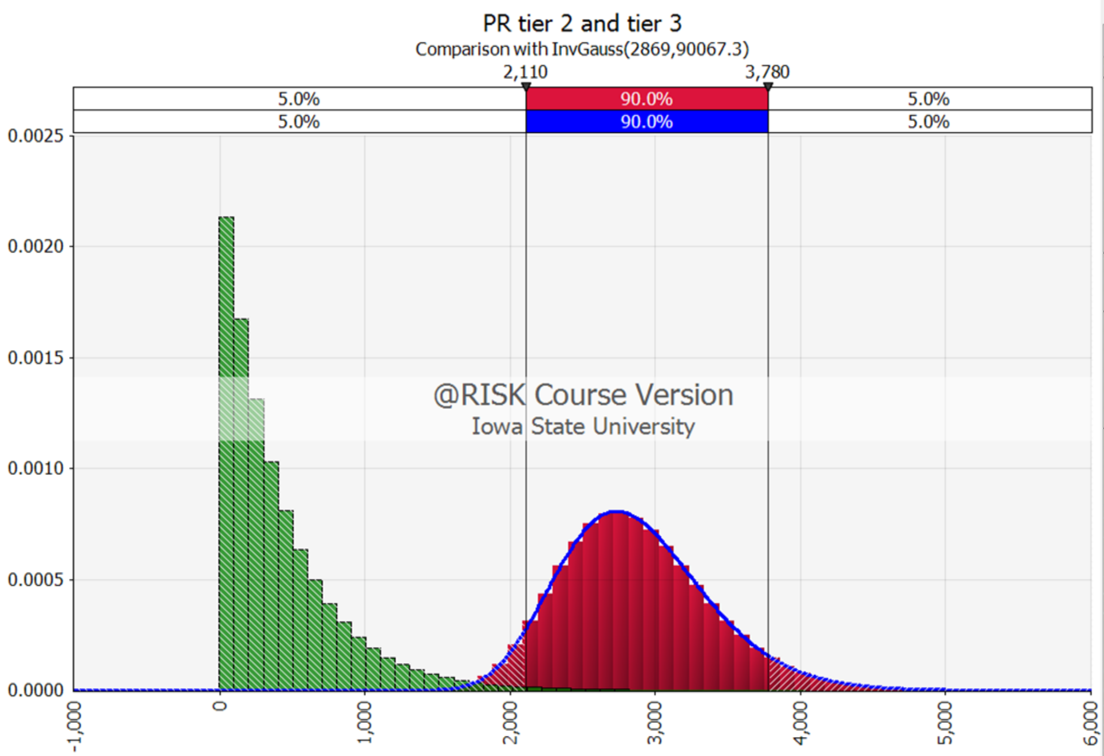


Figure 6.11: Production rate simulation curves for all three categories of contractors

b.) Simulation between Tier 2 and Tier 3 contractors for Crushed Aggregate Course

This analysis used @Risk software for performing Monte Carlo simulation on the production rates for tier 2 and tier 3 contractors to develop a range of possible production rates by each tier. Figure 6.12 shows the production rate simulation curves for these two tiers.

Tier 3 contractors have significantly lower production rates as compared to Tier 2 contractors. Green portion of the graph represents tier 3 contractor production rates while red portion represents the production rate of tier 2 contractors. These differences in production rates that can be achieved by different tiers, should be taken into consideration by DOTs before awarding the project.



	PR tier 2	InvGauss (2869,90067.3)	PR t
Cell	Crushed aggr..	Crushed aggr..	Crus
Minimum	1,464.97	0.00	
Maximum	5,630.09	+∞	
Mean	2,868.99	2,869.00	
90% CI	± 8.42		
Mode	2,730.78	2,735.19	
Median	2,824.09	2,824.14	
Std Dev	512.03	512.05	
Skewness	0.5345	0.5354	
Kurtosis	3.4701	3.4778	
Values	10000		
Errors	0		
Filtered	0		
Left X	2,110	2,110	
Left P	5.0%	5.0%	
Right X	3,780	3,780	
Right P	95.0%	95.0%	
Dif. X	1,669.80	1,669.80	
Dif. P	90.0%	90.0%	
1%	1,873.62	1,873.75	
5%	2,110.48	2,110.74	
10%	2,250.03	2,250.16	
15%	2,349.73	2,349.73	
20%	2,432.13	2,432.17	
25%	2,505.25	2,505.30	
30%	2,572.90	2,572.91	
35%	2,637.16	2,637.23	
40%	2,699.68	2,699.79	
45%	2,761.68	2,761.75	
50%	2,824.09	2,824.14	
55%	2,887.85	2,887.93	
60%	2,954.21	2,954.24	
65%	3,024.28	3,024.36	
70%	3,099.91	3,100.03	
75%	3,183.71	3,183.79	
80%	3,279.57	3,279.65	

Figure 6.12: Production rate simulation curves for Tier 2 and Tier 3 contractors (Crushed Aggregate Course)

c.) Simulation between Tier 2 and Tier 3 contractors for PCCP

This analysis used @Risk software for performing Monte Carlo simulation on the production rates possible for tier 2 and tier 3 contractors to make a distinction between these tiers. Figure 6.13 shows the production rate simulation curves for these two tiers. The mean production rate of tier 2 contractors is 6300 yd^2/day which is significantly higher than tier 3 contractors with mean production rate of 180 yd^2/day. The other reasons for the enormous difference might also be due to less data points being available in tier 3 contractors. This might have led the simulation to give such drastic difference in possible production rates between each tier.

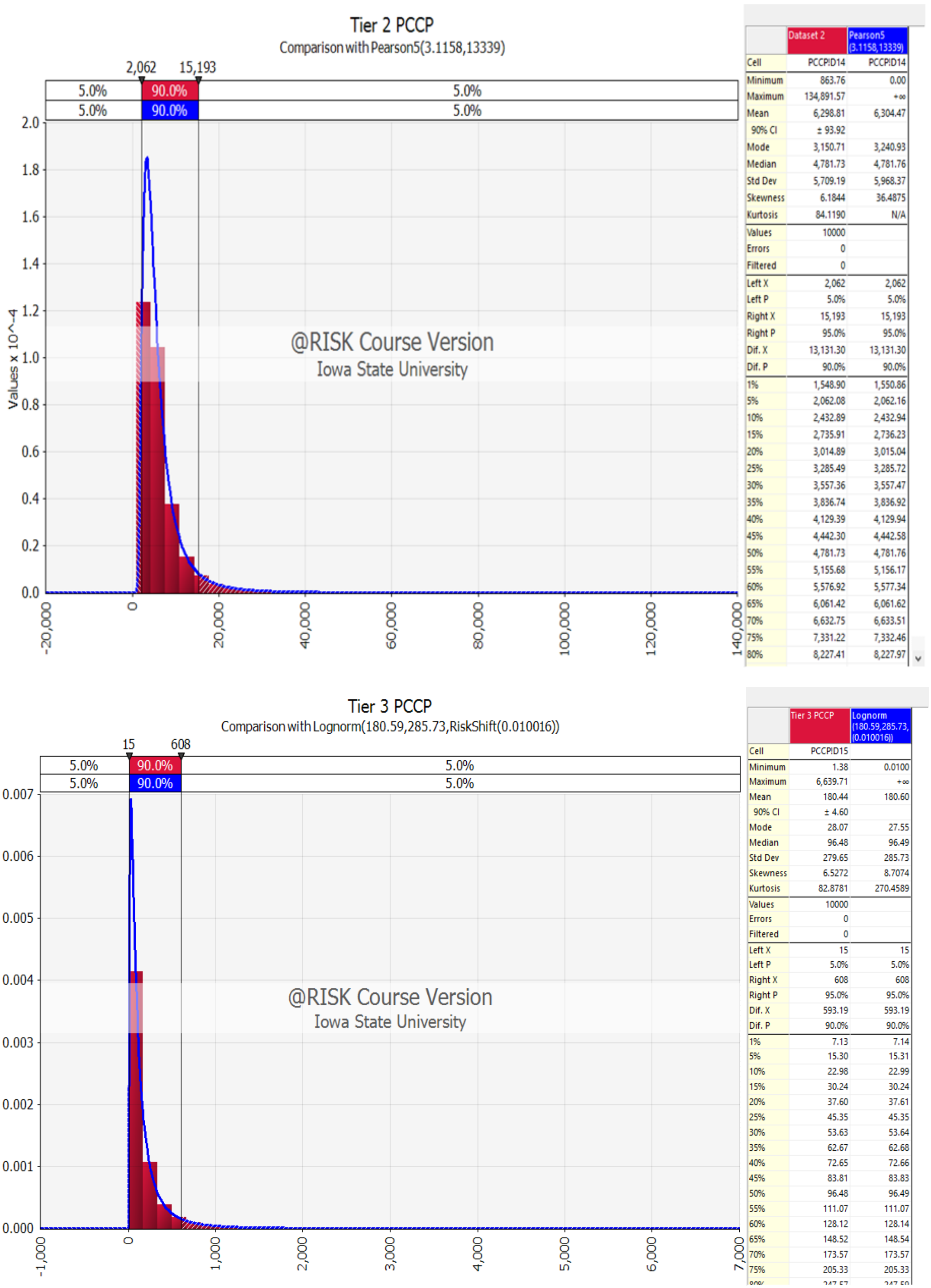


Figure 6.13: Production rate simulation curves for Tier 2 and Tier 3 contractors (PCCP)

d.) Sensitivity analysis for crushed aggregate course contractors

The number of equipment a contractor has at his disposal for a project has a significant influence on the production rates that can be achieved by the contractor especially when we are referring to tier 3 contractors. Change analysis was performed to determine the effect of increase in equipment on production rates for crushed course aggregate for a tier 1 contractor keeping quantity, location and project type constant. The results of this analysis are showed in Table 6.16. It is observed that the equipment available for disposal has a clear impact on production rates of crushed aggregate course.

Table 6.16: Percentage Change Estimate for Production Rate Changes

Equipment Used on the project	**Estimated Production rates**	**% Change in Production rate**	**Average Production Rate for crushed aggregate course**
15	1460	-	2600
30	1903	30.34	2600
45	2346	60.68	2600
60	2790	91.10	2600

The data that is obtained from this analysis was used to develop a database stating the average equipment availability of contractors for different work activities. The process of evaluating contractors is especially useful on alternate delivery projects where we need to select a contractor before having final designs. This data can be utilized by the DOT to evaluate contractors based on project and schedule requirement.

6.6 Summary

This chapter has discussed the impact of various factors on production rates and their significance. It is noteworthy that quantity to be produced is a consistent factor that has impact on production rates of 30 work items. Production rates of work items are significantly dependent on quantity. After a threshold value is reached, the production rate does not increase drastically and becomes constant. This relation between quantity and production rates is used to set upper limits on predicted production rates.

Depending on the district in which the project is located, production rates of 13 work items are significantly influenced. It is interesting to note that when the topography of the location is plain, work items that involve use of heavy equipment like crushed aggregate course, excavation, etc. recorded higher production rates than districts where the topography is mountainous.

Budget category has significant impact on 7 work items while urban location plays an important role in determining production rates for 6 major work items. It is important to note that tier 3 contractors evaluated for crushed aggregate course have predominantly worked in urban locations. DOTs must evaluate contractors in urban location and select tier 1 or tier 2 contractors if there is a need to expediting project schedule.

CHAPTER 7. CONSTRUCTION PRODUCTIVITY TOOL

Chapter 7 describes the concluding section of this research project which is the construction productivity tool. This chapter explains how the tool was developed by the research team and provides guidelines on how it can be used by the engineers to get an estimate of the production rates for MDT upcoming projects. This chapter also goes through the limitations of the tool and it also provides tables of production rates achieved on past project for major work items according to district, area and budget category.

7.1 Significance of the Tool

The MDT construction productivity tool provided in this research is of crucial importance for the Montana highway industry. This tool allows MDT engineers to estimate production estimations for future projects in a more systematic and efficient way while considering the main factors that significantly affect productivity of each work item. Since this tool is statistically based on the relationships found between the production rates and these factors from historic construction project data. MDT personnel will obtain more accurate results of estimated production rates and thus more intrinsically leading to better contract time estimate.

7.2 Development of the Tool

The MDT construction productivity tool is Excel based which used excel macros for taking the input from the end user. The tool takes the input of various factors such as the district location, if the project is implemented in a rural or urban area, the budget category and contract amount allocated for the project, season of work, project work type and the quantity of the work item to be produced. The background data consists of average supervisors, equipment availability and hours of work and equipment usage in the past projects of each work item. These are calculated by considering all historic projects for each work item and calculating the mean of the variable in consideration. The significant factors identified in Table 6.14 are used for each work item to determine the regression equation that would accurately predict production rates

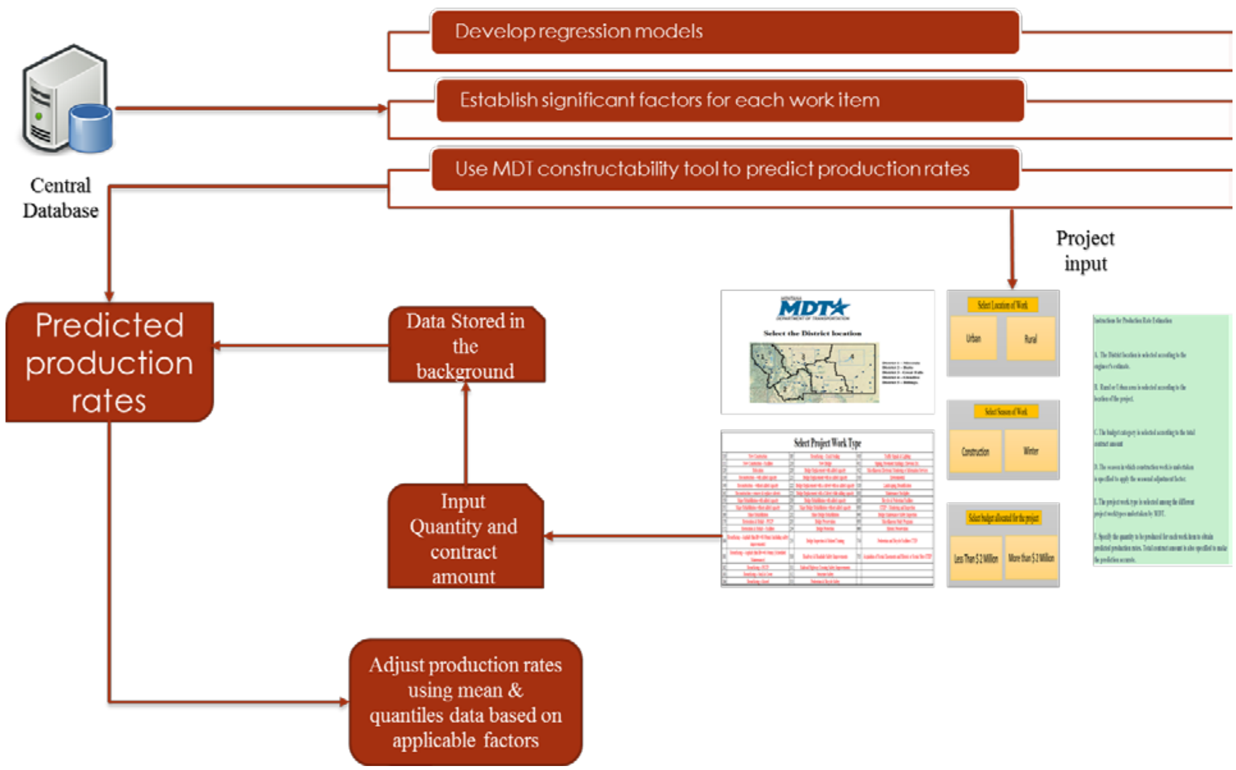


Figure 7.1: Development of MDT construction productivity tool

Figure 7.1 shows a flowchart describing the working of the MDT construction productivity tool. The input provided by the end user is stored in the background to predict production rates for each item. Different work items have different factors and their degrees of impact are different. The effects of project location, project type, work quantity, work season, and others are quantitatively evaluated using the historical data and are incorporated into the estimation system to predict production rates. These predicted production rates can be compared with the mean and inter quartile range (25 percentile value, median value and the 75 percentile value) that was achieved for each work item in the past projects. This provides the MDT engineer with a complete perspective on the production rates that were achieved on the field. The tool also provides mean and interquartile range for production rates achieved in each district, urban areas, rural areas and in different budget categories.

7.3 Guideline for Usage of the Tool

When the MDT engineers will open the tool, they will be provided with a brief introduction about the tool and its use as shown in Figure 7.2 below. After reading the introduction, the users will be given the option to launch the tool. When they do so, they will be transferred to the input screens of the tool shown in Figure 7.3 below. The instruction page addresses the user on what project inputs are required for predicting the production rate using this tool. The tool generates production rates for 35 major work items of Montana DOT. The page has an option “Launch Tool” which the users need to click after gathering the necessary project input as described in the introduction.

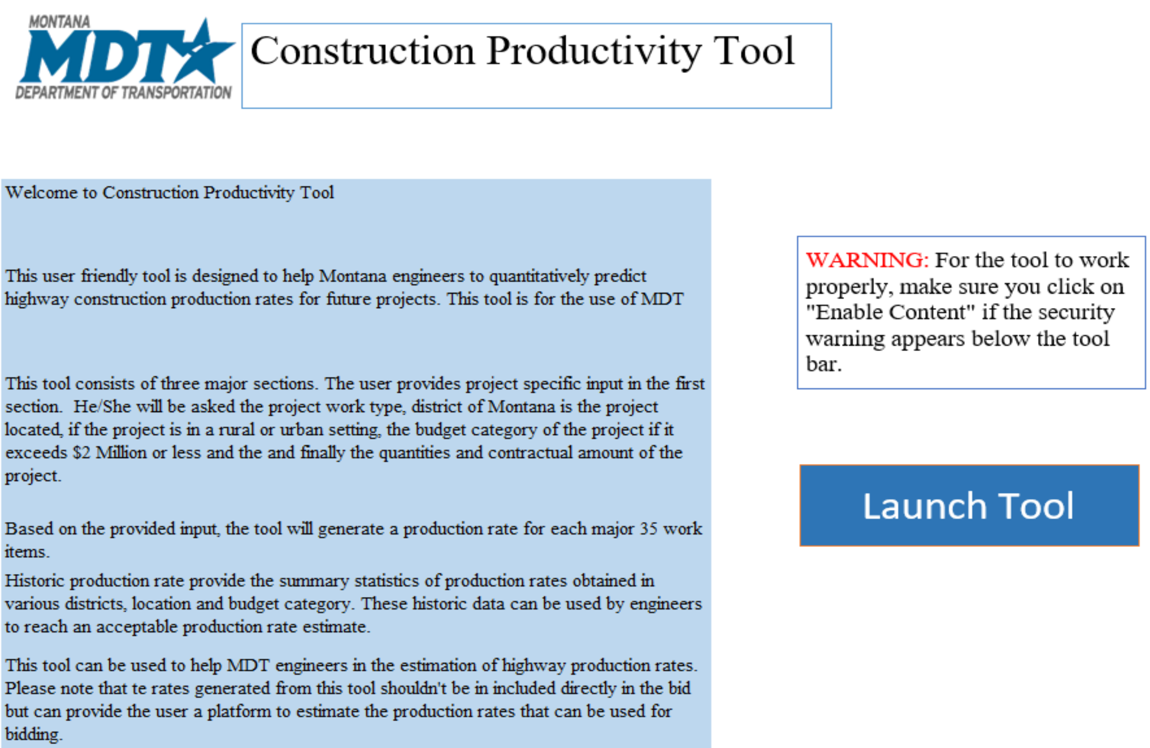


Figure 7.2: Introduction sheet in MDT construction productivity tool

This tool consists of three major sections. The user provides project specific input in the first section. He/She will be asked to provide the following input: project work type as shown in Figure 7.3 (a), maintenance district where the project is being undertaken in Montana, if the project is located in a rural or an urban setting, if the project budget is greater or less than $2 million and if the work is taking place in construction season or winter season (November 16 to April 15) as shown below in Figure 7.3 (b).

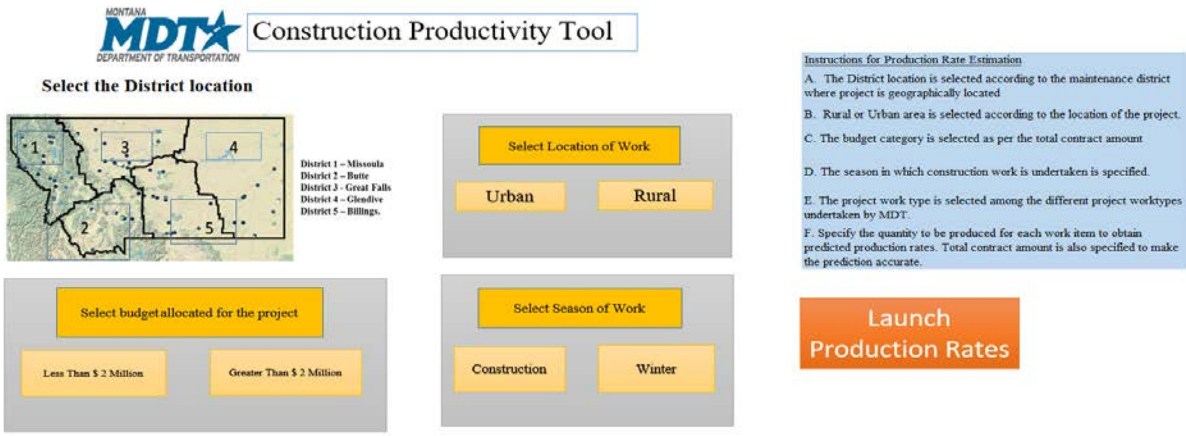
MONTANA MDT DEPARTMENT OF TRANSPORTATION | Construction Productivity Tool

Select Project Work Type

110	New Construction	185	Resurfacing – Crack Sealing	410	Traffic Signals & Lighting
111	New Construction – Facilities	210	New Bridge	411	Signing, Pavement Markings, Chevrons Etc..
120	Relocation	220	Bridge Replacement with added capacity	412	Miscellaneous Electronic Monitoring or Information Services
130	Reconstruction – with added capacity	221	Bridge Replacement with no added capacity	510	Environmental
140	Reconstruction – without added capacity	222	Bridge Replacement with a culvert with no added capacity	520	Landscaping, Beautification
141	Reconstruction – remove & replace culverts	223	Bridge Replacement with a Culvert while adding capacity	610	Maintenance Stockpiles
150	Major Rehabilitation-with added capacity	230	Bridge Rehabilitation with added capacity	620	Bicycle & Pedestrian Facilities
151	Major Rehabilitation-without added capacity	231	Major Bridge Rehabilitation without added capacity	630	CTEP – Monitoring and Inspection
160	Minor Rehabilitation	232	Minor Bridge Rehabilitation	640	Bridge Maintenance Safety Inspection
170	Restoration & Rehab – PCCP	233	Bridge Preservation	650	Miscellaneous Study Programs
172	Restoration & Rehab – Facilities	234	Bridge Protection	660	Historic Preservation
180	Resurfacing – Asphalt (thin lift<=60.00mm) (including safety improvements)	235	Bridge Inspection & Related Training	710	Pedestrian and Bicycle Facilities CTEP
181	Resurfacing – Asphalt (thin lift<=60.00mm) (Scheduled Maintenance)	310	Roadway & Roadside Safety Improvements	715	Acquisition of Scenic Easements and Historic or Scenic Sites CTEP
182	Resurfacing – PCCP	311	Railroad/Highway Crossing Safety Improvements		
183	Resurfacing – Seal & Cover	312	Structure Safety		
184	Resurfacing – Gravel	313	Pedestrian & Bicycle Safety		

Figure 7.3 a.) Input sheet for project work type in MDT construction productivity tool

The project work type codes available in the DWR data are named according to MDT standard project work type definitions (MDT 2015). There are a total of 45 different work type classifications and the user needs to double click on the work type name box and the input is recorded in the background as shown in Figure 7.3 (a).

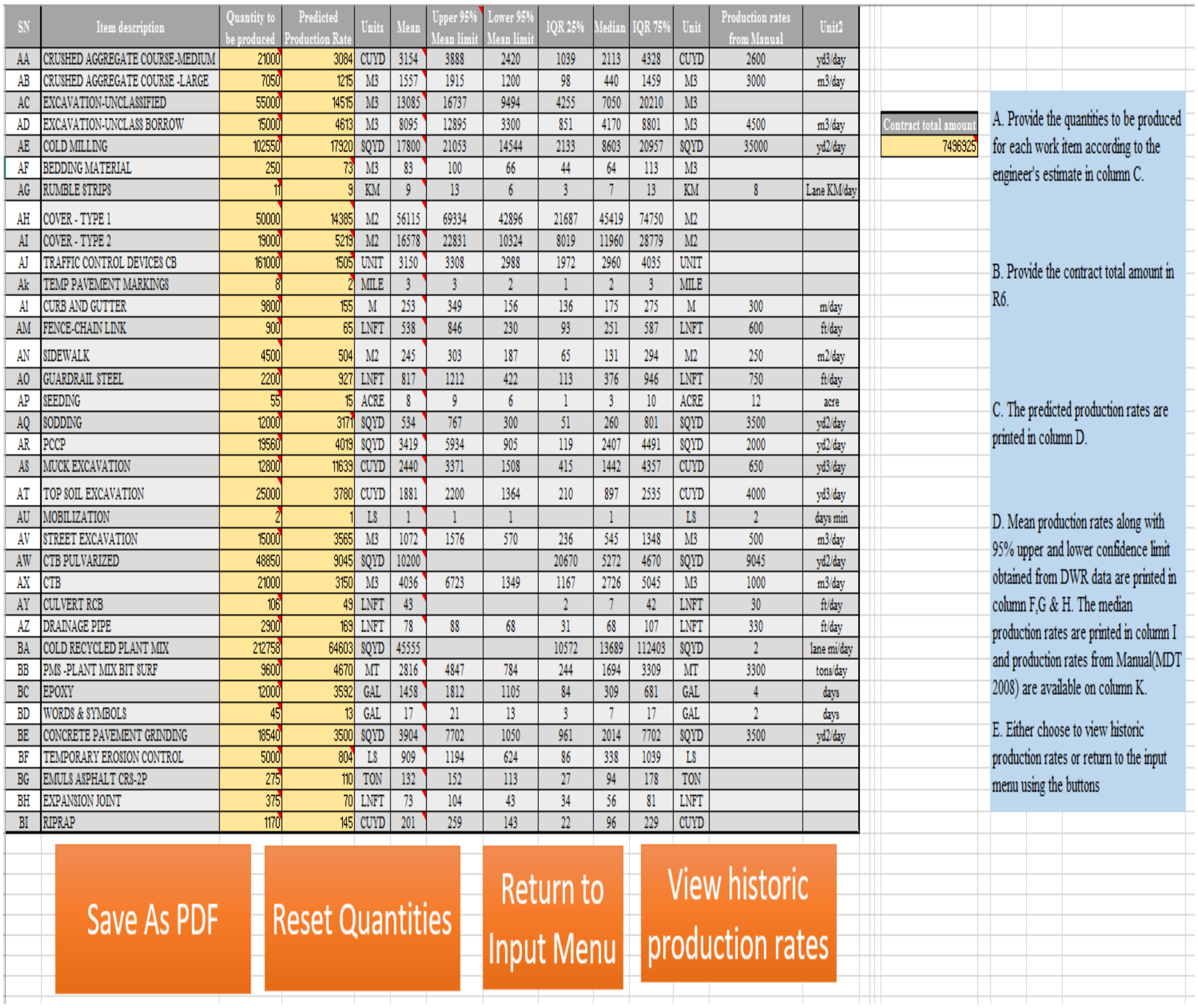


b.) Input sheet for project parameters in MDT construction productivity tool
Figure 7.3: Input sheets in MDT construction productivity tool

The tool will redirect the user to project parameters input screen as shown in Figure 7.3 (b).The user has to click on the following project input:

- Click on the district number box in which project is located. The name of each district and topographical map of Montana is provided for the ease of selection for the end user.
- Click on the appropriate budget category box. The input required from the user is if project budget is less than $2 million or greater the $2 million.
- Click on the appropriate box weather the project is located in urban location or rural location.
- Click on construction box if the project is not in-between November 16 to April 15.
- Click on launch production rates box.

After clicking on launch production rates box, the tool is redirected to production rate estimates sheet as shown in Figure 7.4. The user need to provide the input of work quantities of major work items that are critical for the project. The user is also asked to provide the total contract amount of the project. User must provide the input of the contract budget (in case of multiple projects in the same contract) for better accuracy of production rate estimates. In the column beside the quantity input, the predicted production rates for the project appears dynamically and change with the quantity input provided by the user. The tool provides comments on the statistical summaries of quantities for each work item calculated from the DWR data. The comments provide information regarding mean quantities produced in past projects as well as the inter quartile range of quantities. The tool is sensitive to the inputs provided and the predicted rates must be compared with the mean production rates of them work items which are calculated from the DWR data. Confidence limits for the mean (Snedecor and Cochran, 1989) are an interval estimate for the mean. Interval estimates are often desirable because the estimate of the mean varies from sample to sample. Instead of a single estimate for the mean, a confidence interval generates a lower and upper limit for the mean. The interval estimate gives an indication of how much uncertainty there is in our estimate of the true mean. The narrower the interval, the more precise is our estimate. The upper 95% confidence limit of the mean and the lower 95% confidence limit of the mean is provided for each work item available in the tool. The quartiles and published production rates of MDT are also provided in the table of estimates.

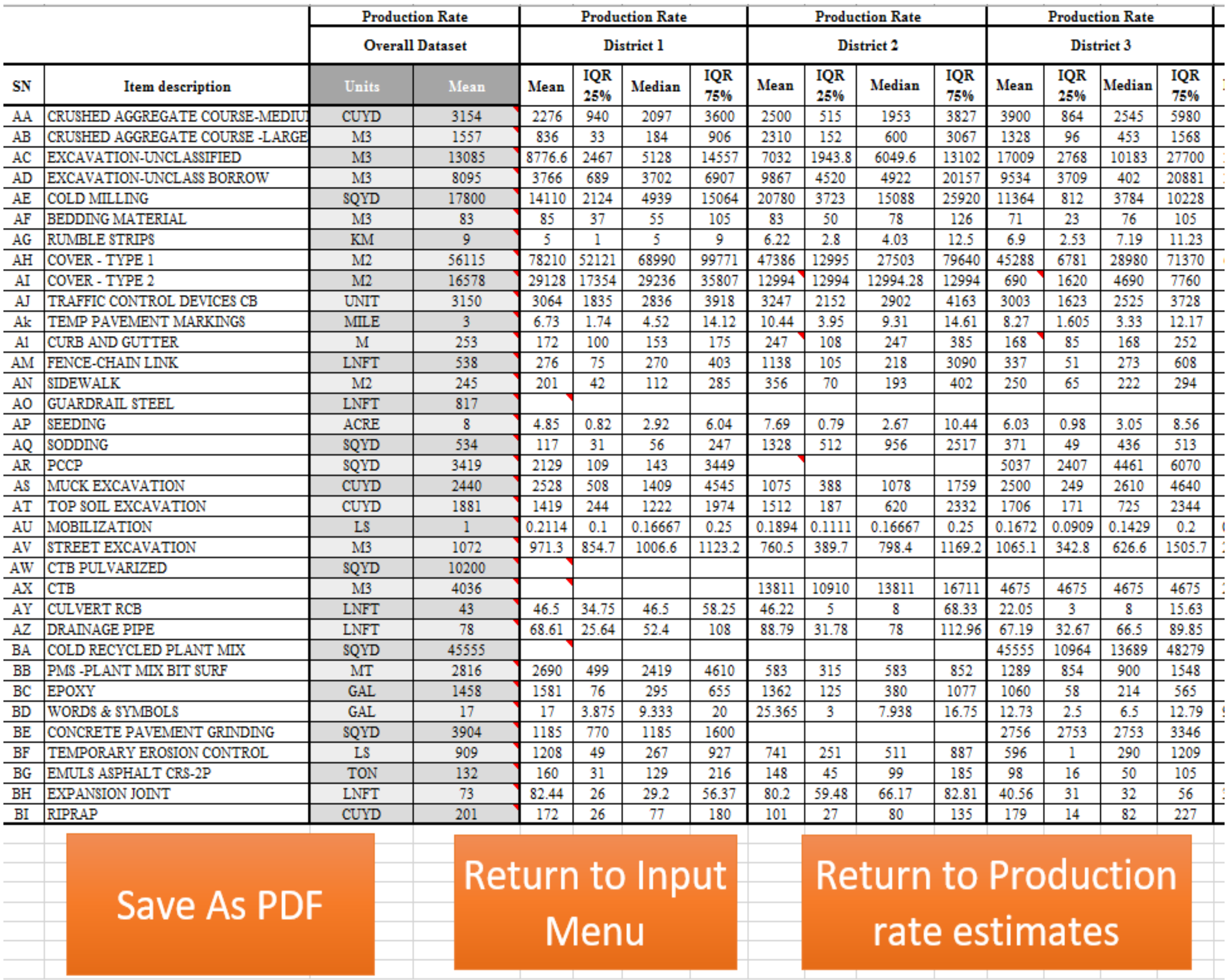


SN	Item description	Quantity to be produced	Predicted Production Rate	Units	Mean	Upper 95% Mean limit	Lower 95% Mean limit	IQR 25%	Median	IQR 75%	Unit	Production rates from Manual	Unit2
AA	CRUSHED AGGREGATE COURSE-MEDIUM	21000	3084	CUYD	3154	3888	2420	1039	2113	4328	CUYD	2600	yd3/day
AB	CRUSHED AGGREGATE COURSE -LARGE	7050	1215	M3	1557	1915	1200	98	440	1459	M3	3000	m3/day
AC	EXCAVATION-UNCLASSIFIED	55000	14515	M3	13085	16737	9494	4255	7050	20210	M3		
AD	EXCAVATION-UNCLASS BORROW	15000	4613	M3	8095	12895	3300	851	4170	8801	M3	4500	m3/day
AE	COLD MILLING	102550	17920	SQYD	17800	21053	14544	2133	8603	20957	SQYD	35000	yd2/day
AF	BEDDING MATERIAL	250	73	M3	83	100	66	44	64	113	M3		
AG	RUMBLE STRIPS	11	9	KM	9	13	6	3	7	13	KM	8	Lane KM/day
AH	COVER - TYPE 1	50000	14385	M2	56115	69334	42896	21687	45419	74750	M2		
AI	COVER - TYPE 2	19000	5219	M2	16578	22831	10324	8019	11960	28779	M2		
AJ	TRAFFIC CONTROL DEVICES CB	161000	1505	UNIT	3150	3308	2988	1972	2960	4035	UNIT		
Ak	TEMP PAVEMENT MARKINGS	8	2	MILE	3	3	2	1	2	3	MILE		
Al	CURB AND GUTTER	9800	155	M	253	349	156	136	175	275	M	300	m/day
AM	FENCE-CHAIN LINK	900	65	LNFT	538	846	230	93	251	587	LNFT	600	ft/day
AN	SIDEWALK	4500	504	M2	245	303	187	65	131	294	M2	250	m2/day
AO	GUARDRAIL STEEL	2200	927	LNFT	817	1212	422	113	376	946	LNFT	750	ft/day
AP	SEEDING	55	15	ACRE	8	9	6	1	3	10	ACRE	12	acre
AQ	SODDING	12000	3171	SQYD	534	767	300	51	260	801	SQYD	3500	yd2/day
AR	PCCP	19560	4019	SQYD	3419	5934	905	119	2407	4491	SQYD	2000	yd2/day
AS	MUCK EXCAVATION	12800	11639	CUYD	2440	3371	1508	415	1442	4357	CUYD	650	yd3/day
AT	TOP SOIL EXCAVATION	25000	3780	CUYD	1881	2200	1364	210	897	2535	CUYD	4000	yd3/day
AU	MOBILIZATION	2	1	LS	1	1	1		1		LS	2	days min
AV	STREET EXCAVATION	15000	3565	M3	1072	1576	570	236	545	1348	M3	500	m3/day
AW	CTB PULVARIZED	48850	9045	SQYD	10200			20670	5272	4670	SQYD	9045	yd2/day
AX	CTB	21000	3150	M3	4036	6723	1349	1167	2726	5045	M3	1000	m3/day
AY	CULVERT RCB	106	49	LNFT	43			2	7	42	LNFT	30	ft/day
AZ	DRAINAGE PIPE	2900	169	LNFT	78	88	68	31	68	107	LNFT	330	ft/day
BA	COLD RECYCLED PLANT MIX	212758	64603	SQYD	45555			10572	13689	112403	SQYD	2	lane mi/day
BB	PMS -PLANT MIX BIT SURF	9600	4670	MT	2816	4847	784	244	1694	3309	MT	3300	tons/day
BC	EPOXY	12000	3592	GAL	1458	1812	1105	84	309	681	GAL	4	days
BD	WORDS & SYMBOLS	45	13	GAL	17	21	13	3	7	17	GAL	2	days
BE	CONCRETE PAVEMENT GRINDING	18540	3500	SQYD	3904	7702	1050	961	2014	7702	SQYD	3500	yd2/day
BF	TEMPORARY EROSION CONTROL	5000	804	LS	909	1194	624	86	338	1039	LS		
BG	EMULS ASPHALT CRS-2P	275	110	TON	132	152	113	27	94	178	TON		
BH	EXPANSION JOINT	375	70	LNFT	73	104	43	34	56	81	LNFT		
BI	RIPRAP	1170	145	CUYD	201	259	143	22	96	229	CUYD		

Figure 7.4: Production rate estimates sheet in MDT construction productivity tool

The user is provided with four options on the page after the predicted production rates of work items are obtained. The user can save the production rates as a PDF file, reset the quantities of work to be produced for a different production rate estimate and same project parameters, return to the input menu which will redirect the user to the select project work type sheet for new input and view historic production rates. The “View historic production rates” box if clicked, will direct the tool to historic production rates sheet as shown in the Figure 7.5.

Historic production rates sheet consists of data regarding statistical summary of production rates achieved on past project for different work items. This data provides production rates achieved for work items in each district, urban production rates achieved for each item, rural production rates achieved for each item, production rates for projects with budget greater than $2 million and production rates for projects with budget less than $2 million. The mean production rates achieved and the three quartiles are calculated from the central database for each category of projects. This input better equips the MDT engineer to finalize the production rate used for the work activity. As shown in Figure 7.5 the tool provides three options to the user to save the historic production rates in a PDF, return to the input menu which will redirect the tool to select project work type screen and return to production rate estimates which redirects the user to production rates estimation screen to finalize the production rate. The Figure 7.5 shows a screenshot of the historic production rates for some categories while other categories are provided in the tool.



		Production Rate Overall Dataset		Production Rate District 1				Production Rate District 2				Production Rate District 3			
SN	Item description	Units	Mean	Mean	IQR 25%	Median	IQR 75%	Mean	IQR 25%	Median	IQR 75%	Mean	IQR 25%	Median	IQR 75%
AA	CRUSHED AGGREGATE COURSE-MEDIU	CUYD	3154	2276	940	2097	3600	2500	515	1953	3827	3900	864	2545	5980
AB	CRUSHED AGGREGATE COURSE -LARGE	M3	1557	836	33	184	906	2310	152	600	3067	1328	96	453	1568
AC	EXCAVATION-UNCLASSIFIED	M3	13085	8776.6	2467	5128	14557	7032	1943.8	6049.6	13102	17009	2768	10183	27700
AD	EXCAVATION-UNCLASS BORROW	M3	8095	3766	689	3702	6907	9867	4520	4922	20157	9534	3709	402	20881
AE	COLD MILLING	SQYD	17800	14110	2124	4939	15064	20780	3723	15088	25920	11364	812	3784	10228
AF	BEDDING MATERIAL	M3	83	85	37	55	105	83	50	78	126	71	23	76	105
AG	RUMBLE STRIPS	KM	9	5	1	5	9	6.22	2.8	4.03	12.5	6.9	2.53	7.19	11.23
AH	COVER - TYPE 1	M2	56115	78210	52121	68990	99771	47386	12995	27503	79640	45288	6781	28980	71370
AI	COVER - TYPE 2	M2	16578	29128	17354	29236	35807	12994	12994	12994.28	12994	690	1620	4690	7760
AJ	TRAFFIC CONTROL DEVICES CB	UNIT	3150	3064	1835	2836	3918	3247	2152	2902	4163	3003	1623	2525	3728
Ak	TEMP PAVEMENT MARKINGS	MILE	3	6.73	1.74	4.52	14.12	10.44	3.95	9.31	14.61	8.27	1.605	3.33	12.17
Al	CURB AND GUTTER	M	253	172	100	153	175	247	108	247	385	168	85	168	252
AM	FENCE-CHAIN LINK	LNFT	538	276	75	270	403	1138	105	218	3090	337	51	273	608
AN	SIDEWALK	M2	245	201	42	112	285	356	70	193	402	250	65	222	294
AO	GUARDRAIL STEEL	LNFT	817												
AP	SEEDING	ACRE	8	4.85	0.82	2.92	6.04	7.69	0.79	2.67	10.44	6.03	0.98	3.05	8.56
AQ	SODDING	SQYD	534	117	31	56	247	1328	512	956	2517	371	49	436	513
AR	PCCP	SQYD	3419	2129	109	143	3449					5037	2407	4461	6070
AS	MUCK EXCAVATION	CUYD	2440	2528	508	1409	4545	1075	388	1078	1759	2500	249	2610	4640
AT	TOP SOIL EXCAVATION	CUYD	1881	1419	244	1222	1974	1512	187	620	2332	1706	171	725	2344
AU	MOBILIZATION	LS	1	0.2114	0.1	0.16667	0.25	0.1894	0.1111	0.16667	0.25	0.1672	0.0909	0.1429	0.2
AV	STREET EXCAVATION	M3	1072	971.3	854.7	1006.6	1123.2	760.5	389.7	798.4	1169.2	1065.1	342.8	626.6	1505.7
AW	CTB PULVARIZED	SQYD	10200												
AX	CTB	M3	4036					13811	10910	13811	16711	4675	4675	4675	4675
AY	CULVERT RCB	LNFT	43	46.5	34.75	46.5	58.25	46.22	5	8	68.33	22.05	3	8	15.63
AZ	DRAINAGE PIPE	LNFT	78	68.61	25.64	52.4	108	88.79	31.78	78	112.96	67.19	32.67	66.5	89.85
BA	COLD RECYCLED PLANT MIX	SQYD	45555									45555	10964	13689	48279
BB	PMS -PLANT MIX BIT SURF	MT	2816	2690	499	2419	4610	583	315	583	852	1289	854	900	1548
BC	EPOXY	GAL	1458	1581	76	295	655	1362	125	380	1077	1060	58	214	565
BD	WORDS & SYMBOLS	GAL	17	17	3.875	9.333	20	25.365	3	7.938	16.75	12.73	2.5	6.5	12.79
BE	CONCRETE PAVEMENT GRINDING	SQYD	3904	1185	770	1185	1600					2756	2753	2753	3346
BF	TEMPORARY EROSION CONTROL	LS	909	1208	49	267	927	741	251	511	887	596	1	290	1209
BG	EMULS ASPHALT CRS-2P	TON	132	160	31	129	216	148	45	99	185	98	16	50	105
BH	EXPANSION JOINT	LNFT	73	82.44	26	29.2	56.37	80.2	59.48	66.17	82.81	40.56	31	32	56
BI	RIPRAP	CUYD	201	172	26	77	180	101	27	80	135	179	14	82	227

Figure 7.5: Historic production rates sheet in MDT construction productivity tool

7.4 Limitations of the Tool

One of the major limitations of the MDT construction productivity tool developed in this research is that it couldn't account to all possible factors that might affect production rates in a project. The factors were restricted to data available in the DWR data. The DWR data has wide range of projects each work item. The leads to increase in variability in the prediction accuracy of different work items. The R^2 obtained for each regression model is documented in Table 7.12. The DWR data consisted of considerable number of null values for some work items for quantities and models were developed after cleaning the data appropriately. The accuracy of production rate estimate produced by the tool is dependent on a similar project undertaken in the past. The tool is sensitive some project work types. The tool does not predict production rates for certain work items as the historic data does not contain the selected project type for these work items. For example, if a landscaping and beautification (520) is selected as project work type, the predicted production rate for traffic control devices will not be displayed as this project work type category has never undertaken that work item.

CHAPTER 8. CONCLUSIONS

Accurate and practical production rate estimates are crucial for an accurate forecast of contract completion time. As costs of highway projects increase with time, the importance of estimating highway construction contract time has increased in significance which emphasizes the need for effective production rates due to the interrelatedness between both. Before this research project, Many DOTs still use production rate charts with engineering judgement, but DOTs acknowledge the need for improving the accuracy of production rates used.

This study uses daily work report data provided by Montana DOT to derive meaningful insights on how different factors affect construction productivity. The dataset includes various project characteristic information such as, daily quantity of work accomplished for each work item, start and end date of each work item, labor and equipment usage information, weather, etc. This rich data set is used to estimate realistic production rates of major work items. Usage of production rate charts by MDT to estimate production rates of their projects highlighted the importance of this study and the huge contribution that it provides to the Montana highway construction industry. MDT contract time determination manual set a guideline to update production rate system every two years in 2008. The production rates used by MDT haven't been revised since. This research allows MDT to be equipped with a powerful data driven tool to enhance the production rate estimation but also allow MDT to be one of the leading state DOTs to provide a benchmarking example that other DOTs can follow. The results of this project will be immediately available and used by MDT engineers.

Major challenges faced in this research was during the data cleaning phase. The DWR data contains data points of quantity produced on each day for a specific work item in a project. Accurately extracting production rates that were achieved in past projects for the major work items is very crucial. A central database was developed for this study which extracted information of various factors that influence production rates. This database is used to develop regression models for predicting production rates for future projects.

The influence of factors on production rates were tested using descriptive and predictive statistics. This research developed the production rates estimates of excavation, portland cement concrete paving as well as 33 other construction activities for highway projects in Montana. It also provided MDT with a statistical summary of the major factors that influence production rates based on location and budget. The research uses information from DWR data to perform contractor evaluation for two major work items. Contractor evaluation provides the user with valuable information regarding which tier of contractors are schedule driven to complete highway projects. There is a clear distinction between various tiers as described in chapter 6 and MDT engineers should consider the distinction before awarding a project to a contractor.

Descriptive analysis phase of this study revealed the difference in production rates achieved under different project parameters. This analysis showed that there is a clear difference between production rates achieved in the construction season and the winter season. Around 90 % of work activities, production rates in construction season are double or more than production rates in the winter season. It is widely accepted in the construction industry that production rates are lower during winter and this analysis reinforces the belief showing statistical proof from past projects. This analysis also compares production rates achieved across various districts and determines for which work items, district location plays an important factor. It is also observed that mean production rates achieved in rural location are higher than urban locations for 26 work items.

The summary statistics provides information relating to the mean and quartiles of production rates for the category in consideration. Estimator is provided with this data for each district, urban areas, rural areas, budget category and major project types. This would add value to the predicted production rate calculated by construction productivity tool as the estimator can use summary statistics to adjust the predicted production rates according to project requirement.

The project type, quantity to be produced, district location and the workforce available turned out to be two main factors effecting the production rates of earthwork. The project type and the quantity were significant factors for PCCP. It is noteworthy that quantity to be produced is a consistent factor that has impact on production rates of 30 work items. Production rates of work items are significantly dependent on quantity. After a threshold value is reached, the production rate does not increase drastically and becomes constant. This relation between quantity and production rates is used to set upper limits on predicted production rates.

Depending on the district in which the project is located, production rates of 13 work items are significantly influenced. It is interesting to note that when the topography of the location is plain, work items that involve use of heavy equipment like crushed aggregate course, excavation, etc. recorded higher production rates than districts where the topography is mountainous.

Budget category has significant impact on 7 work items while urban location plays an important role in determining production rates for 6 major work items. It is important to note that tier 3 contractors evaluated for crushed aggregate course have predominantly worked in urban locations. DOTs must evaluate contractors in urban location and select tier 1 or tier 2 contractors if there is a need to expediting project schedule.

Using the statistical results generated from running stepwise linear regressions in the JMP pro software, the research team was able to develop regression models for major work items to determine the most significant factors and their effects on production rates. A user-friendly production rate estimation tool incorporates the results of this analysis. This tool allows estimators to calculate estimated production rates on future project.

The extensive literature review that was conducted for this study showed that the highway contract time estimation has lot of opportunities for future research about production rates on highway construction projects as many DOTs still rely on static production rates and engineering judgement to determine contract time. This research provides a quantitative analysis of production rates and significance of different factors. Further research would be beneficial to develop activity sequencing logics to expand this research study to accurately estimate contract time for a construction project. Weather data available in the DWR data can be utilized to develop weather patterns that have impact on productivity every year.

DWR data is a rich source for research on production rate estimation and to derive valuable insights on how different parameters interact with each other and have an influence on construction productivity. State DOTs which haven't updated their procedures should develop integrated tools which predict project specific production rates. This will lead to reduction in road user costs, better project delivery and increased worker and road user safety. State DOTs gather valuable feedback on past projects by using the methodology suggested in the study regarding different factors of construction productivity.

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APPENDIX A- PRODUCTION RATES USED BY MDT

Average Production Rate		April 2008	
		Metric	English
Work Activity	Type	Production Rate	Production Rate
Moblilization Size method	Small (seal coat)	2 days min	2 days min
	Medium (< $2mil)	5 days	5 days
	Large (> $2mil)	8 days	8 days
	Extra Large (> $10mil)	15 days	15 days
BMP(or include in			
mob) Size method	Small (seal coat)	2 days	2 days
	Medium (< $2mil)	4 days	4 days
	Large (> $2mil)	6 days	6 days
Earthwork (per vehicle) Topsoil	Small (shoulder work)	600 m3/day	750 yd3/day
	Medium (or truck work)	1500 m3/day	2000 yd3/day
	Large (or scraper work)	3000 m3/day	4000 yd3/day
Excavation	Small (shoulder work)	1000 m3/day	1300 yd3/day
	Medium (or truck work)	3000 m3/day	4000 yd3/day
	Large (or scraper work)	4500 m3/day	6000 yd3/day
Borrow	Truck	3000 m3/day	4000 yd3/day
	Scraper	4500 m3/day	6000 yd3/day
Rock –Blasting	Small	500 m3/day	650 yd3/day
	Large	1500 m3/day	2000 yd3/day
Muck Exc.		500 m3/day	650 yd3/day
Street Exc.		500 m3/day	650 yd3/day
Aggregate Base Course	Small (tonnage)	1800 tons/day	2000 tons/day
	Medium (volume)	2000 m3/day	2600 yd3/day

	Large	3000 m3/day	4000 yd3/day
Pulverization		15000 m2/day	18000 yd2/day
CTB		1000 m3/day	1300 yd3/day
Drainage Culverts	<=450 mm	90 m/day	300 ft/day
=600 mm	60 m/day	200 ft/day	
>600 mm	45 m/day	150 ft/day	
RCB	10 m/day	30 ft/day	Storm Drain Pipe
(avg. depth	6-8 ft;coventional backfill)	100 m/day	330 ft/day
	Manholes/Inlets	4 each/day	4 each/day
Plant Mix Cold Milling	Mainline	30000 m2/day	35000 yd2/day
	Taper	250 m2/day	300 yd2/day
Cold Recycle		3 lane km/day	2 lane mi/day
PMS		3000 tons/day	3300 tons/day
PMS Urban		2000 tons/day	2200 tons/day
Seal & Cover		12 lane km/day	7.5 lane mi/day
Rumble Strips		8 lane km/day	5 lane mi/day
Concrete Paving PCCP	Uniform Width	8300 m2/day	10000 yd2/day
	Non-uniform Width	1600 m2/day	2000 yd2/day
Repair	Grinding	3000 m2/day	3500 yd2/day
	Joint Sealing	3000 m/day	10000 ft/day
Pavement Markings Epoxy	Small	2 days	2 days
	Large	4 days	4 days
	Words & Symbols	additional 1-2days	additional 1-2days
	Thermoplastic Intersection	3 days	3 days
Miscellaneous Curb & Gutter		300 m/day	1000 ft/day
Sidewalk		250 m2/day	300 yd2/day
Fencing	Woven wire/Barbwire	300 m/day	1000 ft/day
	Chain Link	200 m/day	600 ft/day

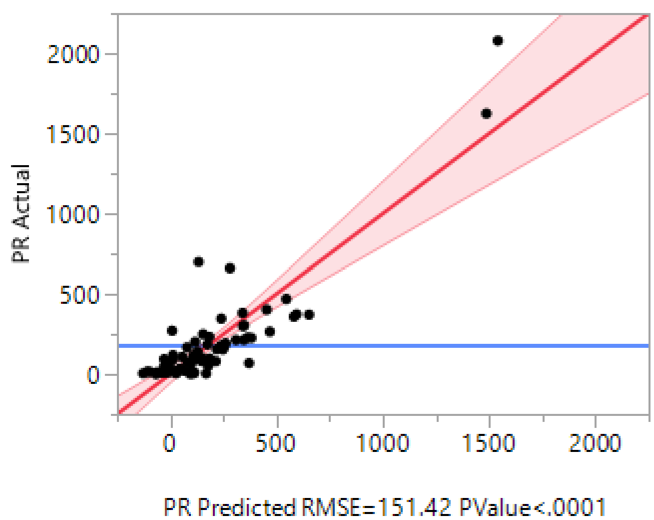
Guardrail	Concrete	365 m/day	1200 ft/day
	Steel	225 m/day	750 ft/day
Vegetation	Seeding	5 ha/day	12 acre/day
	Sodding	3000 m2/day	3500 yd2/day

APPENDIX B- STATISTICAL OUTPUT FOR PRODUCTION RATE ESTIMATION

This Appendix provides results of statistical analysis performed on work items using JMP Pro. Software.

BEDDING MATERIAL

Actual by predicted plot



Effect Summary

Source	LogWorth	PValue
Total quantity	22.205	0.00000
Budget Category	3.316	0.00048
FINANCIAL_DIST	0.785	0.16411
NBR_SUPRVSR	0.706	0.19667

Summary of fit

RSquare	0.790302
RSquare Adj	0.768715
Root Mean Square Error	151.4218
Mean of Response	185.0512
Observations (or Sum Wgts)	76

Parameter Estimates

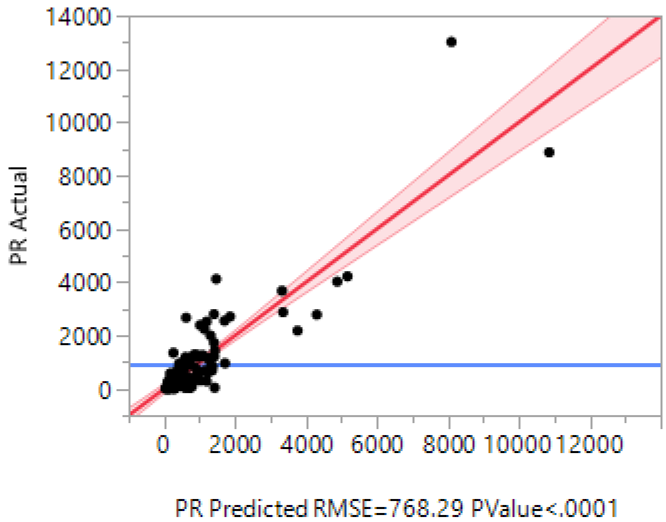
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	20.734838	25.76071	0.80	0.4237
FINANCIAL_DIST[1]	65.694337	32.79099	2.00	0.0491*
FINANCIAL_DIST[2]	26.265644	41.89751	0.63	0.5328
FINANCIAL_DIST[3]	-19.93963	34.19906	-0.58	0.5618
FINANCIAL_DIST[4]	-74.22405	39.7426	-1.87	0.0661
Total quantity	0.1727515	0.011682	14.79	<.0001*
Budget Category[0]	79.123325	21.58059	3.67	0.0005*
NBR_SUPRVSR	0.5250975	0.402714	1.30	0.1967

Prediction Expression

$$
\begin{aligned}
&20.734838334 \\
&+\text{Match}\left(\text{FINANCIAL\_DIST}\right)\begin{pmatrix} 1 & \Rightarrow 65.694336636 \\ 2 & \Rightarrow 26.265644204 \\ 3 & \Rightarrow -19.93962983 \\ 4 & \Rightarrow -74.22404505 \\ 5 & \Rightarrow 2.2036940408 \\ \text{else} & \Rightarrow . \end{pmatrix} \\
&+0.1727515228 \bullet \text{Total quantity} \\
&+\text{Match}\left(\text{Budget Category}\right)\begin{pmatrix} \text{"0"} & \Rightarrow 79.123324951 \\ \text{"1"} & \Rightarrow -79.12332495 \\ \text{else} & \Rightarrow . \end{pmatrix} \\
&+0.5250974725 \bullet \text{NBR\_SUPRVSR}
\end{aligned}
$$

TEMPORARY EROSION CONTROL PR-0

Actual by predicted plot



Effect Summary

Source	LogWorth		PValue
Total quantity	26.812		0.00000
CONTRCT_TTL_AMT	6.913		0.00000

Summary of Fit

RSquare	0.783375
RSquare Adj	0.779703
Root Mean Square Error	768.2939
Mean of Response	909.0675
Observations (or Sum Wgts)	121

Parameter Estimates

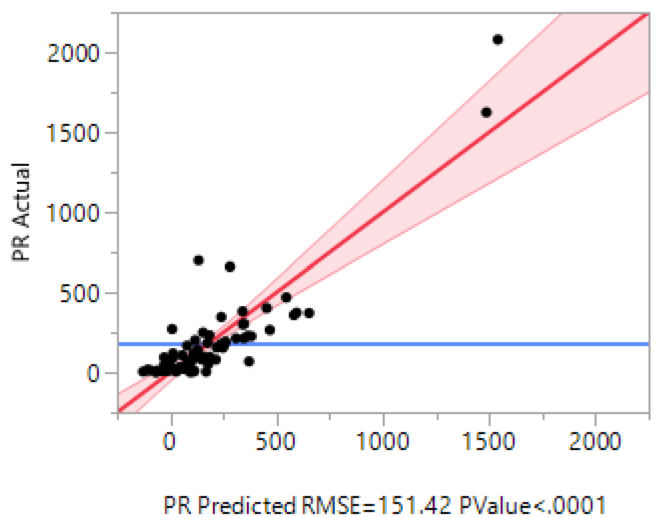
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	38.000151	104.2858	0.36	0.7162
Total quantity	0.0236978	0.001657	14.31	<.0001*
CONTRCT_TTL_AMT	8.642e-5	1.534e-5	5.63	<.0001*

Prediction Expression

38.00015078 + 0.023697753 • Total quantity + 0.0000864196 • CONTRCT_TTL_AMT

RIPRAP

Actual by Predict Plot



Effect Summary

Source	LogWorth	PValue
Total quantity	22.205	0.00000
Budget Category	3.316	0.00048
FINANCIAL_DIST	0.785	0.16411
NBR_SUPRVSR	0.706	0.19667

Summary of Fit

RSquare	0.790302
RSquare Adj	0.768715
Root Mean Square Error	151.4218
Mean of Response	185.0512
Observations (or Sum Wgts)	76

Parameter Estimtes

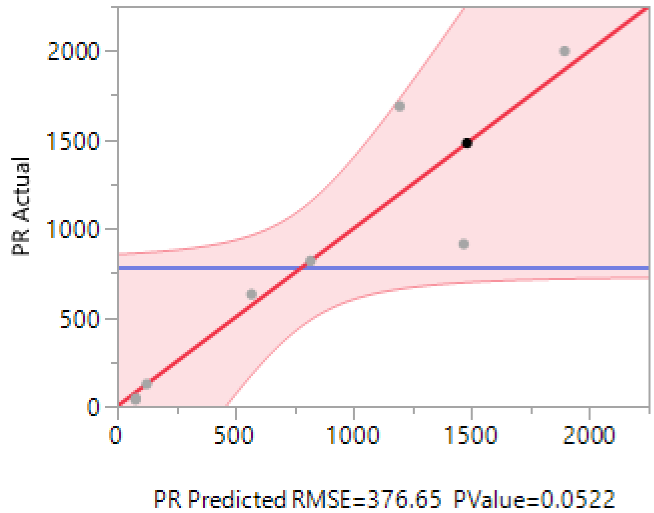
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	20.734838	25.76071	0.80	0.4237
FINANCIAL_DIST[1]	65.694337	32.79099	2.00	0.0491*
FINANCIAL_DIST[2]	26.265644	41.89751	0.63	0.5328
FINANCIAL_DIST[3]	-19.93963	34.19906	-0.58	0.5618
FINANCIAL_DIST[4]	-74.22405	39.7426	-1.87	0.0661
Total quantity	0.1727515	0.011682	14.79	<.0001*
Budget Category[0]	79.123325	21.58059	3.67	0.0005*
NBR_SUPRVSR	0.5250975	0.402714	1.30	0.1967

Prediction Expression

$$
\begin{aligned}
&20.734838334 \\
&+\text{Match}\left(\text{FINANCIAL\_DIST}\right)\begin{pmatrix} 1 & \Rightarrow 65.694336636 \\ 2 & \Rightarrow 26.265644204 \\ 3 & \Rightarrow -19.93962983 \\ 4 & \Rightarrow -74.22404505 \\ 5 & \Rightarrow 2.2036940408 \\ \text{else} & \Rightarrow . \end{pmatrix} \\
&+0.1727515228 \bullet \text{Total quantity} \\
&+\text{Match}\left(\text{Budget Category}\right)\begin{pmatrix} \text{"0"} & \Rightarrow 79.123324951 \\ \text{"1"} & \Rightarrow -79.12332495 \\ \text{else} & \Rightarrow . \end{pmatrix} \\
&+0.5250974725 \bullet \text{NBR\_SUPRVSR}
\end{aligned}
$$

GUARDRAIL

Actual by Predicted Plot



Effect Summary

Source	LogWorth		PValue
Total quantity	1.972		0.01068
Project work typecode	1.164		0.06852

Summary of Fit

RSquare	0.884019
RSquare Adj	0.739042
Root Mean Square Error	376.6464
Mean of Response	778.3724
Observations (or Sum Wgts)	10

Parameter Estimates

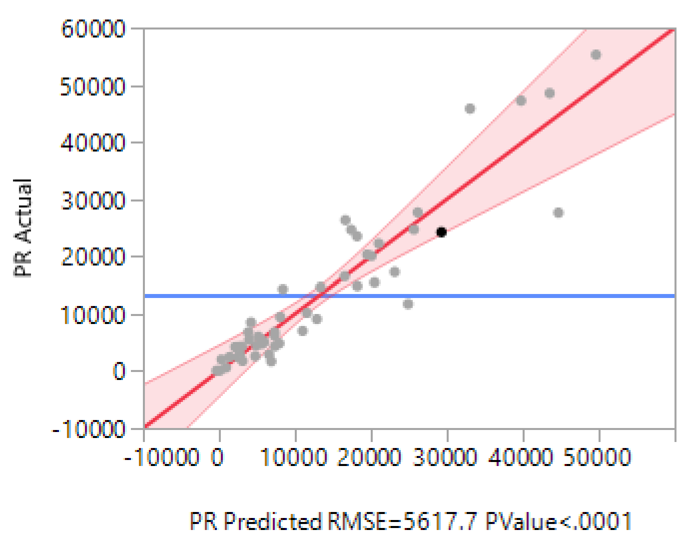
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1687.365	570.1464	-2.96	0.0416*
Total quantity	0.2283763	0.050552	4.52	0.0107*
Project work typecode[160]	-4608.415	1213.522	-3.80	0.0191*
Project work typecode[180]	1756.1287	493.4853	3.56	0.0236*
Project work typecode[221]	1783.8176	635.018	2.81	0.0484*
Project work typecode[232]	-1043.358	399.9371	-2.61	0.0595

Prediction Expression

$$
\begin{aligned}
&-1687.364627 \\
&+0.2283763475 \cdot \text{Total quantity} \\
&+\text{Match}\left(\text{Project work typecode}\right)\begin{pmatrix} 160 \Rightarrow -4608.415224 \\ 180 \Rightarrow 1756.1287186 \\ 221 \Rightarrow 1783.817584 \\ 232 \Rightarrow -1043.357587 \\ 310 \Rightarrow 2111.8265083 \\ \text{else} \Rightarrow . \end{pmatrix}
\end{aligned}
$$

EXCAVATION – UNCLASSIFIED

Actual by Predicted Plot



Effect Summary

Source	LogWorth		PValue
Total quantity	15.004		0.00000
FINANCIAL_DIST	4.409		0.00004
Project work typecode	1.506		0.03116

Summary of Fit

RSquare	0.868541
RSquare Adj	0.823569
Root Mean Square Error	5617.678
Mean of Response	13125.8
Observations (or Sum Wgts)	52

Parameters of Estimate

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2900.318	1764.24	1.64	0.1084
Total quantity	0.0650996	0.004946	13.16	<.0001*
FINANCIAL_DIST[1]	445.45953	1800.473	0.25	0.8059
FINANCIAL_DIST[2]	4524.4595	2668	1.70	0.0981
FINANCIAL_DIST[3]	5305.9112	2309.833	2.30	0.0272*
FINANCIAL_DIST[4]	-13916.06	2597.955	-5.36	<.0001*
Project work typecode[110]	3010.4472	3301.596	0.91	0.3676
Project work typecode[120]	-6159.071	5630.769	-1.09	0.2809
Project work typecode[130]	-2591.502	2089.099	-1.24	0.2224
Project work typecode[140]	-3675.263	2126.071	-1.73	0.0920
Project work typecode[151]	-2144.561	5522.779	-0.39	0.7000
Project work typecode[160]	20022.251	5893.835	3.40	0.0016*
Project work typecode[310]	-8144.196	5638.481	-1.44	0.1568
Project work typecode[510]	1048.9474	4012.673	0.26	0.7952

Prediction Expression

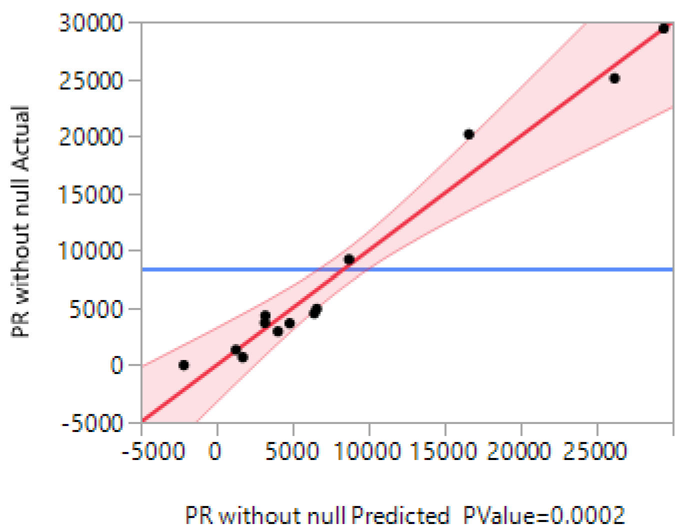
$$+0.0650996013 \cdot \text{Total quantity}$$

$$+\text{Match}\left(\text{FINANCIAL\_DIST}\right)\begin{pmatrix} 1 & \Rightarrow 445.45952796 \\ 2 & \Rightarrow 4524.4594685 \\ 3 & \Rightarrow 5305.9111832 \\ 4 & \Rightarrow -13916.06147 \\ 5 & \Rightarrow 3640.2312856 \\ \text{else} & \Rightarrow . \end{pmatrix}$$

$$+\text{Match}\left(\text{Project work typecode}\right)\begin{pmatrix} 110 \Rightarrow 3010.4471871 \\ 120 \Rightarrow -6159.071134 \\ 130 \Rightarrow -2591.502294 \\ 140 \Rightarrow -3675.263325 \\ 151 \Rightarrow -2144.560592 \\ 160 \Rightarrow 20022.25099 \\ 310 \Rightarrow -8144.196079 \\ 510 \Rightarrow 1048.9474003 \\ 620 \Rightarrow -1367.052154 \\ \text{else} \Rightarrow . \end{pmatrix}$$

EXCAVATION-UNCLASS BORROW

Actual by Predicted Plot



Effective Summary

Source	LogWorth	PValue
Total quantity	3.684	0.00021
FINANCIAL_DIST	1.457	0.03495
OTH_WRKR	0.680	0.20904

Summary of Fit

RSquare	0.973791
RSquare Adj	0.947583
Root Mean Square Error	2246.919
Mean of Response	8457.482
Observations (or Sum Wgts)	13

Parameter Estimates

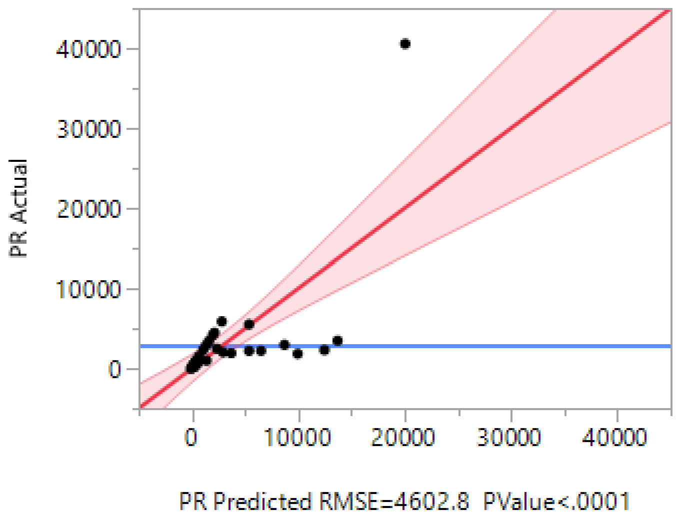
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-8343.228	3429.564	-2.43	0.0510
Total quantity	0.2681873	0.033623	7.98	0.0002*
FINANCIAL_DIST[1]	8504.3493	2745.359	3.10	0.0212*
FINANCIAL_DIST[2]	6378.8373	1616.714	3.95	0.0076*
FINANCIAL_DIST[3]	153.84794	1515.769	0.10	0.9225
FINANCIAL_DIST[4]	-20799.22	5502.599	-3.78	0.0092*
OTH_WRKR	11.158974	7.930764	1.41	0.2090

Prediction Equation

$$
\begin{aligned}
&-8343.227747\\
&+0.2681872546 \cdot \text{Total quantity}\\
&+\text{Match}\left(\text{FINANCIAL\_DIST}\right)\begin{pmatrix} 1 & \Rightarrow 8504.3493415 \\ 2 & \Rightarrow 6378.8373042 \\ 3 & \Rightarrow 153.84794141 \\ 4 & \Rightarrow -20799.21541 \\ 5 & \Rightarrow 5762.1808217 \\ \text{else} & \Rightarrow . \end{pmatrix}\\
&+11.158974051 \cdot \text{OTH\_WRKR}
\end{aligned}
$$

PMS

Actual by Predicted Plot



Effective Summary

Source	LogWorth		PValue
Total quantity	6.274		0.00000

Summary of Fit

RSquare	0.488257
RSquare Adj	0.47479
Root Mean Square Error	4602.834
Mean of Response	2815.598
Observations (or Sum Wgts)	40

Parameter Estimates

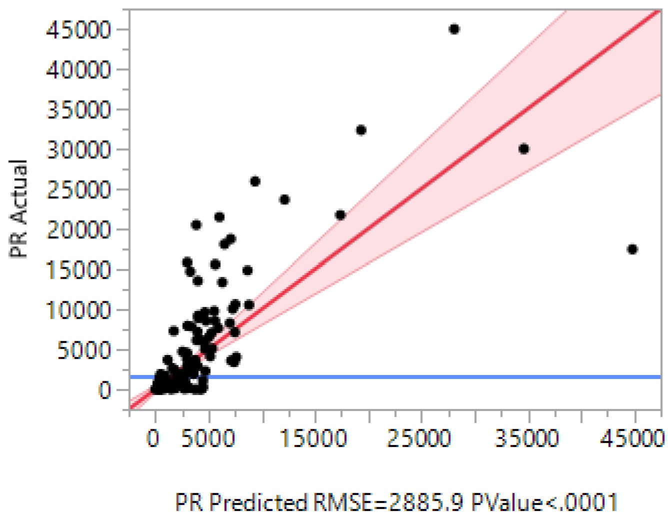
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-97.81812	873.9361	-0.11	0.9115
Total quantity	0.4966786	0.082487	6.02	<.0001*

Prediction Expression

$$-97.81811857 + 0.4966786455 \cdot \text{Total quantity}$$

EPOXY

Actual by Predicted Plot



Effective Summary

Source	LogWorth	PValue
Total quantity	58.770	0.00000
Project work typecode	5.961	0.00000

Summary of Fit

RSquare	0.597831
RSquare Adj	0.576665
Root Mean Square Error	2885.92
Mean of Response	1601.23
Observations (or Sum Wgts)	481

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1385.2107	326.6756	4.24	<.0001*
Total quantity	0.0483414	0.002551	18.95	<.0001*
Project work typecode[110]	1626.5395	975.7685	1.67	0.0962
Project work typecode[120]	453.97827	1980.916	0.23	0.8188
Project work typecode[130]	1309.7735	649.6955	2.02	0.0444*
Project work typecode[140]	489.61264	458.7758	1.07	0.2864
Project work typecode[141]	-1194.159	2782.282	-0.43	0.6680
Project work typecode[150]	-1087.151	1278.096	-0.85	0.3954
Project work typecode[151]	87.982203	712.2699	0.12	0.9017
Project work typecode[160]	-931.2225	532.9522	-1.75	0.0813
Project work typecode[170]	-1199.705	894.802	-1.34	0.1807
Project work typecode[180]	-965.018	415.8675	-2.32	0.0208*
Project work typecode[181]	-550.5449	932.6851	-0.59	0.5553
Project work typecode[182]	-1377.984	2782.301	-0.50	0.6206
Project work typecode[183]	-972.2449	445.5299	-2.18	0.0296*
Project work typecode[185]	-963.1146	1628.3	-0.59	0.5545
Project work typecode[220]	5054.4761	1277.897	3.96	<.0001*
Project work typecode[221]	2984.192	824.7584	3.62	0.0003*
Project work typecode[231]	2808.0884	1249.056	2.25	0.0250*
Project work typecode[232]	2326.8261	1180.191	1.97	0.0493*
Project work typecode[310]	-1054.742	623.5913	-1.69	0.0914
Project work typecode[311]	-1367.377	2782.301	-0.49	0.6233
Project work typecode[313]	-1385.211	2782.302	-0.50	0.6188
Project work typecode[410]	-1365.148	713.1081	-1.91	0.0562
Project work typecode[620]	-1367.129	1980.898	-0.69	0.4904

Prediction Equation

1385.2107133

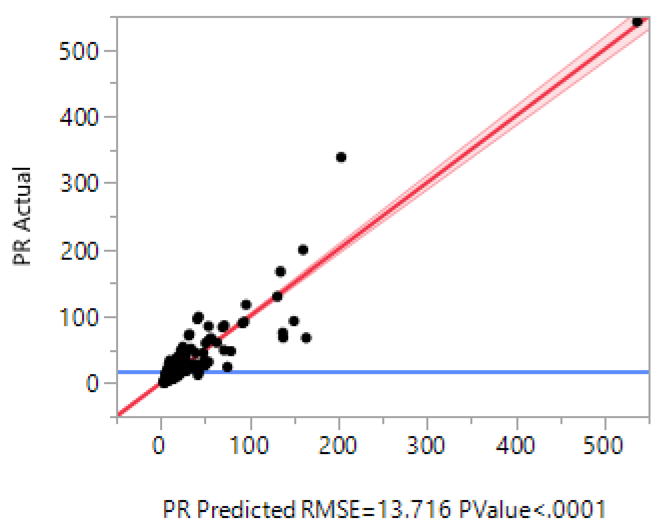
+ 0.048341412 • Total quantity

+ Match(Project work typecode)
(
110 ⇒ 1626.5395412
120 ⇒ 453.97826556
130 ⇒ 1309.773476
140 ⇒ 489.61264148
141 ⇒ -1194.159131
150 ⇒ -1087.151244
151 ⇒ 87.982203382
160 ⇒ -931.2224629
170 ⇒ -1199.70523
180 ⇒ -965.0180024
181 ⇒ -550.544945
182 ⇒ -1377.984176
183 ⇒ -972.2448897

185 ⇒ -963.114629
220 ⇒ 5054.4761119
221 ⇒ 2984.1919861
231 ⇒ 2808.0884371
232 ⇒ 2326.8260895
310 ⇒ -1054.741543
311 ⇒ -1367.376631
313 ⇒ -1385.210713
410 ⇒ -1365.147819
620 ⇒ -1367.1292
710 ⇒ -1360.718136
else ⇒ .

WORDS AND SYMBOLS

Actual by Predicted Plot



Effective Summary

Source	LogWorth		PValue
Total quantity	176.739		0.00000

Summary of Fit

RSquare	0.87459
RSquare Adj	0.874268
Root Mean Square Error	13.71629
Mean of Response	16.80845
Observations (or Sum Wgts)	391

Parameter Estimates

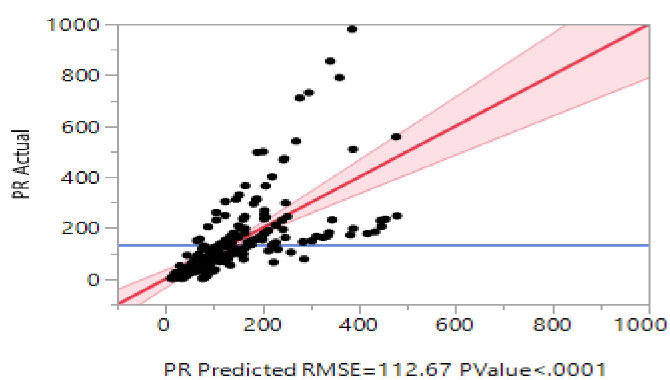
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.5867516	0.738652	4.86	<.0001*
Total quantity	0.1969189	0.003781	52.08	<.0001*

Prediction Expression

$$3.5867516037 + 0.1969188698 \cdot \text{Total quantity}$$

EMULS ASPHALT CRS-2P

Actual by Predicted Plot



Effective Summary

Source	LogWorth	PValue
Total quantity	30.105	0.00000
FINANCIAL_DIST	1.395	0.04026

Summary of Fit

RSquare	0.457576
RSquare Adj	0.445681
Root Mean Square Error	112.6709
Mean of Response	132.4638
Observations (or Sum Wgts)	234

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	31.386867	10.60456	2.96	0.0034*
FINANCIAL_DIST[1]	44.453044	14.11325	3.15	0.0019*
FINANCIAL_DIST[2]	2.1192829	12.93829	0.16	0.8700
FINANCIAL_DIST[3]	-9.208498	15.05507	-0.61	0.5414
FINANCIAL_DIST[4]	-17.11634	18.56279	-0.92	0.3575
Total quantity	0.359402	0.026672	13.48	<.0001*

Prediction Expression

$$31.386867123 + \mathrm{Match}\left(\mathrm{FINANCIAL\_DIST}\right)\begin{pmatrix} 1 & \Rightarrow 44.45304394 \\ 2 & \Rightarrow 2.1192829438 \\ 3 & \Rightarrow -9.208498286 \\ 4 & \Rightarrow -17.11633713 \\ 5 & \Rightarrow -20.24749147 \\ \mathrm{else} & \Rightarrow . \end{pmatrix} + 0.3594020277 \bullet \mathrm{Total\ quantity}$$