CPM Schedule Density: A New Predictor for Productivity Loss

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Abstract

This dissertation addresses construction labor trade stacking, which oftentimes creates adverse labor inefficiencies, delay and cost overruns on construction projects. Present industry practice holds that Critical Path Methodology (CPM) scheduling is more accurate with resource loading assigned to construction activities, and that likelihood for trade stacking is reduced when managing a resource-loaded schedule. However, despite the potential benefits, and for many reasons, most contractors choose not to resource load their schedules. This research sought to create a predictive model for construction labor productivity loss using non-resource loaded CPM schedules as the primary input. This research advanced under a primary assumption that regardless of whether a contractor utilizes resource loading or not, the contractor will allocate enough daily resources to a scheduled activity so that that activity will be completed within its planned duration. This assumption is captured in a new metric called a Crew Day Resource (CDR). When planned schedule activities overlap in time, trade stacking occurs and the number of CDR's for that day likewise increases. Schedule density refers to the increasing degree of overlapping activities in a CPM schedule. How that density measure changes from schedule update to update allowed a predictive mathematical model to be created with strong correlation between the schedule density and actual observed labor productivity. Five construction projects were evaluated with emphasis on specific trades including mechanical and electrical work on three high rise buildings, large bore piping on a power plant, and structural steel work on a marine maintenance structure. Results of this research are encouraging and justify expansion of the project sample size, particularly for mechanical and electrical trades in high rise building projects. Additionally, this study provides the basis for development of a project management tool that may alert managers of potential construction labor inefficiencies before they occur.

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1 Introduction, Scope and Outline

Benjamin Franklin is credited to say, “By failing to prepare, you are preparing to fail.” (“Benjamin Franklin: By failing to prepare, you are preparing to fail.,” n.d.) A Critical Path Methodology (CPM) schedule serves as a fundamental planning tool for owners, architects and contractors in construction projects (O’Brien, 2006). Used properly, industry available CPM software can assist contractors to control construction projects by planning work sequences, allocating sufficient resources to specific work activities (known as “resource-loading” a schedule) and in tracking budgeted to actual expended costs. CPM has existed since the 1950’s, but little expansion for use of its basic tenets has occurred since. This research seeks to utilize data within the CPM schedule and analyze it differently with intent to derive a predictive model for potential construction labor productivity loss. Such a model, if used, may help contractors avoid or mitigate productivity losses.

The Trouble with Labor Productivity

Excluding change orders, equipment and material needs on construction projects generally remain as determinable or fixed variables. Labor, however, often is volatile and changes frequently. Crew sizes vary day by day depending upon the numbers of workers and the skill set each worker possesses relative to the task at hand. Even when at full strength and given the inherent difficulties in construction, the productivity of a given crew changes depending upon environmental variables such as a learning curve for new tasks, poor weather conditions, or insufficient space to perform work in an unimpeded manner. Because of this variability and other constraints placed upon the contractor, not enough contractors use resource-loading capabilities of CPM software. Even when utilized, by the time all resource data is inserted into the software, the dynamic nature of construction almost immediately renders that plan obsolete. Consequently, instead of resource loading the schedule, contractors rely upon past experience, or chance that nothing unusual will occur that may jeopardize timely project completion when creating its schedules.

Common to all schedules, however, are planned work activities and logic (whether specific or implied) that define intended work sequence. Whether these schedule activities are resource loaded or not, they represent a planned and coordinated management effort of time and resources. Provided the contractor can meet the dates in its schedules with adequate resources, it follows that at least time-wise, the project will finish on time.

A New Metric – Crew Day Resources (CDR)

This research validates a methodology that was presented in a conference paper entitled, "Schedule Activity Density Analysis" (Ottesen & Hoshino, 2013). The same paper was later selected for publication in the AACE's Cost Engineering Journal (Ottesen & Hoshino, 2014). These papers introduced the notion of a new measure called a Crew Day Resource (CDR) that describes an assumed amount of resources necessary for one day of planned work to be completed within that activity's planned time duration. For example, if an activity representing electrical work called "Pull Wires" had a planned original duration of five work days, the number of CDR's for this activity is simply one CDR per planned work day, or five CDR's total, distributed one CDR per day over the planned five-day duration. The primary assumption here is that the electrical contractor will provide whatever labor, equipment and material resources are necessary to meet this planned five-day duration. Without specific resource loading in the schedule, the analyst cannot know the crew size or required hours each crew member will work each day to meet the five-day duration.

Thus, in a non-resource loaded schedule, the planned resources for an activity are not identified in the CPM schedule and remain undefined or unknown. The CDR measure intends to remove these unknowns by assigning an assumed value equal to one CDR unit. As such, the CDR measure is likened to assigning "X" to an unknown variable in an algebraic equation, however, in the case of CDR's, we assign the CDR value a numeric value equal to one, or rather "one crew day resource," with specific reference to the labor requirement and assuming that the required equipment, tools and materials are readily available to support the labor. Stacking, or overlapping, of say two CDR's for the same trade on a given day indicates that twice the amount of labor resources is allocated to that activity on that same day, and implies that if the contractor is to complete both activities as planned, then twice the amount of resources must be provided for that day of overlap. Stated another way, as the amount of activity overlapping increases for a given trade, the schedule density of the planned CDR's likewise increases. Experience shows that contractors rarely have twice the available resources on the ready on a day by day basis to adjust to unexpected events. Instead, they must make adjustments with the labor resources they do have in trying to recover from experienced inefficiencies and delays.

The CDR schedule density, or for simplicity, use of the term "schedule density", represents trade stacking, a term used to describe multiple trades working simultaneously within close proximity of each other. The schedule density metric may be measured for a single trade or for multiple trades for any given project with a CPM schedule. This research focused primarily on evaluating a single trade for each project evaluated.

Experience and the literature review herein confirm that trade stacking usually results in labor productivity loss. Because this research utilizes measures that quantify the amount of trade stacking and the resulting adverse effects on labor productivity, use of the term "labor productivity loss" or "labor inefficiencies" herein is deemed to be a result of an increase in trade stacking.

By evaluating how the CDR schedule densities change from schedule update to update, a new analysis tool may be developed to identify potential problems in a construction schedule early on, thereby allowing the contractor to proactively make adjustments in the present to mitigate potential future labor productivity inefficiencies. With a strong correlation, development and use of a methodology tool may become a staple provision in public and private works contracts.

Scope and Breadth of this Research

Schedule data is typically extensive and almost always requires use of computers and software to properly manage it. This research relies on these data. Large construction projects have planned durations that span multiple years. This research targets large projects, which inherently generate large data sets, particularly regarding scheduling.

Achieving strong statistical validation of findings demands a large sample size and that extensive data be utilized, which likewise requires a tremendous amount of time to acquire and properly analyze it. Recognizing that practical time and data constraints exist, this research utilized a triangulation technique to validate its findings. First, this study focused on five projects with intent to demonstrate the proposed methodology, the reasonableness of results this methodology generates, and to determine whether pursuit of a larger sample size was warranted for future study. Statistical methods and regression analysis are employed within these five projects. Strong correlations identified between variables within these five projects support, but do not represent a large enough sample size to drive statistical significance of these correlations broadly. Therefore, a second validation approach was executed by gathering a quorum of industry experts to solicit their experiences and to compare these experiences with results of the five projects.

Collectively, the five projects included in the empirical portion of this research serve as a study to test whether a meaningful and quantifiable methodology for predicting labor productivity loss is possible. The sample projects utilized for this study included:

1. A high rise hotel building and its mechanical trade work,
2. A combined cycle power plant and its bulk piping construction trade,
3. A large structural steel project and its ironworkers' trade,
4. Twin condominium towers and its electrical trade work, and
5. A resort hotel and its mechanical trade work.

Evaluation focuses primarily with mechanical, electrical and plumbing trade work because experience and research show that these trades are most likely to experience productivity loss due to trade stacking. A structural steel project was added to the study for comparative purposes of a trade that rarely experiences trade stacking to results of the mechanical trade work which frequently experiences trade stacking. Productivity data for each trade was documented contemporaneously. The calculated labor productivity rates for each project were computed and compared against various measures of the schedule densities. These results support that a predictive model may be developed and viable for each trade analyzed.

Each of the sample projects evaluated experienced claims. Consequently, the sample set presented herein is admittedly biased. However, whereas projects that experience claims are most likely to benefit from the model generated from this data set, it follows that application of this approach may help to avoid claims, or to at least be able to predict potential labor productivity inefficiencies and allow mitigation before these inefficiencies become pervasive and unrecoverable.

There are two main practical applications of this methodology for any construction project, regardless of whether the project experiences delay claims or not. First, when the intent is to avoid claims the methodology described herein could be applied to a construction project immediately after notice to proceed, so that any change in the centroid from schedule update to update could be calculated and tracked. If the trending of those changes followed similar patterns as those quantified herein, then this trending could serve as a warning to the contractor that forthcoming labor inefficiencies were likely. Appropriate resource management actions could then be taken before measurable inefficiencies emerged thereby averting potential claims.

Second, this methodology also has significant application in retrospective forensics because it would allow to track similar trends and then utilize the project's contemporaneous records to identify root causes for any delays and labor productivity inefficiencies.

Whereas this study is designed to provide preliminary findings that are significant to the field, its methodology is of an exploratory nature, meaning that it is only designed to outline and test a path that can be later used to perform a robust empirical validation of both applications through the analysis of a larger number of sample projects.

Dissertation Outline

This dissertation begins with an Executive Summary, which highlights key findings of the research. Chapter 1 presents an introduction, the problem definition, research question and outline. Chapter 2 presents findings of a literature review. Outside of the author's own published paper, this literature review found no mention of the term "Crew Day Resource(s)," CDR's, or any similar type model presented in this research. For a resource-loaded schedule, the concept of stacking resources is commonplace. This research follows a similar approach in that the stacking of planned activities is treated like stacked resources, but unique because that stacking, i.e., increase in schedule density, is assigned an unknown quantity to represent those resources.

Following the literature review, Chapter 3 speaks to the research methodology employed. It shows the conceptual framework, introduction of variables and methodology in developing the predictive model.

Chapter 4 describes development of the application technique by presenting the fundamental building blocks of the analysis. Step by step, each principle is presented that demonstrates how a CPM schedule is utilized to generate a schedule density histogram. From this histogram, centroids are calculated, and successive centroids are then connected together in series by vectors. These vectors formulate the basis for correlating the schedule's density to labor productivity.

Chapter 5 applies the application technique to one of the five projects – a 20-story high rise construction project, with emphasis on the mechanical trade work. Schedule density histograms and best-fitting curves for each of this project's 18 schedule updates are presented and analyzed. Results of this analysis demonstrate a strong correlation between the centroid measure and construction labor productivity. Intent of this chapter is to allow others to apply the same methodology to their own construction projects.

Chapter 6 presents results of the other projects. In total, four projects were considered herein (the first four of five listed above) in deriving results. This chapter then compares and contrasts findings for each of these four projects.

Chapter 7 describes efforts to validate results and the applied technique in two ways. First, application of findings from the first four sample projects were applied to a fifth project. Notwithstanding the small sample size, results of the analyses for four of the projects were then applied to the fifth project under a 'what if' scenario, or rather, assuming results of the first four projects were transferrable to similar projects, how would the results fit when applied to another project?

Second, a quorum of experts was assembled to compare their experiences with findings of the study. Because this research presents a new approach that is not documented in existing literature, validation of the results required assembly and consensus of a quorum, or panel, of experts. A two-step Delphi methodology that relied on surveys was used to solicit expert judgement from the panel. Phase 1 served as a pre-qualification step of each panelist that required more than five years of actual field experience, witnessing of trade stacking and an understanding CPM scheduling. Phase 2 relied on phone interviews wherein results of the study were presented to panel members. It relied on a common semi-structured interview guide designed to reinforce the validation of this study's findings.

The final chapter, Chapter 8, summarizes conclusions and identifies potential additional research opportunities related to this study.

2 Literature Review

Contractors and owners alike have long sought ways to avoid labor productivity inefficiencies. Consequently, the literature review included searching for research and case studies related to construction labor productivity. The literature review revealed that authors recognize labor productivity loss, have devised means to quantify it, and have acknowledged its importance and integration with construction scheduling. Results of this literature review and professional experience were used as a roadmap to derive a methodology wherein the construction schedule, absent resource loading, may be used to predict productivity loss before it occurs, thereby giving management opportunity to make adjustments to mitigate the losses before they occur. The derived methodology is unique and based upon industry accepted guidelines of CPM scheduling and resource management.

A construction project begins with a need, thought or vision of what may be. Architects and engineers are designers of what we call the "Built Environment," a field including "architecture, building science and engineering, construction, landscape and urbanism"(Chynoweth, 2009). Contractors convert those designs into tangible realities, which efforts require significant planning, resources, skill and execution. The successful completion of any construction project requires many input elements such as labor, material and equipment. Present industry best practices hold that use of proper planning and scheduling to manage resources generates favorable project outcomes.

The following subsections discuss construction labor productivity and establish accepted best practices for CPM scheduling, and how these schedules may be used for managing resources. Then, findings of the literature review are synthesized to derive a plausible approach for developing a predictive model for potential productivity loss.

Construction Labor Productivity

Of the many required elements in construction, labor performance is the most volatile, particularly in its impact on construction cost and scheduling (Roche, 1981). The basis for this statement lies in the many variables that can affect how a construction worker performs on a project. Error! Reference source not found. categorizes human factors and site factors that can affect construction labor performance. Because no one can effectively control or eliminate all of these variables, it follows that this greater uncertainty leads to higher risk of variability and greater likelihood for adverse impacts.

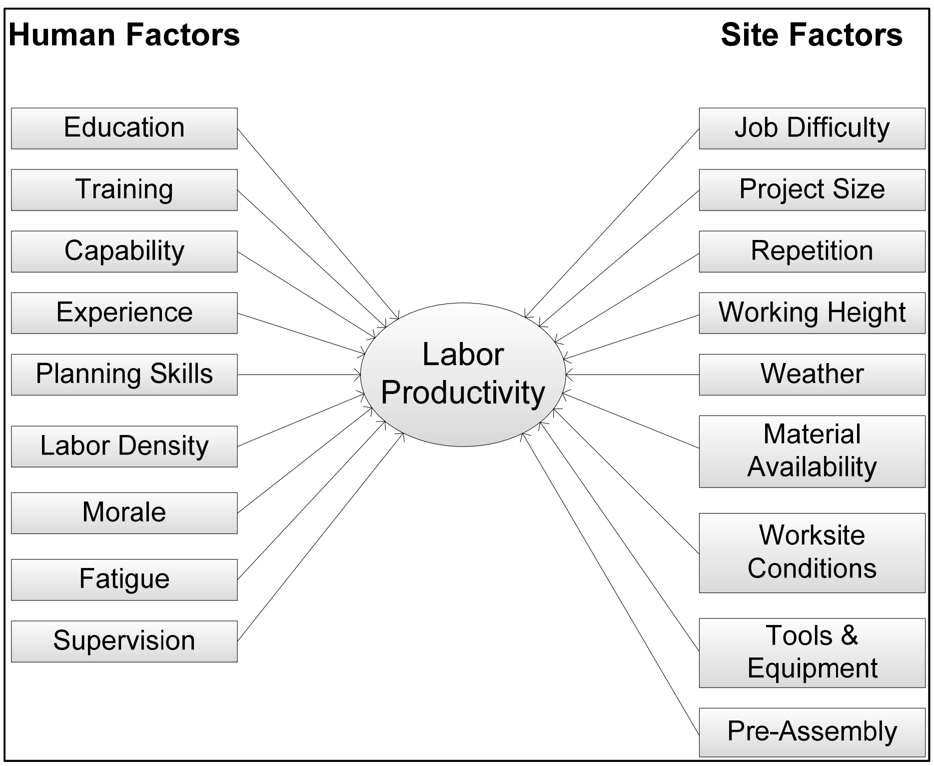


Figure 2-1 Factors That Affect Labor Productivity [Adapted from (Quakkelaar, 1977) and (Jergeas, Chishty, & Leitner, 2000)]

The amount of labor expended (input) to produce a given unit (output) is known as *labor productivity* (Ciccarelli & Bennick, 2010). When bidding for new projects, a contractor must forecast its labor productivity rates for various trades. Cost overruns and delays can occur if the contractor's forecasted labor productivity is inaccurate. Thus, it behooves the contractor to track its planned versus actual labor productivity, and to understand why the two may significantly differ.

Specific standards for measuring construction labor productivity exist and have been in effect for decades. Considerable research has occurred on the subject of labor productivity and in trying to quantify the impacts of each of the variables listed in Figure 2-1Error! Reference source not found., whether individually or in combinations with two or more of these variables. A few notable works are mentioned below.

Dr. James Adrian published a book entitled, "Construction Productivity: Measurement and Improvement" wherein he researched the adverse impacts, expressed as percentages of reduced productivity, of trade stacking (labor density), prolonged overtime (fatigue) and other factors (Adrian, 1987). The Mechanical Contractors Association of America (MCAA) published a manual on change orders which identifies and quantifies factors affecting labor productivity as percentages of productivity loss ("Change Orders Productivity Overtime," 2012). Stacking of Trades is listed first in MCAA's "Factors Affecting Labor Productivity" table and shows the percent loss in productivity to range from 10 percent for minor impacts to 30 percent for severe impacts ("Change Orders Productivity Overtime," 2012, p. 77). In the author's experience, this manual is referenced frequently in contractor-prepared change orders and claims where productivity inefficiencies were experienced despite MCAA's explanation that, *"To the best of MCAA's current knowledge, the information contained in the MCAA Factors was gathered anecdotally from a number of highly experienced members of the MCAA's Management Methods Committee. MCAA does not have in its possession any records indicating that a statistical or other type of empirical study was undertaken in order to determine the specific factors or the percentages of loss associated with the individual factors.*

Dr. John Borcherding prepared a dissertation on attitudes that affect human resources in construction, (Borcherding, Stanford University., & Department of Civil Engineering, 1972). AACE released a Recommended Practice for estimating lost labor productivity in construction claims ("Estimating Lost Labor Productivity in Construction Claims," 2014). AACE describes crowding of labor or stacking of trades as follows:

To achieve good productivity each member of a crew must have sufficient working space to perform their work without being interfered with by other craftsmen. When more labor is assigned to work in a fixed amount of space it is probable that interference may occur, thus decreasing productivity. Additionally, when multiple trades are assigned to work in the same area, the probability of interference rises and productivity may decline.

AACE provides accepted methods for quantifying productivity losses due to trade stacking and other factors.

These sources are important because they address the primary focus of this study regarding trade stacking. Isolating this variable amidst the many other variables poses a veritable challenge and may be impossible, which is why correlative results are most likely applicable.

In a CPM schedule, the duration of a planned activity is directly related to the planned productivity for that work ("AACE International Recommended Practice No. 23R-02: Identification of Activities," 2007). Forecasting productivity rates can be difficult, which in turn makes predicting accurate activity durations likewise difficult. Zhou et al. reported (Zhou, Love, Wang, Teo, & Irani, 2013),

> *Construction projects are unique in nature and each has their own site characteristics, weather condition, and crew of labour and fleet of equipment. As a result, it is difficult to accurately predict the exact duration of each activity.*

Other sources confirm that there are many factors that affect productivity and consequently, the ability to meet planned durations. Lacouture et al. (2014) prepared a list of 169 parameters that affect productivity (Castro-Lacouture, Irizarry, & Ashuri, 2014). Other survey research identified 83 different factors affecting productivity (Delbecq, 1975). These sources and others listed below identify the factors that create greatest uncertainty in meeting planned durations, and therefore, have the greatest influence on productivity. The following paragraphs present a few of the most salient factors.

Material & Equipment Availability (Dai, Goodrum, & Maloney, 2009) – A simple question is, "Does the contractor have sufficient materials and tools necessary to perform the work within the planned durations?" A contractor may have the best, brightest and most skilled personnel in the world on site, but without materials and proper tools to install them, progress stalls. The potential downside to both the contractor and project stakeholders is huge. Ways to mitigate these factors include proactive planning and scheduling, early procurement of long lead equipment and materials, inclusion of tool allowances such that the latest and best available technologies are being used, and use of schedule analysis tools that provide early detection of potential problems so resource reallocations can be assessed and implemented.

Construction Management Factors - Dai et al cite studies by Rojas and Aramvareekul (2003) and Liberda et al. (2003) whose independent studies drew the same conclusion -- that inefficient management systems, such as inadequate [CPM] scheduling and planning, contributed to significant productivity loss. This category includes inefficient management. Nasirzadeh likewise found that project management inefficiencies caused significant productivity loss (Nasirzadeh & Nojedehi, 2013). These factors adversely affect productivity, but are difficult to quantify. Criticism of an incomplete or error-riddled CPM schedule comes easy, but linking those omissions to a quantified productivity loss quantum is essentially impossible. Mitigation measures include mandatory submittals of schedules and schedule updates per the contract documents with monetary penalties for noncompliance. Development of new protocols for schedule and productivity analyses may also prove useful, provided a contractor and owner will mutually agree to utilize them. This research seeks to create such a protocol to assist in the management and planning processes.

Advancements in Equipment Technology & Tools (Goodrum & Haas, 2002) - Goodrum and Haas evaluated productivity rates published in RS Means and found that advancements in equipment technologies resulted in significant improvements in productivity. Labor productivity rates have not changed much at all over the past 25 years. However, significant increases in productivity have resulted from technology advancements. Goodrum and Haas (2002) provide examples of technology advancements that have increased productivity includingadvancements in hydraulic controls and microprocessors allows site work machinery to operate with greater precision and a longer reach for booms and buckets such that excavators and backhoes are capable of digging deeper. As a result, site earthwork activities are being completed faster than prior to these equipment advancements; andadvent of the pneumatic nail gun significantly increased framing productivity. Carpenters were able to drive nails with precision by simply pulling a trigger on the nail gun rather than having to hammer each nail by hand. The issue here is not so much a mitigation measure as it is looking for ways to implement new technologies to improve productivity. Use of drones to monitor construction progress is an example of this (Knight, 2015). Drones utilize video images to photograph progress, or lack thereof, on large construction projects allowing management to better allocate and utilize resources. Building information modeling (BIM) is another example (Eastman, Teicholz, Sacks, & Liston, 2011). BIM allows designers to build three dimensional models of the project and to identify and resolve potential clashes thereby averting field discovery and the resulting time delays associated with those undesired discoveries.

Severe Weather and Temperatures (Adrian, 1987) - For hot and humid conditions, production output losses are near 50%. Constructing in cold temperatures likewise creates production output losses at or greater than 40%. Depending upon the type of construction, for example structural steel erection, wind can also severely impact productivity. Best mitigation measures here are to plan for lesser productivity during historically adverse weather periods, which flows into proper scheduling and management of the work.

Factors Affecting Labor Resources – This category includes historically understood factors which continue to impact labor productivity to the present day. These factors are still significant. Without skilled labor (absenteeism), you may have all the equipment and materials you need, but the equipment will not operate, nor will the materials install themselves. Spatial constraints and overcrowding can restrict laborers' ability to work without interruption and adversely affects labor productivity. The US Army Corps of Engineers (USACE) defines overcrowding as the increase of all labor types within a given construction work area (Army Corps of Engineers, 1979). USACE found an adverse impact to construction productivity as overcrowing increased. Through interviews conducted with foremen and laborers, Borcherding (1980) also found that overcrowded working conditions adversely affect productivity. Human factors and fatigue come into play with prolonged overtime. Mitigation measures include compliance with labor laws, proper planning and scheduling for resources, and implementation of fair pay and bonus programs to motivate workers to consistently show up for work. This research taps into this impacting factor via schedule density measurements, which is linked to trade stacking and increased congestion in work areas.

Utilizing a literature review and several sources, Duah and Syal (2017) identified 24 significant impact factors that affect productivity including (Duah & Syal, 2017):

1. Stacking of trades – one or more trades working in similar work space at the same time;
2. Morale and attitude – low moral adversely affects a laborer's motivation and work effort;
3. Reassignment of manpower – relocating crews takes time to take down and reset at another location;
4. Crew size inefficiency – too few or too many workers on a crew affect the rate at which work progresses;
5. Concurrent operations – work activities occurring in similar times may affect logistics and movement of materials on a job site;
6. Dilution of supervision – supervised laborers work more efficiently than when supervision is diluted;

7. Learning curve – new work tasks require the workers to first learn how to perform that task, then productivity increases as the task becomes repeated;
8. Errors and omissions – design deficiencies lead to lost time in the field when trying to coordinate with the architect or engineer to resolve the issue;
9. Beneficial occupancy – an owner may occupy a portion of the project before construction is fully completed causing coordination issues that affect a contractor's productivity;
10. Joint occupancy – where two or more parties have equal right occupy a job site, coordination and collaborative synchronization is required which takes more time than if the site were singly occupied;
11. Site access – material availability and laydown areas may be directly affected by restricted site access, as can the workers' inabilities to access the site easily themselves;
12. Logistics – movement of equipment, materials and labor within the site can directly affect productivity;
13. Fatigue – workers require rest and if fatigued are less productive;
14. Ripple effect – caused by changes to the work which can negatively affect other aspects of the work that are not directly related to the changed work;
15. Overtime – extended periods of overtime cause labor productivity to diminish in part due to fatigue;
16. Season and weather changes – severe heat or cold affect worker productivity, as does wind, for example, where cranes would be unable to lift and place materials safely under windy conditions;
17. Aggravation and stress – similar issue as morale and attitude where a worker's mental state may adversely influence their productivity;

18. Interference and disruptions – construction labor works most efficiently when a crew gets into a 'flow' of the work without interference and disruptions;
19. Down or idle time – when equipment or labor are idle, progress on those tasks stalls;
20. Acceleration – a broad term referring to completing planned work tasks in shorter time durations than originally planned where one or more steps are taken to achieve that goal. Adding a night crew or second shift is an example. With two different crews performing similar work, additional setup and take down time, and coordination are required that can reduce productivity for each crew;
21. Working in finished areas – constructing in finished areas leads to unintentional nicks and damage to previously completed work, which requires rework and repair;
22. Congested drawings – makes reading the plans difficult and delays the contractor's ability to execute the work efficiently;
23. Suspension of work – extended down time where a contractor may need to fully demobilize during the suspension;
24. Phasing and sequence – coordination and proper timing of various trades in performing their work is essential to efficient productivity.

With so many different variables that can hurt productivity, which is most important? The answer lies in the specific project at hand and varies from project to project. This research seeks to find a relationship between CPM scheduling and labor productivity with trade stacking as its primary focus. Therefore, this research is perhaps most applicable to construction projects prone to conditions where trade stacking may occur such as with mechanical, electrical and plumbing trades on building projects, piping activities for process and power plants, and structural steel erection.

Network Scheduling

Given the importance of planning and labor productivity, many planning tools have been developed to assist the builder to stay on time and within budget. Construction projects may be categorized broadly by those in which a forecasted completion date may be determined based upon expected or known quantities, and those where so many unknowns exist that it is implausible to accurately predict a completion date. For example, construction of a school based on a completed set of architectural drawings differs significantly from constructing a mine shaft to unknown depths based upon what soils are actually encountered. In the school example, quantities, construction methods and work scope are generally known, whereas in the mine example, quantities, methods and the work scope are essentially unknown. Different network scheduling techniques apply to each category. Deterministic modeling, such as the widely recognized Critical Path Methodology (CPM), better applies to generally known work scope and indeterministic modeling is better suited for projects with undetermined scope and durations.

Other types of construction schedules exist that do not adhere to CPM precepts including, for example, line of balance (LOB) or linear balance charts (Su & Lucko, 2015), linear scheduling (Su & Lucko, 2015), graphical evaluation and review technique (GERT) (Nelson, Azaron, & Aref, 2016), and the project evaluation and review technique (PERT) developed initially by the US Navy (Smith, 2008, p. 43). Another schedule methodology utilizes a bar chart or Gantt chart (Baldwin & Bordoli, 2014) (Trauner, Manginelli, Scott, Nagata & Furniss, 2009). Each of these methodologies is presented briefly below. Refer to the cited references for detailed explanations.

Deterministic Network Modeling

The most notable deterministic network modeling methodology is Critical Path Methodology (CPM) scheduling (Kelley & Walker, 1959) (O'Brien, 2006). CPM finds the longest chain of work activities in a schedule network, which defines the critical path, or longest path, and establishes a forecasted completion date for the project. Successfully completing that project timely is dependent upon many factors and in large part by the contractor's labor productivity.

James E. Kelley, Jr. and Morgan Walker in 1956 developed CPM algorithms that became the "Activity-on-Arrow" scheduling methodology for E.I. duPont de Nemours & Co (DuPont) (Kelley & Walker, 1959) (Associated General Contractors of America, 1965) (O'Brien, 2006) (Kelleher, 2003) (Weaver, n.d.-a) (Weaver, n.d.-b). Fundamental premises of CPM scheduling include (Ottesen & Martin, 2011):

1. Use of a single master plan for all project task activities facilitates a high degree of coordination.
2. Work activities are logically linked together based upon required sequencing of predecessor and successor activities.
3. Based on estimated durations to complete each activity, early and late start and finish dates for each activity can be calculated.
4. If the maximum time available for an activity to complete equals its duration the activity is called critical.
5. A project's longest path is defined as the sum of durations for the chain of activities that are critical. This path determines the completion date for all activities in the project.
6. A delay to a critical activity will cause a comparable delay in the project completion time.

7. If the maximum time available to complete an activity exceeds its duration, the activity is said to have float. Only after float is absorbed will a delay to that activity cause a downstream displacement of successor activities.
8. “Crashing,” (or accelerating) a schedule entails changing the schedule’s critical path activities such that the projected completion date is made earlier.

In 1965, the Associated General Contractors of America (AGC) published the textbook “CPM in Construction” (Associated General Contractors of America, 1965). AGC identified ways to control and monitor the CPM schedule during a project, which adds to the premises above including providing periodic updates to reflect changed work, means, resource availability, etc. Periodic updates require reevaluation to determine whether the original critical path had changed.

These principles of CPM scheduling have proven invaluable to the organizations who use them properly, particularly for large complex projects. Literature on CPM is well consolidated. With the advent of personal computers, the number of published papers increased exponentially in 1980’s. Survey results taken in 1990 from Tavakoli and Riachi found 93% of contractors used CPM scheduling (Tavakoli & Riachi, 1990). This percentage seems to have decreased in later years according to Galloway (2006) who found that 67% of contractors use CPM and that 50% of owners require CPM by specification (Galloway, 2006). Regardless, CPM still remains widely used and will continue to be used in the future as affirmed by a panel of scheduling experts at AACE International’s 2013 Annual Meeting in Washington, DC (Kelly, Nagata, Sanders, & Thorndike, 2013). Nagata summed it up succinctly, “CPM scheduling established an extremely strong foothold in construction by embedding itself into the fabric of project and time management processes of public (US federal and state) and private contracting.”

Indeterministic Network Scheduling

A parallel development of an indeterministic technique called Project Evaluation and Review Technique (PERT) was underway by the U.S. Navy and the Lockheed Company (Associated General Contractors of America, 1965). PERT is explained in a later section. From both efforts emerged The project evaluation and review technique PERT and graphical evaluation and review technique GERT are useful when the time required to complete an activity is unknown. Both rely upon stochastic, or probabilistic approaches to estimate construction activity durations, and follow logical rules for planned sequencing of activities. Monte Carlos simulation, which relies upon probability distribution functions, may be used to generate these durations (Karabulut, 2017). GERT differs from PERT in that it allows for both deterministic and probabilistic approximations, and in allowing use of logical loops in the modeling (Nelson et al., 2016) (Tao, Wu, Liu, & Lambert, 2017).

Line of Balance and Linear Scheduling Methods

Both the line of balance (LOB) and linear scheduling method (LSM) focus more on work productivity and delivery in completing a given number of installed units than on planned time durations to complete a given construction activity. These methods work well where repetitive activities recur on construction projects. Su and Lucko (2015) explain the primary difference between these two methods, “In linear schedules, an activity is represented as one line, work starts from 0, and velocity (productivity) is calculated as the slope of the line; whereas in LOB, two lines (start and finish events) are needed to represent an activity, work starts from 1, and the slope of either of its two lines represents the delivery rate.” The difference is subtle. The LSM utilizes a planned productivity rate, for example, in forecasting a target rate for cubic yards of concrete placed per day whereas LOB uses a metric for the forecasted average units to be delivered per day based upon expected interruptions to the crew's work. In effect, LOB allows the scheduler a bit more control over when the crew resources are deployed and actively working.

Bar Chart or Gantt Chart

History credits American mechanical engineer Henry L. Gantt for developing a time-scaled, graphical representation of project activities using horizontal bars (Mubarak, 2015, p. 16). The terms "bar chart" and "Gantt chart" are essentially synonymous. This approach has application in construction where individual tasks may be arranged and displayed sequentially on a time-scaled horizontal axis. The level of detail provided in a Gantt chart is determined by the scheduler. Shorter bars indicate shorter time durations planned to complete the task shown. Displaying bars sorted by the start date shows the planned sequencing, i.e., logic, in performing the work, however, the bar chart model itself does not physically contain or show local ties between the bars. Progress may be observed by comparing actual durations to the planned durations. Given its simplicity and understandability, use of Gantt charts is perhaps the most commonly utilized scheduling methodology.

The primary difference with bar chart schedules and CPM schedules is that the bar chart schedules do not show logical relationships between the work tasks. However, lack of visible logic on paper does not undermine the required sequencing in the field to complete the work. The same is true for the other scheduling examples mentioned above. The logic still exists whether shown in the schedule or not. Some schedules are based solely on estimated labor and progress is calculated based upon the actual labor hours expended, as observed in turnkey companies who provide solar installations. In this case, there is no defined critical path per se, and instead project managers rely upon experience to define work task priorities. Similarly, there is a logical progression to completing the field work regardless of whether that sequencing is defined in a schedule.

The schedule density measurement used in this study can be applied to bar chart schedules regardless of whether schedule logic exists or not because the bar chart reflects planned sequencing of work activities anyway. Care must be taken to verify that if using bar chart schedules, sufficient detail exists to generate meaningful results. For other non-CPM scheduling methods, the approach defined herein does not apply.

Synchronizing CPM and Resources

In an effort to synchronize CPM scheduling and resources, resource loading techniques were developed whereby planned labor resources are assigned to planned work activities in the construction schedule. CPM software allows the scheduler to assign labor resources to specific work activities. For example, if a planned wood framing activity requires two carpenters to spend 8 hours each for two days, 32 hours of required carpentry time can be assigned to a two day activity in the schedule (i.e., 2 carpeners x 8 hrs per day x 2 days = 32 hrs). In complex schedules, resource loading all activities can require significant efforts.

To ease understanding of resource loaded schedules, histograms and cumulative density curves are used as graphical representations of schedules. (Peterman, 1978) Histograms showing the planned laborers per work task on a timescale can be developed from the CPM schedule similarly to that shown in **Error! Reference source not found.**. This planning technique sought to alleviate untenable labor density situations and at the same time, provide for project continuity (Stumpo, 1986). Error! Reference source not found. demonstrates how the shifting of labor resources can reduce the peak number of workers needed on a given calendar day, or rather, in minimizing the number of workers while still completing the planned work on time. Fewer workers mean less input and if the output remains the same, a better productivity rate results.

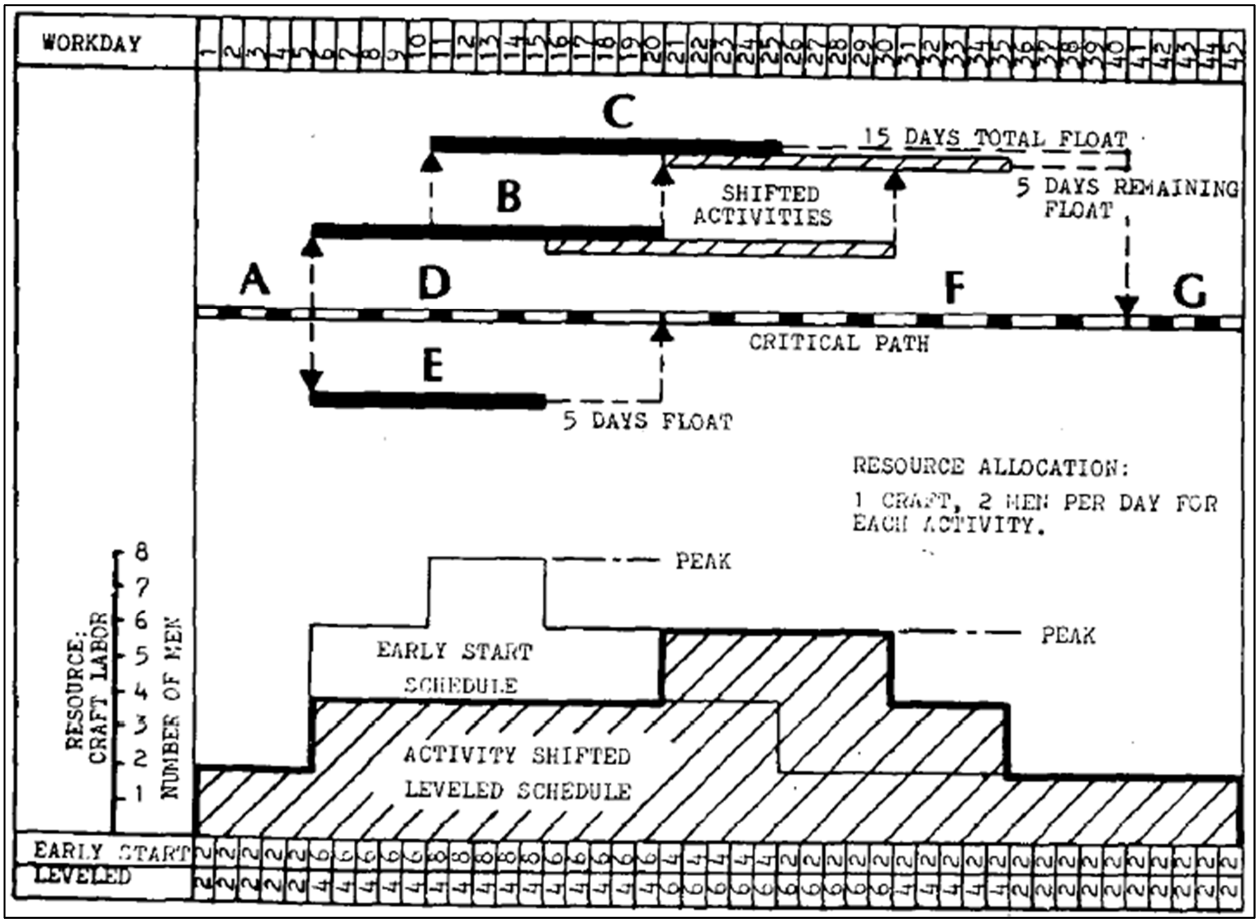


Figure 2-2 Example Resource Histogram (Stumpo Jr., 1986)

The histogram in Figure 2-2**Error! Reference source not found.** can be used to derive the density of workers (using units of workers per day) on any given calendar day. For example, on workday 11, a peak of 8 workers per day was forecasted, but was reduced to 4 workers per day by shifting the planned work activities B and C out in time. Whereas these activities had float, no delay to the forecasted completion date results by shifting these activities out in time. In CPM scheduling, float is defined as the difference in days between an activity's planned early finish date and its planned start date. If this value is greater than 0, then float is said to exist for that activity. In general, if this calculated value is zero, then the activity is on the critical path and shifting it out in time would cause delay to the project. The output remains the same in that the work activities B and C are still completed, but with fewer workers, which means a better overall productivity rate. The methodology described in this article most closely resembles the schedule density concept proposed in this dissertation, but only to the extent that overlapped resources may be summed on a given day and that these summations may vary depending upon the planned dates for performing that work. As explained in Chapter 3 herein, this research uses a metric called a crew day resource (CDR) in place of undefined resources within a CPM schedule, whereas Stumpo's methodology merely explains what resource leveling can do to a resource-loaded schedule. The summation of CDR's and displaying them in a histogram is similar to this resource loading. Stumpo's approach was not new in 1986 (the year the article was written) and remains axiomatic today, which strengthens the derived methodology herein albeit using the CDR metric.

Utilizing float in a CPM schedule is one way to optimize productivity. Assuming no float, physical constraints at a site may restrict the maximum number of workers that can safely and efficiently coexist in a given work space (Peles, 1977). In these instances, preparation of accurate labor loading charts in combination with the CPM schedule is imperative. For bar chart schedules, float and a critical path must be estimated (Trauner et al., 2009, p. 56).

Despite the benefits of using such planning techniques, not enough contractors utilize them because of the perceived additional costs to generate them. Further, this literature review revealed few defined rubrics by which to determine the effectiveness of a resource-loaded schedule. One possible rubric involves use of engineering statics principles wherein the centroid position of any given histogram can be calculated. One article was found where the author utilized engineering concepts of centroids with idealized manning calibrations curves (Clark, 1985). A centroid is defined as the center of mass of a geometric object of uniform density through which the weight of a body acts through a definite point in the body (Sharma, 2010, Chapter 6), and is analogous to a thin, flat metal plate. If one were to take a thin wire and attach it to the face of this metal plate and then lift the plate upward, if attached at the centroid position, the metal plate would remain perfectly parallel to the original flat surface regardless of the shape of the surface. The centroid position can be defined in an X and Y Cartesian coordinate system. The X value is in units of time whereas the Y value represents the number of workers required to complete the activities planned for a given calendar day. By observing differences in the X and Y values with different CPM schedule updates, inferences relative to productivity loss and delay can be made. This study will utilize similar principles of engineering statics in the developed model.

A similar concept to labor density was found in Ron Winter's Schedule Analyzer Pro software (Lucas, 2002) which utilizes a measure called "schedule distribution" when evaluating a baseline CPM schedule for activity detail consistency (Winter, 2010). **Figure 2-3** shows an example of what Mr. Winter calls an activity distribution histograph which he describes as follows:

> *This graph shows the graphical representation of the number of activities expected to be active over the various periods of the project. . . In theory, the histograph should look flat and even throughout the project. In reality, there will probably be a bulge in the middle of the work period. . . this histograph is only an approximation of the work plan. SA Baseline Checker assumes that all activities delay their start by one half of their total float.*

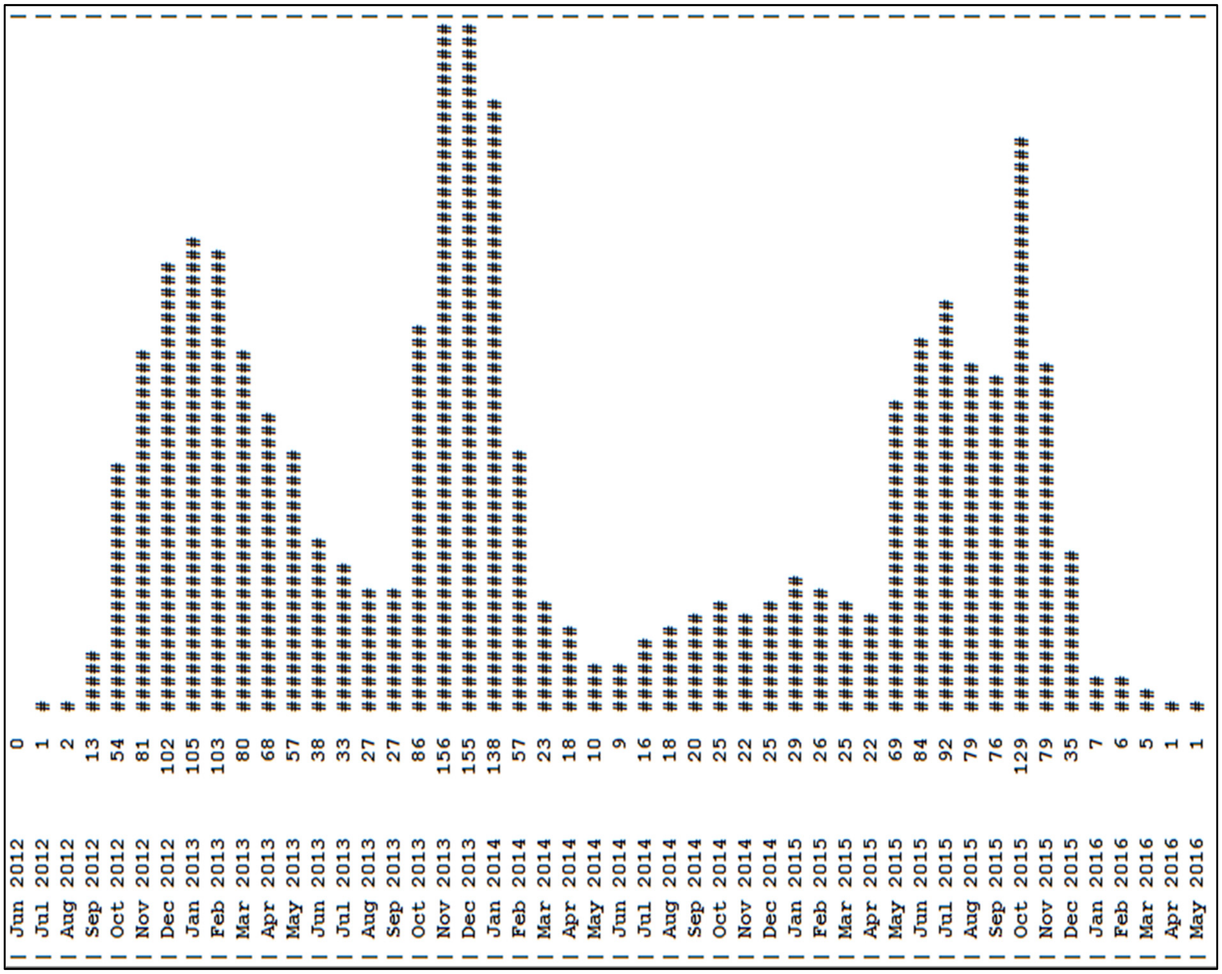


Figure 2-3 Example Schedule Activity Distribution Histogram

While the histogram above contains all activities in a baseline CPM schedule, the software also will provide basic statistics on the number of activities by trade. With this study, in order to have like comparisons, at a minimum, similar trades will be compared within themselves. The method presented herein utilizes similar principles in using histograms, in the form of area charts and use of centroids, to observe the change in schedule activity densities by trade over time.

Finke described changes in schedule density as predictors of future disruption (Finke, 2000). However, his use of the term "schedule density" differs from this study. According to Finke schedule density is defined as:

$$Schedule\ Density = \frac{Sum\ of\ Activity\ Durations}{Sum\ of\ Activity\ Durations + Sum\ of\ Activity\ Free\ Floats}$$

This equation creates a ratio value greater than zero, but less than or equal to 1. Finke then adds labor costs for each of the activities in the above equation to create a weighted schedule density measure based on costs. Following a delaying event, calculated and weighted schedule density values of before and after the event are compared. The greater value indicates greater schedule density, and thus, greater impact. In effect, this approach measures the consumption of float in a CPM schedule. The weighting aspects are used to more accurately quantify related cost damages. The model will exclude costs, but must account for float as the Fenke, Stumpo and Winter models do.

The Chartered Institute of Building (CIOB) in its Code of Practice for Project Management for Construction and Development uses the term "schedule density" to describe the level of detail reflected in CPM work activities (Chartered Institute of Building Great Britain, 2014) p. 126 The concept holds that it is practically impossible to fully detail a schedule for a complex project at the first day because too many factors are unknown or yet to be developed. As more information becomes available, more detail can be integrated into the CPM schedule, thus, greater number of activities with shorter durations would indicate greater schedule density. Thus, CIOB's use of the term is dissimilar to the use of the term herein.

Trade Stacking

Findings of the literature review herein parallel findings of Duah and Syal (2017) wherein trade stacking was identified as significant factor that affects labor productivity. The following paragraphs summarize trade stacking from a few of the sources that recognize trade stacking as an impacting factor.

Toronto Change Order Protocol (Toronto Protocol 2010, p. 8), describes stacking of trades as “Delays in the planned activities of a project result in a deterioration of the construction schedule. A Change Order, if not properly integrated into the average schedule, can transform an orderly, sequenced work plan into one in which many operations must be performed concurrently. The workmen of several trades could become stacked in a limited work area, creating a situation in which work cannot be done efficiently. A Contractor who was the low bidder and who scheduled his performance on an optimum time-minimum cost program, may find himself faced with a minimum time-maximum cost dilemma.”

Mechanical Contractors Association of America (MCAA) Guideline for Contractors (MCAA 2012, 1976), defines stacking of trades as “operations that take place within physically limited space with other contractors.” MCAA further indicates that “because of the lack of crew and equipment restraints [in the schedule], the mechanical subcontractor's activities may become improperly "stacked" in the schedule in a manner that was totally unanticipated, in turn, leading to unplanned increases in crew or equipment requirements and their associated inefficiency and financial impact to the mechanical subcontractor.” (p. 55) Operations that take place within physically limited space with other contractors results in congestion of personnel, inability to locate tools conveniently, increased loss of tools, additional safety hazards and increased visitors such that an optimum crew size cannot be utilized. (p. 77)

The Electrical Contracting Foundation, a subsidiary of the National Electrical Contractors Association (NECA) studied trade stacking for electrical contractors and found that acceleration and schedule delay are the two primary causes for trade stacking (Hanna, Russell, &

Emerson, 2002). Survey results from 50 NECA members confirmed similarly that acceleration and delay were the top two causes for trade stacking (Rojas, 2008, p. 81). This study also found that trade stacking was most likely to occur in the third and fourth quartiles of the project duration. This finding is consistent with delayed CPM schedules wherein unfinished work activities are 'pushed' outward in time such that absent a time extension, the overlapping or stacking of planned work tasks increases. Rojas (2008, p.93) performed both a qualitative and quantitative analysis. The quantitative analysis included regression analyses for construction productivity for a given number of electrical laborers working within varying square foot areas. The findings show significantly lesser productivity rates with smaller areas, i.e., greater congestion and stacking of trades. Rojas (2008) also found that productivity losses were significantly greater than reported by USACE when non-electrical trades were stacked with electrical trades. (Rojas, 2008, p. 102)

Whereas the literature review shows that trade stacking can have adverse effects on construction productivity, the challenge becomes finding a relationship, if one exists, between CPM scheduling and construction labor productivity.

Cost Considerations

Productivity loss invariably generates financial losses too. On construction projects, quantifying productivity loss generally requires empirical evaluation such as a measured mile analysis. The measured mile analysis considers productivity for a time period where the work progresses unimpeded by external factors or delay that may adversely affect productivity versus a time period where adverse impacts were experienced (Palmer, 2008) (Ibbs, 2012). The difference between these two measures can be converted from labor hours into dollars and represents the inefficiency cost. Recovering these costs, however, may be difficult depending upon provisions of the executed contract between the parties. Duah & Syal (2017) speak to consequential damages when the timing and scope of changed work affect other aspects of the project duration or costs beyond the limits of just that particular change order. They then introduce productivity impact factors that if present can lead to consequential damages and further indicate that contracts typically prohibit recovery of consequential damages. This places greater obligation on the contractor to price the full impacts for productivity inefficiencies at the issuance of a change order, which may be impossible to do accurately in real-time.

Absent acceleration or other means to recover lost time, critical delay on a construction project can increase a contractor's overall home office overhead costs (Ottesen & Dignum, 2003). The critical delay may cause trade labor progress to stall, which adversely impacts productivity. In the author's experience, existence of critical delay, however, does not always mean that productivity losses automatically occur. Each delay must be analyzed (preferably prospectively) relative to the effects it has on the other activities in the schedule to make a determination of whether productivity inefficiencies may also occur.

Calculation of productivity cost impacts due to inefficiencies is beyond the scope of this research. Suffice it to affirm that productivity losses bleed profits and leads to claims. Development of a method that helps the scheduler to forecast inefficiencies before they occur would be useful and therefore, warrants further investigation.

Summary

In summary, the literature review revealed that CPM scheduling has been widely accepted by the construction industry since its inception in the 1950's and that not much has changed with it since. The planned durations for given construction activities, coupled with the logical ties between them, determine the critical path of a given CPM schedule and ultimately, the forecasted project completion date. Establishing reasonable and achievable durations is challenging in large part due to the variability of resources assigned to perform those activities. Present good industry practice holds that assigning resources to activities in a CPM schedule enhances that schedule's accuracy and provides a better resource management tool for the contractor. Regardless of its benefits, however, for a sundry of reasons most contractors do not resource load its schedules and the planned durations for activities remain subjective or loosely based on historic or planned productivity rates to complete those tasks within the assigned durations. The linking of productivity rates to a CPM construction schedule is commonplace and has been utilized in the industry for decades, which rates optimally must align with the planned duration to complete that work, but frequently in practice do not. Consequently, an underlying assumption with any of these schedules is that the contractor will provide sufficient resources to complete the work within the assigned durations.

Other non-CPM scheduling methods that utilize stochastic or probabilistic models have been developed to address the uncertainty within planned durations, but the same underlying assumption exists with each of these models – that the contractor will provide sufficient resources to complete the work within the assigned durations.

Significant research has been performed on productivity loss, its causes and magnitudes of impacts per various factors. The literature review revealed that despite all of the research on factors that affect productivity, the actual inefficiencies to be encountered and the magnitudes of those impacts are simply unknown. This research capitalizes on past research that validates the precepts and rules of construction labor productivity and CPM scheduling, and expands that paradigm to include schedule density as predictor for productivity loss and delay. No similar approach or model to that presented herein was found in the literature review. Consequently, this research expands the body of knowledge by filling a gap in predictive modeling for productivity loss with CPM schedules.

3 Research Methodology

The literature review revealed nothing similar to the proposed methodology described herein. Recognizing this navigating in unchartered waters, the author follows strict interpretation of mathematical, engineering, statistical and industry accepted CPM principles. Consistent with logical reasoning explained in the literature review, the author assumes that if the individually applied precepts are true and adhered to, then when used in combination in structured and logical ways, then the resulting findings will likewise have validity. This chapter presents the underlying theory and bases for evaluating data.

Research Approach

Figure 3-1 illustrates a schematic diagram for this research. Seven steps were followed. The objective was to determine whether CPM schedule data could be used to develop a predictive model for productivity loss.

Pursuant to this objective, first a literature review was performed. The findings of this review were synchronized with the author's 25 years of experience in working with CPM scheduling and construction claims. Despite purported benefits of resource loading a CPM schedule, most contractors do not do it, yet each CPM schedule inherently possesses implied productivity rates for activities, which are directly related to the resources. The literature review revealed no model or methodology for predicting productivity loss where resource loading was absent from a CPM schedule. Thus, a gap in knowledge was discovered and a working hypothesis was developed under Step 2.

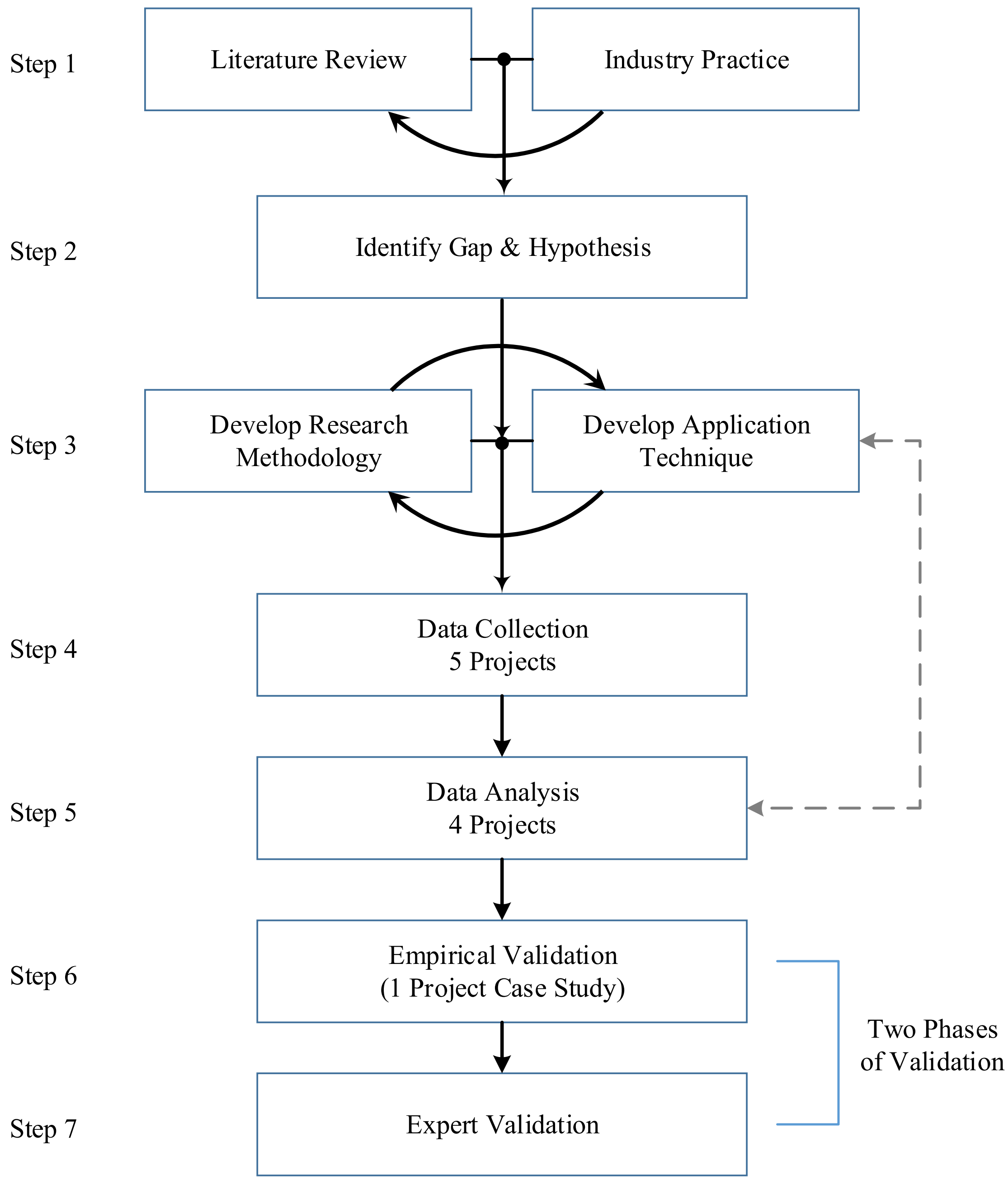


Figure 3-1 Schematic Diagram of Research Approach (Derived in part from Gliner & Morgan, 2000, p. 62 - 73)

Step 2 further defined the original objective to determine whether a correlation exists between a construction schedule's density measure (quantified in units of Crew Day Resources, or CDRs) and field-experienced labor productivity rates. The CDR unit represents whatever crew resources are needed to perform the work for that day. Because the schedule is not resource-loaded, this value is unknown and simply assigned an integer value based upon the number of overlapping schedule activities for a given calendar day. Then, a hypothesis was developed, "If successive construction schedules demonstrate increases in their respective densities, then a correlating decrease in labor productivity occurs." Testing this hypothesis served as the bases for this study. Stated another way, it was believed that the changes in schedule density may provide a basis for deriving a predictive model for labor productivity loss.

When labor productivity loss occurs, the contractor must make some change to its plan to recover the loss otherwise delay results. The underlying theory behind this hypothesis is that when a contractor's labor resources are overlapped with each other, or when more than one workface must be progressed simultaneously, one of two known causes for labor inefficiencies result:

1. Trade stacking, where workers from two or more different trades are required to perform work in close proximity with each other at the same time, but cannot do so efficiently due to induced interferences with each other; or
2. Insufficient labor, where, because of the overlapping of work in the schedule, the contractor either does not or cannot provide sufficient labor resources to perform the work at both work faces simultaneously on the same day.

Because there are so many other variables that can contribute to measurable productivity inefficiency and because there is no way to easily isolate each variable from the available data, perhaps the best result would be to establish a potential correlation between construction schedule density and experienced field productivity inefficiency. Ernst F. Schumacher, German statistician and economist said, “Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius — and a lot of courage to move in the opposite direction” (Schumacher, n.d.). This research, while acknowledging the many variables that affect productivity, their interdependencies and complexities between them, moves in an opposite direction in trying to find an aggregate variable that most saliently addresses trade stacking and insufficient labor, but not mutually exclusively.

Step 3 involved developing a methodology and technique that utilizes non-resource loaded CPM schedule data and measures related to schedule density to predict labor productivity loss. The overall research methodology was derived from established research approaches and from survey results taken at North America’s largest construction trade show, ConExpo, held in Las Vegas, Nevada in March 2017 (“CONEXPO-CON/AGG | Highlights from the 2017 Show in Las Vegas,” n.d.). The application technique was derived from tenets in CPM scheduling with belief that greater acceptance of the results of this study (whatever they may be) would follow if each element utilized were already proven and accepted by the industry experts.

The application technique generates output where comparisons may be made with changes in schedule density versus actual productivity rates over the project’s duration. The intent of observing these comparisons is to identify any correlation between them. Specifically, how does a schedule density measure, correlate with labor productivity? Where associative trends are observed and where individual continuous variables are utilized, regression analysis was used to determine how well the data ‘fits’ a particular mathematical function.

Step 4 involved data collection. Specifically, five actual construction projects were included in the study as presented in Chapter 1. Four of the five projects were used to identify the trends and to derive a predictive model generated by application of the technique from Step 3. The fifth project was used for validation of results generated from the other four projects. Data collected included the contract documents (e.g., executed contract, general conditions, design drawings, etc.), electronic native copies of the contractor's CPM schedules, incremental field-documented progress (weekly or monthly), and actual labor hours expended by week.

Analysis of four of the projects occurred in Step 5. The analysis included generating schedule density histograms for each CPM schedule update for a given trade. Best-fitting mathematical curves, i.e., functions, were derived from the histograms and various metrics utilizing these functions were compared and contrasted from schedule update to update. Trends were identified and correlations were established between these variables and the actual recorded field progress. Results from the analyses led to some modifications to the application technique, thus, the dashed feedback loop line shown in **Figure 3-1**.

Optimally, there is practical value in being able to take the predictive model derived from this study and have a contractor or other practitioner be able to apply it to their own project. In Step 6, results from Step 5 were applied to the fifth construction project with an intent to see how correlation with an outside project compared when overlaying results of the other four projects upon it. Observations and findings of this overlay are presented in Chapter 7.

The final step included assembling an expert panel and soliciting opinions of the panelists via a Delphi Study relative to the findings of the research. Because the methodology developed is new, validation of results via experts establishes credibility.

Applying Theories of Knowledge to Establish a Link Between CPM and Productivity

In the theories of knowledge spectrum spanning from subjectivity to objectivity, without question, this research weighs heavily on the objective, scientifically-based side because this research seeks to establish a correlation between schedule density and experienced productivity loss, which may best be defended using objective and logical measures in mathematics, statistics and probability.

Logical empiricism (Polkinghorne, 1983, p. 65) provides bases for establishing truth and knowledge for this research. Logical empiricism holds that observational evidence that confers high probability on generalizations is sufficient for obtaining general knowledge, and that experience is of primary importance in giving us knowledge of the world. At issue are the productivity rates of various crews in performing construction work tasks and the way in which those rates are inherently or intentionally reflected in a corresponding CPM schedule. Observation of actual work performance, or the lack thereof, requires measurement and observational evidence of real-world events. The CPM schedule updates were analyzed and each of its crew day resource (CDR) densities compared to these performance observations. Consistent with logical empiricism, the observational evidences drawn from the analyses are framed in terms of probability measures and likelihoods of results being true, which is sufficient for making generalizations of knowledge.

When trying to establish truths, scholars generally acknowledge two reasoning approaches, inductive and deductive. Deductive reasoning is considered working from the top down, or rather, beginning with a theory and a hypothesis and working toward proving that theory true or not. Inductive reasoning flows from the bottom up which begins with observations and then follows a process to determine a theory that explains the observed effects. This study initially utilizes inductive reasoning because in the author's career it is observed that when a CPM schedule experiences stacking of activities and trades, productivity losses occur. This research uses these observations as a starting point to then determine whether there's a correlative relationship between the CPM schedule and labor productivity. Theories derived from this approach will then be derived whereby further deductive studies may follow, which deductive nomological explanations satisfy explanatory relevance arguments in the strongest possible sense. (Hempel, 1966) p. 52

Drawing upon research, industry accepted practices and the author's experience, the study utilizes empirical data from actual construction projects. Accepted knowledge on CPM scheduling and labor productivity is applied when developing the study's methodology. Optimally with additional research, the sample size used in this study will allow for statistical analysis and establishing strong correlations backed by tight alpha significance. Unfortunately, the tremendous amounts of data and overall effort required to analyze 20 or more projects that reaches this optimal condition exceeds the scope of this research. Instead, a few projects were evaluated as sample studies and results of these case studies are evaluated with intent to justify evaluation of a larger data sample size. Therefore, results of the study point to principles that are likely to be true, but that will require further analysis with a larger sample size to strengthen the findings. An absolute declaration of truth is unnecessary under logical empiricism theory. Sufficiency arguments based on reliable justification tools and methodologies suffice.

Even though most of this research relies upon external data and objectivity, there cannot be, however, a purely objective measurement in this study because of the human interface between the two primary measurements being made. There are many human factors that affect experienced labor productivity. For example, the Mechanical Contractors Association of

America (MCAA) identifies morale and attitude as being affected by excessive hazard, competition for overtime, over-inspection, multiple contract changes and rework, disruption of labor rhythm and scheduling, and/or poor site conditions (MCAA, 2012, p. 77). MCAA claims that productivity losses for such affects vary from five to 30 percent. These percentages speak to aggregate values because individually, some workers are more resilient or experienced than others and therefore, are not as affected by these factors as perhaps other workers would be.

Consequently, a primary element of this research is inherently biased by human behavior and it will be impossible to isolate any one single of these variables to test its correlation with schedule density. This fact, however, does not diminish potential significance of findings. Case studies in construction management frequently face similar challenges, yet case studies are commonplace in construction management research and provide relevant and useful results. Examples include,

- Case Study of Delay Impact Analysis of Lost Productivity in Construction Projects - University of Washington (Huang, Yang, Lee, & Ku, 2011)
- A New Model for Productivity Evaluation in Construction by New Insight Into the Baseline Productivity (Case Study) (Gavili & Mortaheb, 2015)
- Defining a Mathematical Function for Labor Productivity in Masonry Construction: A Case Study - University of Washington (Florez & Cortissoz, 2016)
- Evaluation of Factors Affecting Labour Productivity In Construction Industry: A Case Study (Muhammad et al., 2015)
- Why Do Work Sampling Studies in Construction? The Case of Plumbing Work in Scandinavia (Josephson & Björkman, 2013)

The measured CPM schedule densities calculated in this study likewise stem from a human's perception of how that particular construction project should be planned and constructed. In the author's experience in having evaluated or worked on more than 180 construction projects, none were completed exactly as originally planned, particularly with complex projects that span many months or years. A myriad of reasons explains these differences including for example, human errors made in creation of the schedule, changes to the work, poorly defined scope, etc.

Limitations and Theoretical Challenges

Because there are so many possible reasons for experienced productivity loss on a construction site, it is difficult to isolate an actual root cause for it, or to attribute a single factor to it. Individuals who lean more to the subjective, relativism side of the spectrum may argue that any resulting model does not specifically include analyses targeted to address human sciences and human understanding – factors that admittedly influence creation of CPM schedules and directly influence labor productivity. Possible responses to such criticisms include:

- Expanding the literature review to include studies that specifically target human influences on CPM scheduling and/or labor productivity rates, and that rely upon findings from those studies to serve as the beginning laws of my research. Significant research exists on factors that affect labor productivity. Less research exists regarding human influences on CPM scheduling.
- Conducting surveys of those people who created the schedules to determine what factors and information were considered when the schedules were created. It is unlikely, however, that such individuals will be available or locatable even if each were willing to participate. Alternatively, schedulers who create CPM schedules similarly to those included in the

analysis may be available and inferences can be made from their survey responses and applied retrospectively to the schedules used in my study.

- Consider other possible variables besides just the schedule density measure. If the schedules were prepared independently of actual field conditions, then any identified correlation between the two would be arbitrary and meaningless.

Ultimately, the interactions between the many plausible causes for productivity loss serve as the greatest threat to internal validity of this study. Other threats to internal validity include:

- Equivalence of Groups – Because virtually no two building projects are alike, it will be difficult to achieve group equivalence. For example, suppose the author is able to get the required data for construction of a new fire station from one city, but only able to receive an office building from another. Both structures are considered buildings, but because they serve different purposes, can the two reasonably be included in the same group?
- Measurement Validity
    - Schedule Data: Vast differences in schedule quality exist from contractor to contractor, and scheduler to scheduler. While organizations such as AACE International, the Project Management Institute (PMI), and the American Society of Civil Engineers (ASCE) and have established criteria for scheduling in terms of level of detail and recommended practices, actual scheduling practice in the construction industry largely lacks any form of quality control. Use of schedules from projects where the contract specifications mandate minimum scheduling criteria will help reduce this validity threat. Performing surveys (as mentioned above) may also help to understand the human factors that affect the CPM

schedules used in my study and satisfy potential arguments made by researchers on the subjective side of the theories of knowledge spectrum.

- Productivity Data: Many contractors are excellent builders, but unfortunately poor at record keeping. Consequently, reported labor productivity rates may represent mere estimates of what actual measures occurred in the field. Worse, it is possible that productivity records were either not ever prepared, or not retained once the project completed. Thus, the very strengths afforded by logical empiricism and reliabilism may be reduced or worse, unrealized because of human error in keeping adequate records.

Threats to external validity include:

- Sample Size – Given the extensive amounts of data required, the sample size is small, albeit sufficient for the assumed normality statistics measures planned to be used. The small sample size may threaten external validity. A larger data set typically yields greater external validity and greater statistical strength; and consequently, stronger justification that my findings are likely true.
- Population and Sample Selection – Access to projects that experienced claims is prevalent to the author, but will create a biased data set, and therefore, results will be only generalizable to other projects of similar characteristics. The sample set of data will represent a target population, but of such refined criteria that it will limit its transferability to only other similar type projects.

Analysis Framework

Error! Reference source not found.**Figure 3-2** below presents the dissertation scope. Three projects will be considered and analyzed. Results from this analysis will be used to prepare a publishable paper with AGC, ASCE or AACE International. Results from an expert opinion survey will then be compared to the results under the first publication and a second publishable paper will be prepared. Depending upon results from both publications, future work may include evaluating 20 projects to generate statistical significance with empirical data.

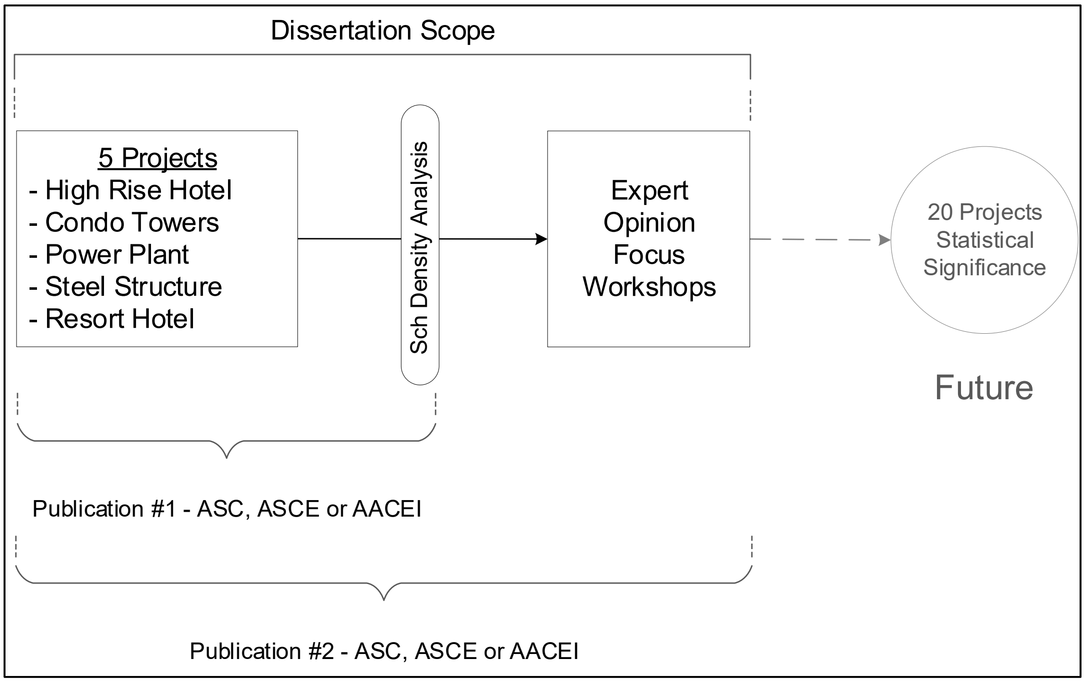


Figure 3-2 Analysis Framework

Summary of Methodology and Research Conclusions

This research opened new perspectives and generated new hope for developing a workable model that may be used to predict construction labor productivity loss from simple construction schedule data. Given the many factors that contribute to experienced labor productivity inefficiency, it is not surprising that much research has been performed to identify and quantify the relative magnitude of their effects. However, the concept of utilizing a non-resource loaded schedule and its measured density as an independent correlative variable for productivity loss is uncommon.

This research relies upon logical empiricism theory which uses observational evidence and probabilities to justify generalizations as sufficient for obtaining general knowledge. Knowledge is expanded by utilizing reliable belief-forming mechanisms and methodologies steeped strongly in scientifically based tools such as statistical analyses and probability theory. While a purely scientific and objective approach and its corresponding results are desired, there are human factors that inherently exist that cannot easily be addressed without stepping away, albeit slightly, from the objective side of the spectrum. Use of surveys and reliance upon other studies that originate from the subjective side of the spectrum assist in addressing this challenge.

Despite inherent challenges to both internal and external validity, results of this research support that an objective predictive model for construction labor inefficiencies can be developed. Significant potential benefits await the owners, architects and contractors that implement a workable model.

4 Application Technique

Development of the research technique stems from recognized truths relative to CPM scheduling, resource allocation, and mathematics. These factors form the building blocks of the technique presented herein. The following subsections describe fundamental concepts utilized to develop the technique presented in this study. An underlying assumption is that a CPM schedule is created by the contractor, but that the contractor chose not to resource load that schedule.

CPM Scheduling and Its Inherent Link to Resources

CPM schedules present planned work activities which are logically linked together on a timescale. Whereas CPM forecasts a project's completion date, it follows that time (planned duration) is a required variable when preparing the sequence of work tasks in a CPM schedule. Each activity duration is the planned amount of time required to complete that task. Optimally, resources (e.g., labor, equipment, material and cost) are assigned to each task in a manner that allows efficient use of those resources in completing the task timely. The assignment of resources to work activities in the CPM schedule causes the schedule to become "resource-loaded." Whether a schedule is resource loaded or not, however, the planned durations of the activities, usually reflect the scheduler's consideration for the resources required to complete the task within that given planned duration.

For example, assume a crew of four carpenters can form up 100 linear feet of a specific size spread footing in a typical eight-hour work day. If a representative activity in the CPM schedule has a planned duration of 5 work days, it follows that the crew is capable of installing 500 linear feet of form work within that 5-day duration. This simple calculation may be overstated because there are a number of assumptions built into it, including:

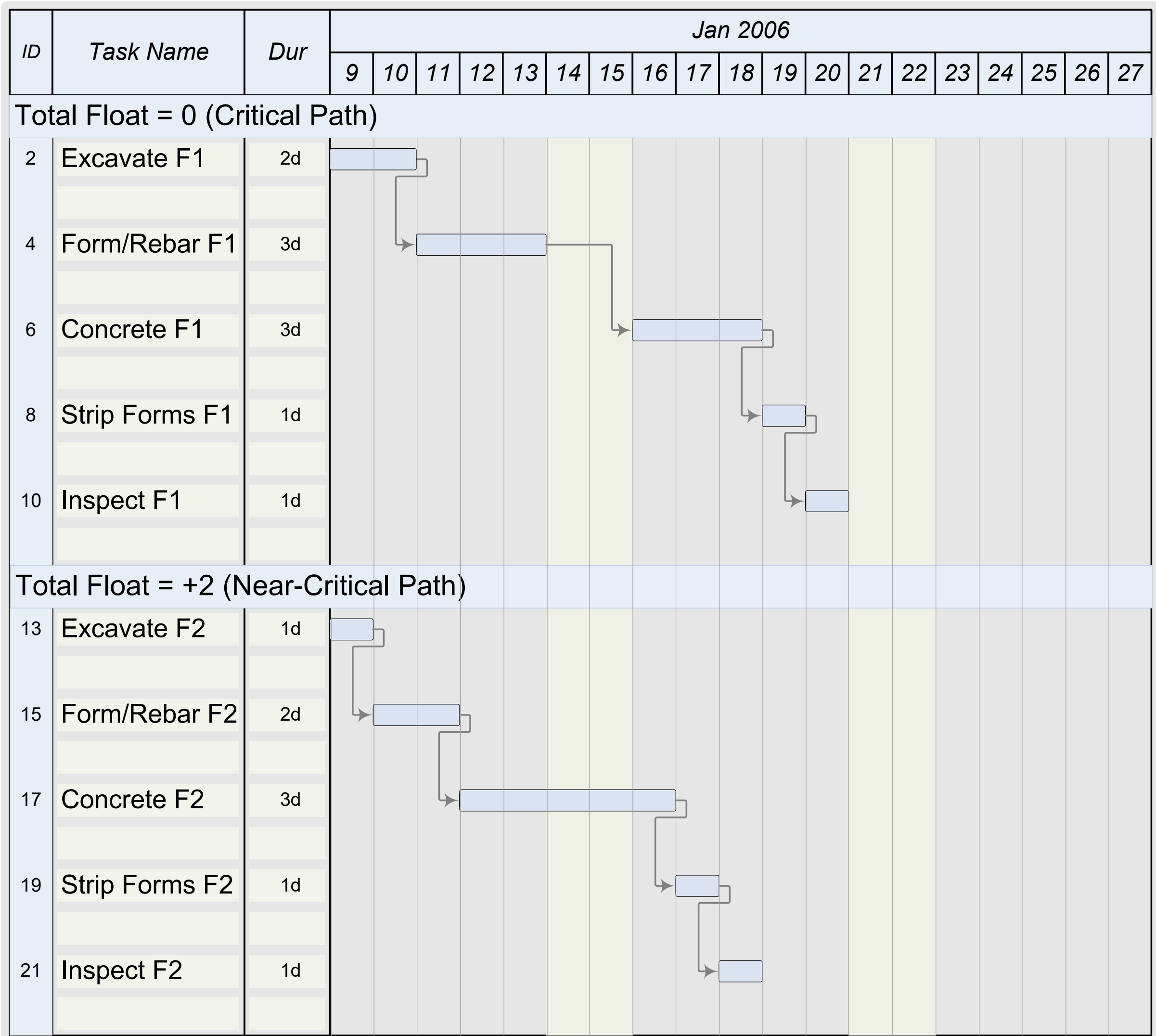
1. That the crew's productivity rate remains constant, or nearly so, for each of the 5 work days thereby reflecting a linear distribution of resources over the full duration of the activity;
2. That the resources assigned are similar to those that were estimated to be able to form 100 linear feet per 8-hour work day;
3. That one "crew," represented by one CDR unit measurement will perform the work, and
4. That field conditions are similar to those experienced when the estimated productivity rate was measured.

Resource loading a detailed CPM schedule for a large project can be a daunting task that requires many hours and availability of a usable and reliable estimating database (Ottesen & Martin, 2019). Few contractors maintain and retain such records. Additionally, collecting reliable information from subcontractors timely is nearly impossible, particularly at the early stages of the project. Consequently, for these and other reasons, contractors usually do not resource-load their CPM schedules regardless of whether an owner's specification requires it or not. Provided the job is constructed timely and without claims, the absence of resource loading proves insignificant. Conversely, a resource loaded schedule can be a useful management tool, particularly if the job is experiencing schedule delays, but keeping the information current is arduous and sometimes pointless because of the dynamic nature of the work. Absent a resource loaded schedule, has a contractor effectively lost its ability to analyze productivity loss and recover the costs? The short answer is "no," but additional effort may be required to establish entitlement and quantum in a claim.

Activity Overlapping and Crew Day Resources (CDR's)

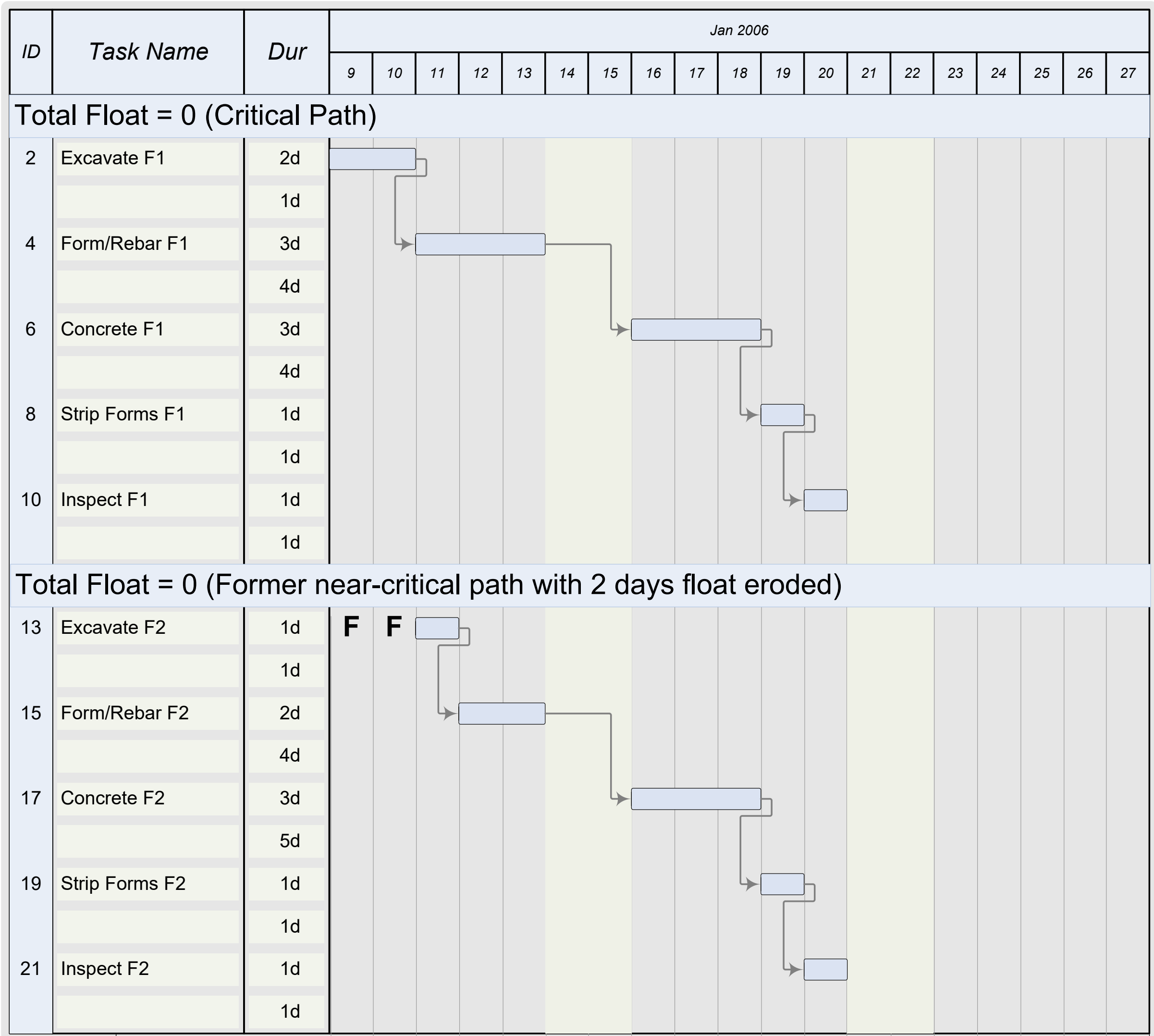
Figure 4-1 below shows two separate strings of similar activities, one on the critical path (with zero total float) and the other on a near-critical path with 2 days of float (based on early dates). Because the strings overlap, there are days where the Excavation and Form, Rebar, Pour, and Strip (FRPS) crews must work concurrently in two locations. A primary assumption here is that whatever resources are required to complete one day's work, those resources must be doubled if work on both strings is to occur on the same day. Assuming that the shown durations are accurate, it follows that for Excavation, there must be sufficient resources to complete that work in two work days. For this study, the author uses the term "crew-day resources" or "CDR" to represent the unit describing the amount of resources necessary for one work day of planned work to be completed per the planned durations. The number of planned CDR's per workday for the early completion dates are summed at the bottom of the Gantt chart.

For purposes of the analysis, knowing the detailed breakdown of what actually constitutes a CDR unit is unnecessary and mimics field conditions wherein the prime contractor establishes a fixed number of workdays to complete a task, whether that task is self-performed or assigned to a subcontractor, and expects that whatever resources and efforts are required will be applied to finish the work within the planned duration. Assume now that the two days of float on the near-critical path string were consumed (delay denoted by the capital letter "F" on January 9^{th} and 10^{th}). This float erosion causes the second string to become critical concurrently with the first string. An updated tally of the CDR's is shown in **Figure 4-2**.



	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Excavation	**2**	**1**																	
FRP Crew		**1**	**2**	**2**	**2**			**2**	**2**	**1**	**1**								
Inspection										**1**		**1**							
TOTAL	**2**	**2**	**2**	**2**	**2**			**2**	**2**	**2**	**1**	**1**							

Figure 4-1 CDRs for Planned Strings of Activities



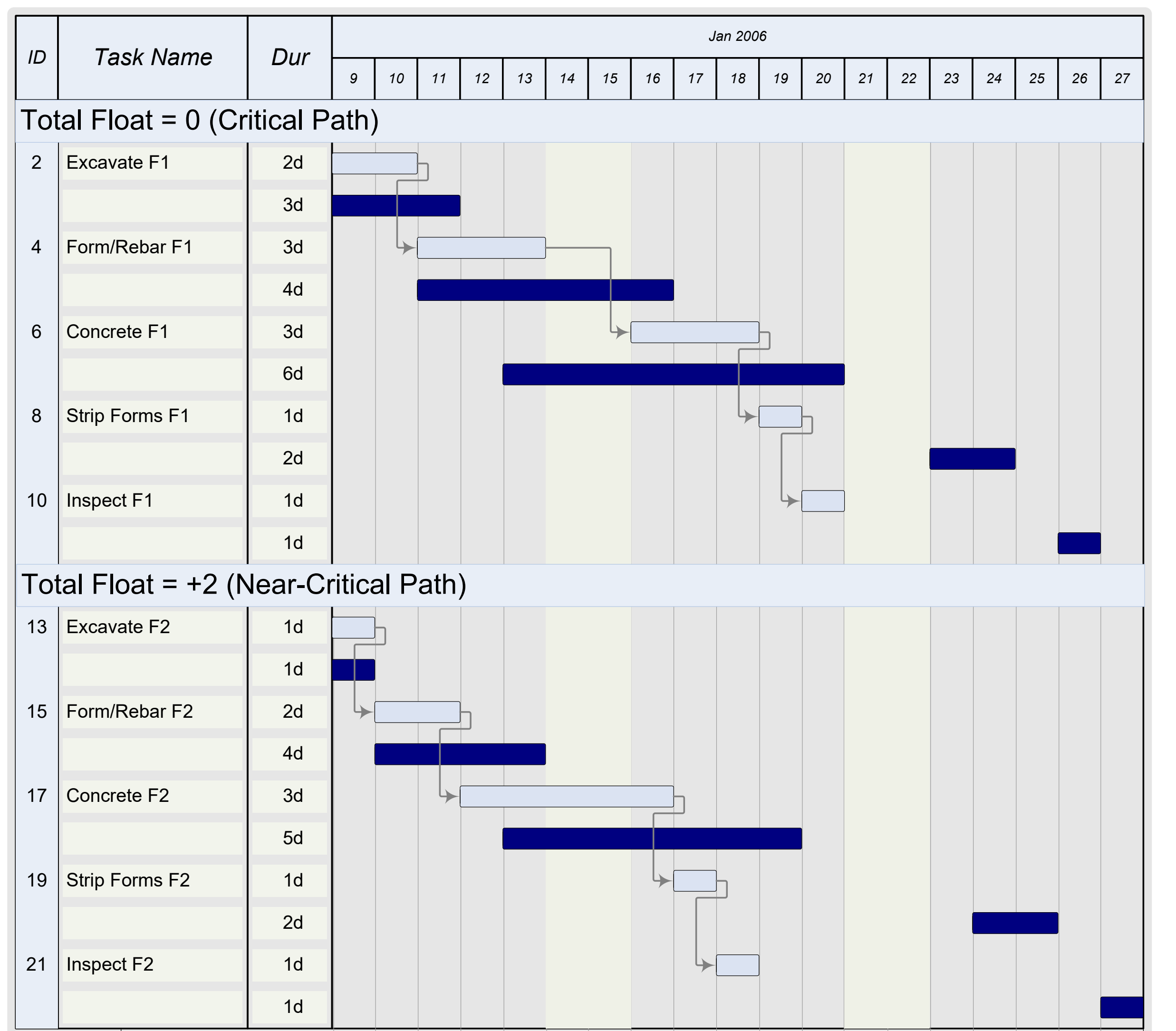
	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Excavation	1	1	1																
FRP Crew			1	2	2			2	2	2	2								
Inspection												2							
TOTAL	1	1	2	2	2			2	2	2	2	2							

Figure 4-2 CDRs Required for Planned Concurrent Critical Paths

In comparing **Figure 4-1** and **Figure 4-2**, a few observations warrant further discussion. First, the Excavation crew is required to have 2 CDR's for one day when operating at the early dates in **Figure 4-1**, but is only required to have 1 CDR for three consecutive days when the near critical path now shares the critical path with zero days of float in **Figure 4-2**. Working to the late dates, therefore, would seem the better option for the Excavation crew because it could perform the work with only one CDR instead of needing two. Also, by consuming the float on the F2 string, note that the Inspection crew must now perform its work on the F1 and F2 string on the same day. This means that the Inspection crew must now provide 2 CDRs for one day instead of just needing one CDR for two consecutive days. If there were only one planned CDR for the Inspection crew, the unexpected change by float consumption caused by the Excavation crew may be an adverse impact to the Inspection crew, and at no fault to the Inspection crew. Finally, the FRPS crew is affected least by the consumption of the float since, in either case, it must provide at most 2 CDRs on any given work day.

In the case where the Inspector was originally planned to only need one CDR, but was in the latter case of being forced to work the late dates, the Inspector's CDR's increased from one to 2 CDRs required. This simple tool can alert the Inspector crew in advance of the need to have two CDRs available and allow it time to mitigate this demand should only one CDR be available. Thus, delayed work can cause overlapping of planned future work, thereby increasing the schedule's activity density, which, in turn, may require additional resources in order to meet the revised planned dates. Stated another way, the observed sudden increase in the number of planned concurrent work activities can serve as an indicator of disruption and potential productivity impacts.

Figure 4-3 shows actual progress against the plan and counts the number of actual concurrently worked activities by day. As shown in the figure, on January 13th, the FRPS crew worked concurrently on four different activities, which was significantly different from its plan. With planned durations, the continuous level of work within each activity-duration is assumed to be the same, that is to say that the work progress is presumed to be equal for each day until 100% completion is achieved. With actualized durations, it is likewise assumed that durations represent continuous work. However, where actual durations are significantly extended beyond the planned durations, it is possible that there are intermittent work stoppages between the actual start and finish date, which may warrant adjustments to the model such that non-work days are not counted.



BASED ON ACTUAL DATES	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Excavation	2	1	1																
FRP Crew		1	2	2	4			3	2	2	2	1			1	2	1		
Inspection																		1	1
TOTAL	2	2	3	2	4			3	2	2	2	1			1	2	1	1	1

Figure 4-3 CDRs for Actual Dates

A comparison of the planned early dates to the actual dates is shown in **Figure 4-4**. Note that the actual number of work activities peaks at four in comparison to a max planned peak of two. There are several possible explanations for this spike. First, the contractor may have increased its CDRs for that day. If not, then this peak could be an indication that the FRPS contractor is experiencing inefficiencies such that the work is taking longer than planned to complete. This latter explanation fits the data shown post-January 22nd, which shows that FRPS work is ongoing despite it being planned to complete by January 20th. Again, the spike in the actual number of concurrently worked activities serves as an indicator of potential productivity loss.

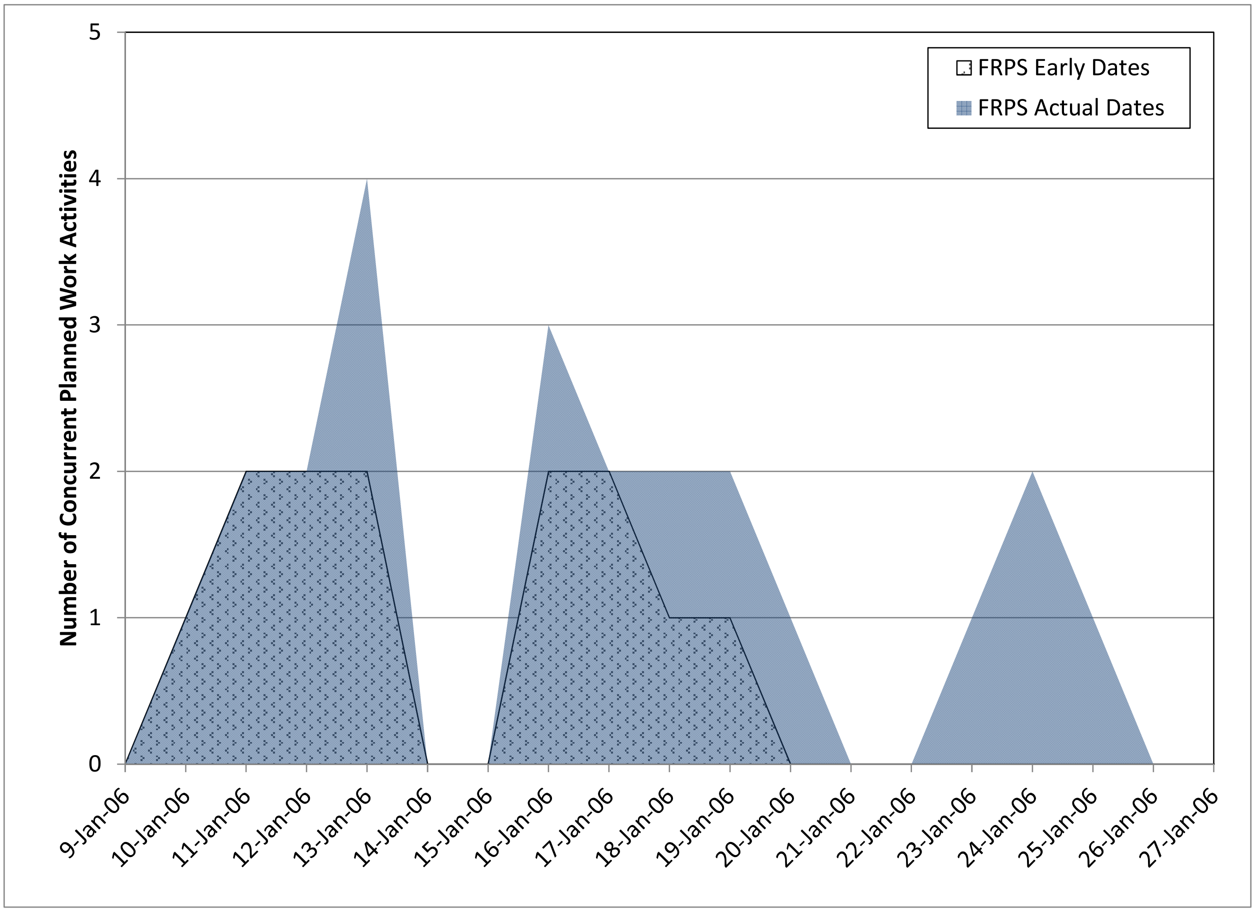


Figure 4-4 Plan v. Actual CDRs for FRPS Crew

The above simple, hypothetical examples demonstrate some basic principles related to the schedule activity distribution density, or rather, the number of planned work activities to occur simultaneously on any given day, which is directly related to the number of CDRs assigned to perform that work.

Schedule Density Histograms and Centroids

Utilizing the numeric data found beneath a Gantt chart such as that in **Figure 4-3** above, a histogram may be prepared. Plotting the number of CDR's for a single trade over time yields a histogram as shown in **Figure 4-5**Error! Reference source not found..

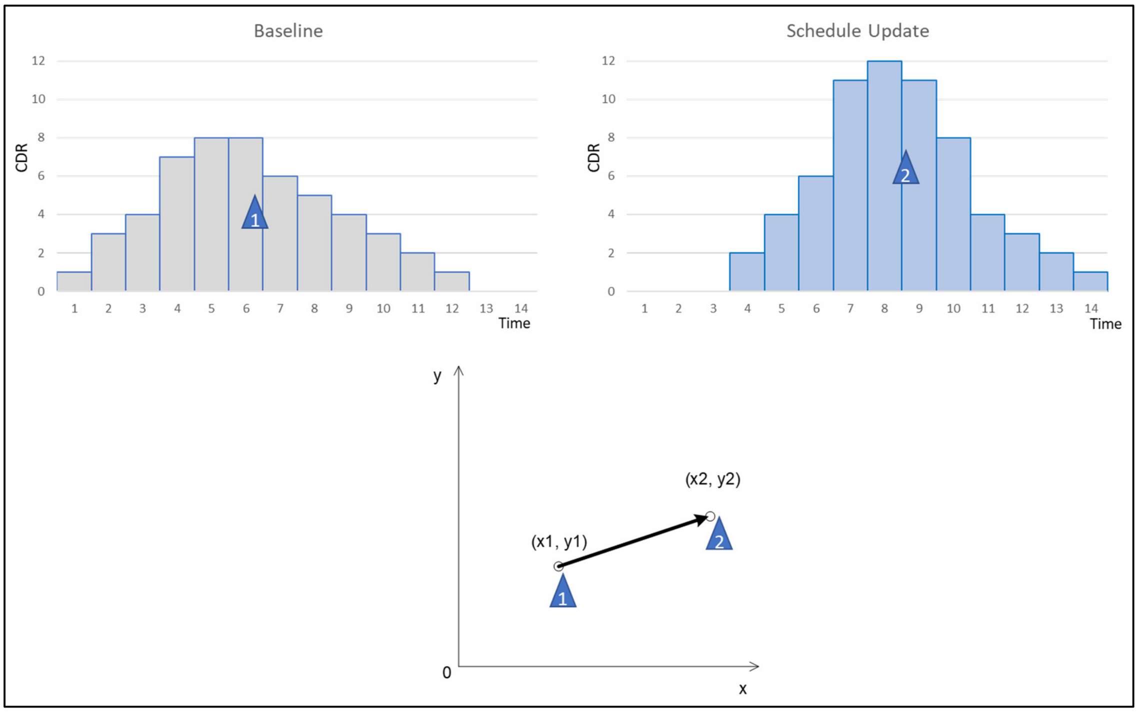


Figure 4-5 Example Schedule Density Histogram with Centroid

Treating the histogram as an area of homogenous material and utilizing the principle of center of mass, the centroid of the histogram can be calculated. According to Rufe, "A centroid is the geometric center of a line, area, or volume. When working with objects having a uniformly distributed mass, also known as being homogeneous, the center of mass and center of gravity coincide with the centroid (Rufe, 2013). The centroid is depicted by the triangle in the figure for a baseline schedule and for a successive schedule update.

For each schedule update, the schedule density histogram for any given trade may be generated and its respective centroid calculated. In the instance where in successive schedule updates, the centroid changes from one position to another, a simple geometric condition arises as shown in **Figure 4-6**. By connecting the 'dots' a vector results, whose scalar magnitude is calculated by Pythagorean Theorem. In this example, the centroids' x-component (time) increased in value, or rather, a delay occurred; and the centroids' y-component (CDR) also increased, or rather, greater trade stacking occurred.

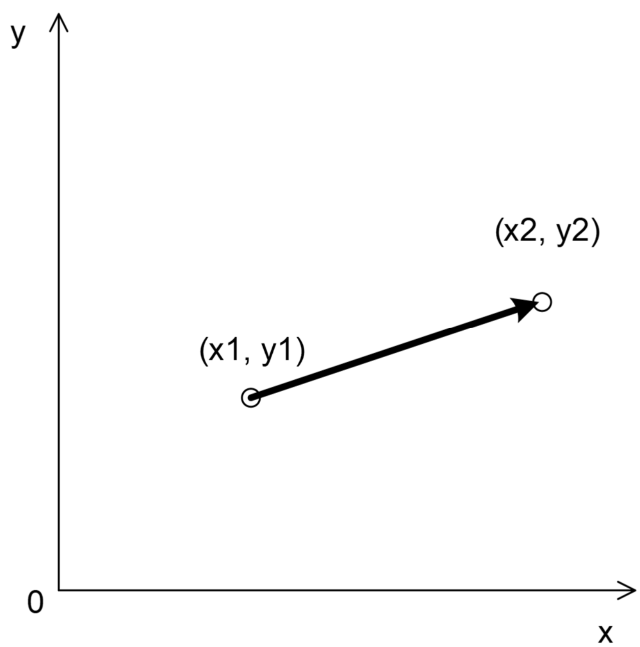


Figure 4-6 Resulting Vector by Comparing Two Centroids

Calculating the centroid for a given schedule density histogram follows basic engineering statics principles. Assume that in a given five-day time period, the schedule shows a single required CDR for each day as shown in **Figure 4-7**. These CDR's depict a simple distribution histogram of one planned CDR per day. The triangle's tip in the figure represents the origin (0,0) on a typical Cartesian coordinate system where the y-axis units are in CDR's and the x-axis units equal Days. Utilizing simple engineering statics principles of force and moments (i.e., a moment is defined as a force times a distance, or in this analogy, a unit CDR times a unit Day), assume that each CDR acts like a weight where gravity pulls downward on a horizontal beam at the end of each day as depicted by the downward pointing arrows in the figure. As presented, the downward forces of the CDR's would cause the static horizontal beam to fall unless there was a resulting equal, but opposing force to keep it the beam still, i.e., static or stationary.

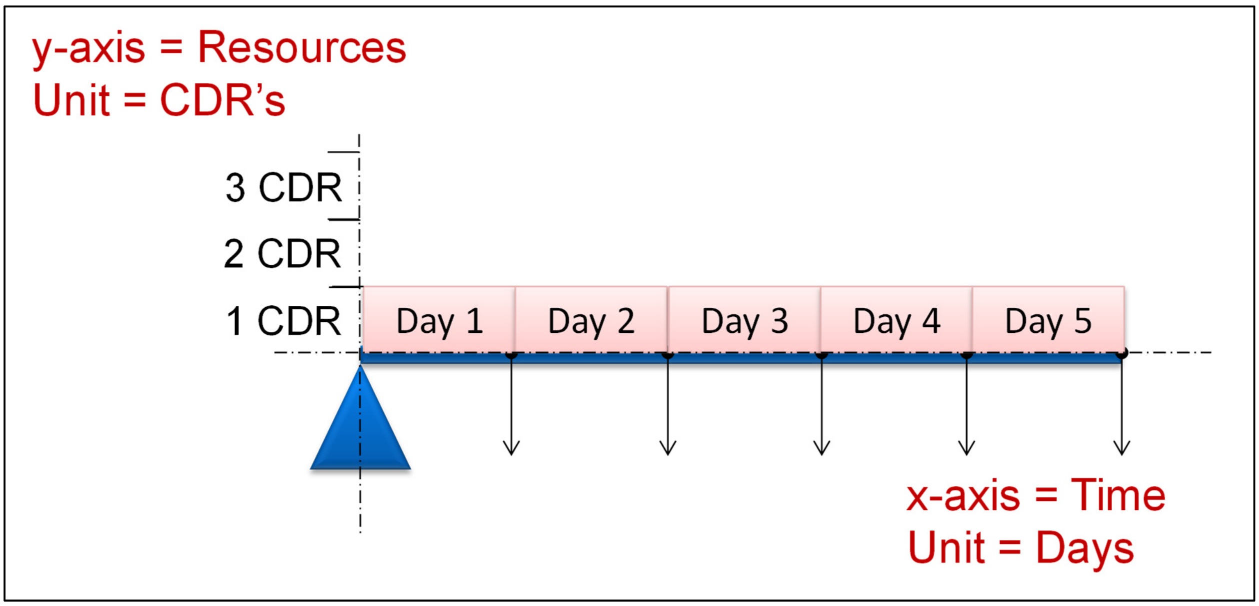


Figure 4-7 Simple CDR Distribution Histogram Showing One Planned CDR per Day

Figure 4-8 shows the simple calculations to determine the opposing force, F_y, (i.e., number of CDR's) and distance (i.e., number of days) to keep the model balanced. The result is a force of 5 CDR's 'pushing' opposite at a time 'distance' of 3.00 days.

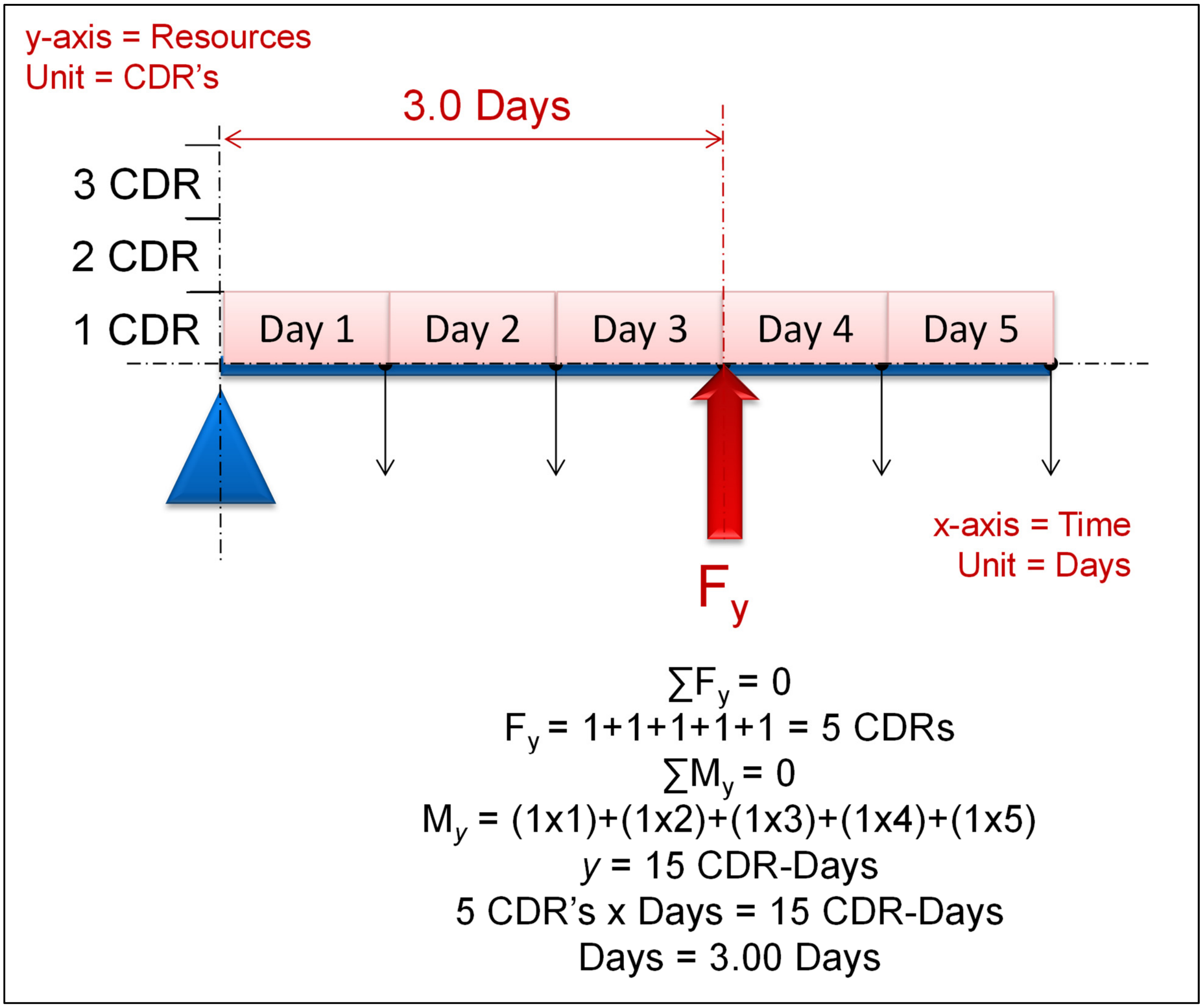


Figure 4-8 Calculated Resultant Force and Distance of Offset CDR's

Next, assume that for various reasons the planned schedule changed such that the CDR distribution histogram changed to that shown in **Figure 4-9**. Instead of a single CDR for each day, we now have stacked work activities that require three CDR's on Day 3 and two CDR's on Days 4 and 5. Again using simple engineering statics principles, a resulting force (CDR) and distance (Days) are calculated. Now the single resulting force is 9 CDR's at a time 'distance' of 3.33 days.

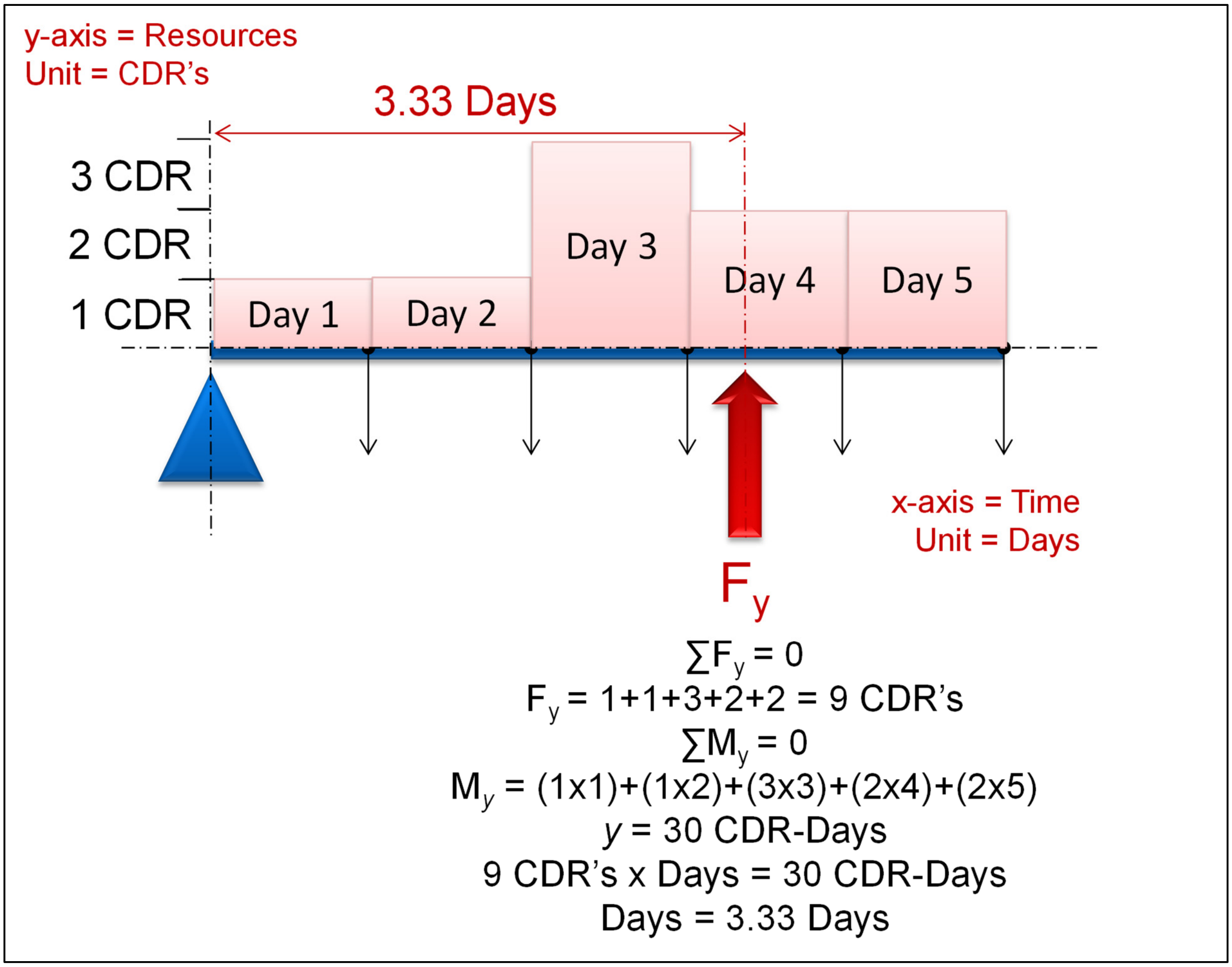


Figure 4-9 Changed Condition and Resulting CDR Distribution Histogram

Table 4-1 compares the initial and changed conditions for these two calculations. The 80% increase in the average number of CDR's per day warns the contractor of needed adjustments in crew resources to complete the work within the same planned five days. The 0.33 day increase in time represents a delay, or "drift," of the schedule, or rather serves as an indicator of a one-third day delay due to a shift in the required CDR's. In effect, with the end date fixed, this drift value quantifies time inefficiency that must be recovered via proper resource allocation within the original planned duration. This additional 0.33 day increase represents a shift in the x-component of the centroid for this schedule update. The change in the y-component of the centroid is the average CDR's for the five days, or rather, 9 CDR's divided by 5 days equals 1.8 CDR's per day. This value represents a 0.8 increase in CDR's when compared to the initial condition shown in **Figure 4-8**. Applying this approach to large CPM schedule networks may help to explain productivity losses and cost creep experienced by contractors.

Table 4-1 Comparison of Initial and Changed Condition

Variable	Initial	Changed	% Change
Ave. CDR's per Day	1.0	1.8	80%
Time	3.00 Days	3.33 Days	11%

Curve Fitting

The histograms created during a schedule density analysis can be used to identify fitted mathematical functions (Jacoby, 1997). Curve fitting, also referred to as goodness of fit, involves finding a mathematical function that captures the "overall behavior" of the data without being too sensitive to the errors. (Hansen, 2013, p. 3) Statistical tests can be performed to determine just how well the data fits the curve. Rayner cites David (1966, p. 399) who indicated, "A goodness of fit procedure is a statistical test of a hypothesis that the sampled population is distributed in a specific way . . . for example, that the sampled population is normal."(Rayner, 2009, p. 2) Use of software such as MatLab allows the user to see how different functions fit the data by iteration. ("MATLAB - MathWorks," n.d.) The resulting shapes, i.e., areas under the fitted curves, of the best fitting functions can then be used in the analysis. Common distribution functions include normal (common bell-shaped curve), skewed, bi-modal (double peaked), exponential and linear fits (Tague, 2005, pp. 296–299). **Figure 4-10**Error! Reference source not found. below demonstrates the general shapes of these fitted curves.

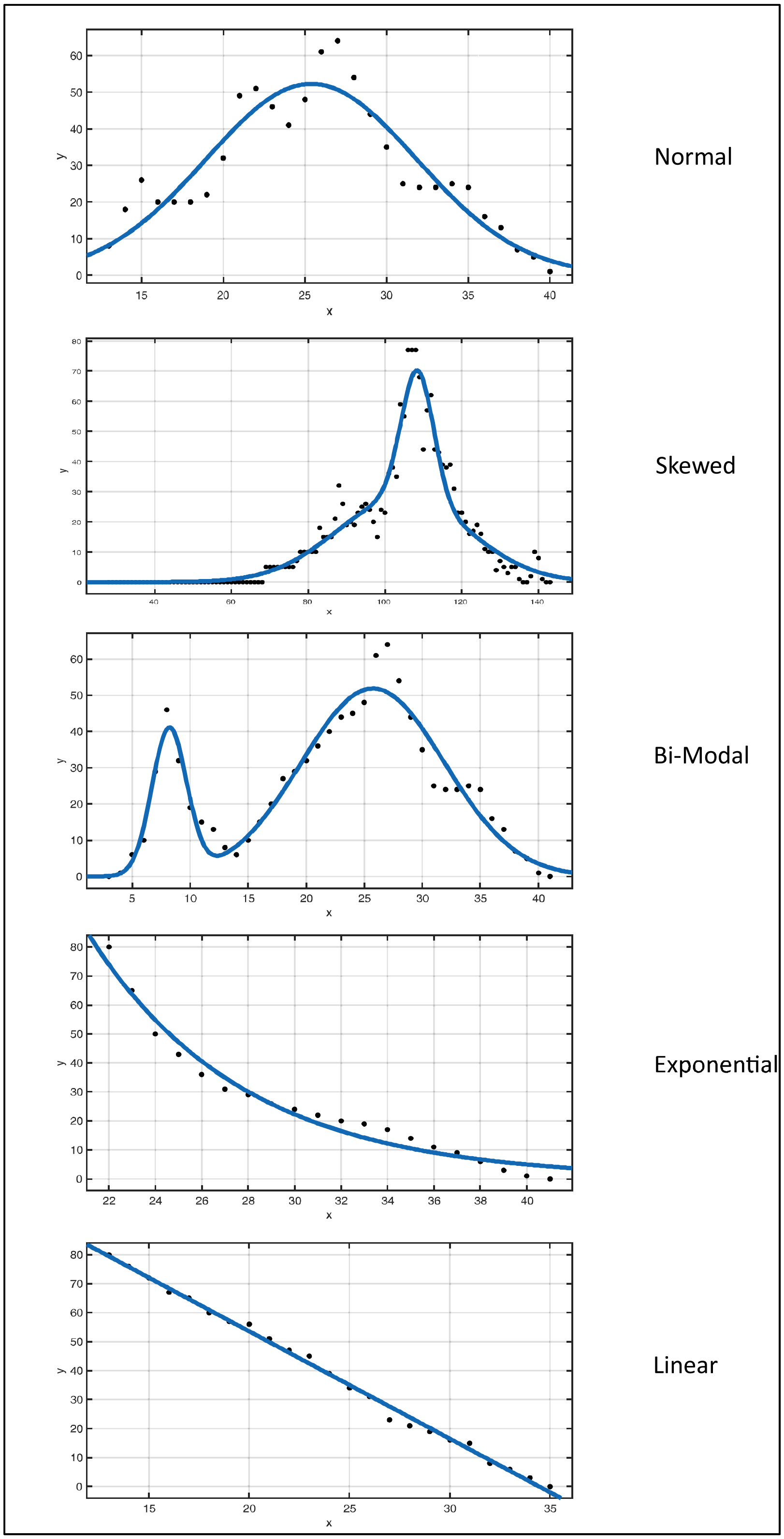


Figure 4-10 Example Best-Fitting Curve Types for Schedule Density Histograms

The generated curves provide additional data that can be evaluated. Measures are included below.

Area Under the Curve

The total area under the curve can be calculated. For each schedule update, changes in the calculated area can be measured and observed. Similarly, just the area under the curve for planned dates may be observed.

Shape of Curve

The shape of the curve may change from update to update. For example, the initial histogram may be shaped like a single mode normal distribution, whereas subsequent updates may have two modes such as the bi-modal image shown above.

Centroid

The centroid for the areas under the curve may change from update to update. These changes may correlate with measured changes in labor productivity.

Skewness

Skewness is a measure of the asymmetry of the data around the sample mean. If skewness is negative, the data are spread out more to the left of the mean than to the right. If skewness is positive, the data are spread out more to the right. The skewness of the normal distribution (or any perfectly symmetric distribution) is zero. The formula for skewness follows.

$$Skewness = \frac{\sum \left(\frac{x - \bar{x}}{\sigma}\right)^3}{n}$$

Kurtosis

Kurtosis is a measure of the combined weight of the tails in relation to the rest of the distribution. As the tails of a distribution become heavier, the kurtosis value will increase. As the tails become lighter the kurtosis value will decrease. A histogram with a normal distribution has a kurtosis of 0. If the distribution is peaked (tall and skinny), it will have a kurtosis greater than 0 and is said to be leptokurtic. If the distribution is flat, it will have a kurtosis value less than zero and is said to be platykurtic. The formula for kurtosis follows.

$$Kurtosis = \frac{\sum\left(\frac{x-\bar{x}}{\sigma}\right)^4}{n} - 3$$

Kurtosis measures the degree to which a distribution is outlier-prone. The kurtosis of the normal distribution is 3. Distributions that are more outlier-prone (tall and skinny) “leptokurtic” than the normal distribution have kurtosis values greater than 3. Distributions that are less outlier-prone have kurtosis less than 3 (wider and flatter) “platykurtic.” The kurtosis of a distribution is defined as where μ is the mean of x, σ is the standard deviation of x, and E(t) represents the expected value of the quantity t.

Use of fitted models may introduce other variables to consider in the analysis that are heretofore unmentioned. For example, research in Brazil in modeling its crude oil offshore post-salt production sought to predict future production for long-term energy planning and policy making. They found that fitted results caused them to consider other variables in their model. (Nogueira Hallack, Salem Szklo, Olímpio Pereira Júnior, & Schmidt, 2017) Similarly, fitting curves in this research may reveal other variables to consider.

Interpretation of Resultant Vectors

Interpretation of a vector between successive centroids is shown graphically in **Figure 0-11**. Concentric rings have been provided on a four-quadrant cartesian plot to serve as a gauge of the relative level of influence of the observed scalar value on the time and CDR variables.

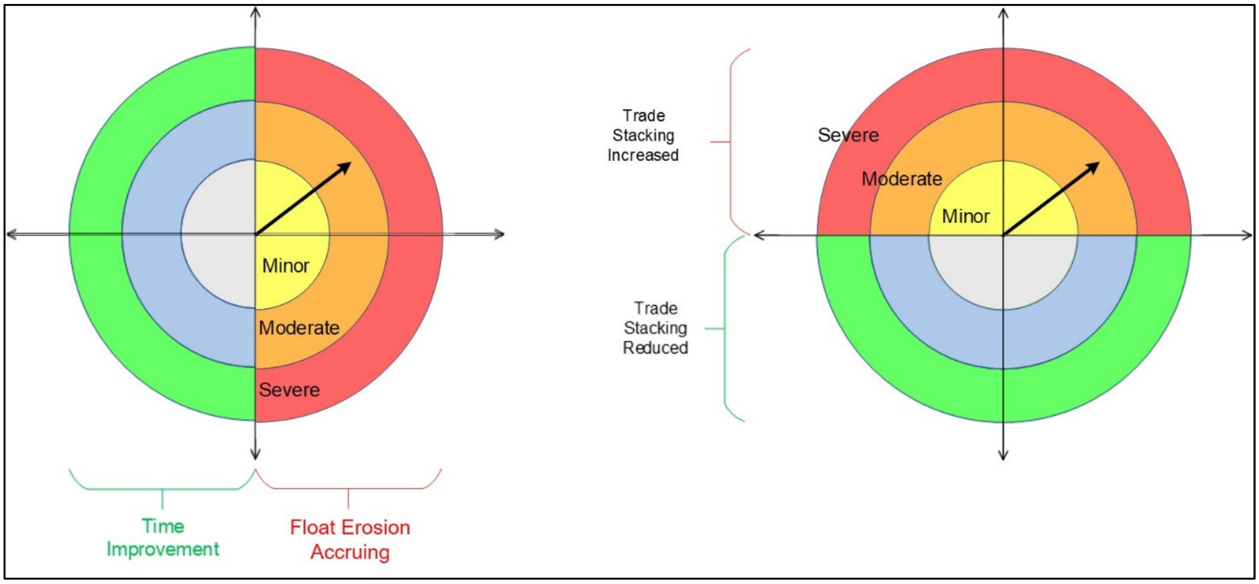


Figure 0-11 Interpretation of a Resultant Vector Between Two Centroids

a. A vector with a positive x-value indicates a centroid shift in the x-coordinate to the right, or rather, shows float erosion to the project. Conceptually, if a contractor performed exactly as planned from one schedule update to the next, the x-coordinate of the centroid would remain unchanged. In this scenario, there would be no vector, just an exact overlap of the two centroids. However, when planned dates are not achieved, a shift in successive centroids occurs.

b. A shift in the x-coordinate to the left, less the previous evaluation period's duration, indicates gained time to the project, and generates a vector with a negative x-value. In effect, gained time results from a contractor's planned performance of the work in less time than planned. Various reasons exist to explain gained time including but not limited to acceleration, reduced work scope, schedule modifications, and better productivity than planned.

c. A shift in the y-coordinate upward indicates greater number of planned work activities to occur in the same time period, or rather, an increase in the schedule's density for that time period. The resulting vector has a positive y-value indicating greater overlapping of trades.
d. A shift in the y-coordinate downward indicates fewer number of planned work activities to occur in the same time period, or rather, a decrease in the schedule's density for that time period.

The scalar values of each resulting vector are then summed cumulatively and used in the analysis. In effect, each vector was joined tail-to-tip with its successive vector and the resulting cumulative totals were plotted (see **Figure 4-12**).

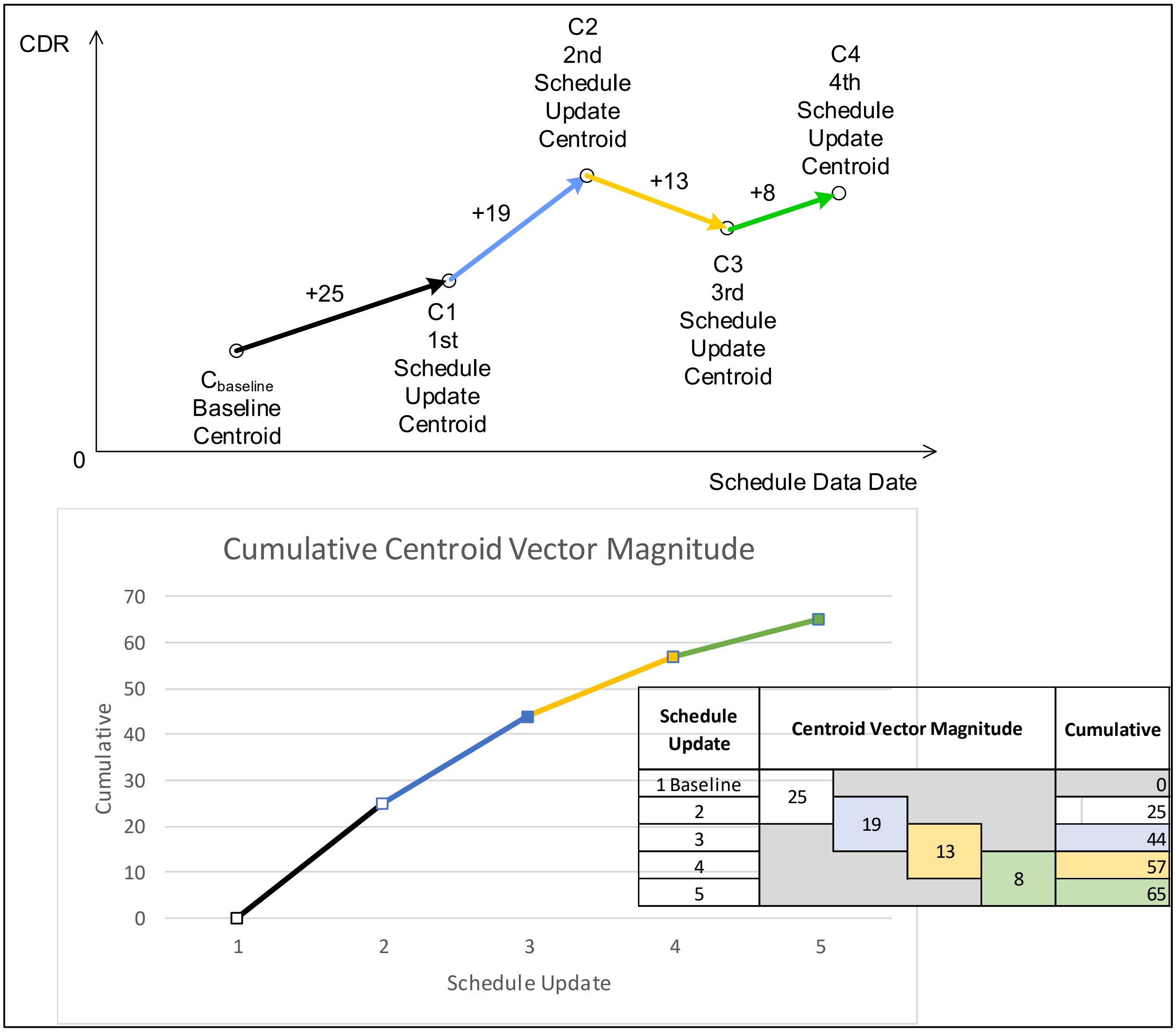


Figure 4-12 Generating the Cumulative Centroid Vector Magnitude Curve

Independent and Dependent Variables

Using the concepts presented above, the following variables are viable and were evaluated in this study:

1. Schedule Density Area – Calculated as the area of the histogram created by the schedule's planned dates. This area has units of time (days) x CDR's. Much like units of a static moment calculation is in foot-pounds and applies for those calculations only, this

time-CDR measurement only has application for this analysis. The area can be quantified for the histogram to the left or right of the status date of the schedule (also referred to by P6 as the "data date"), or for the entire histogram. Areas to the left of the schedule's data date reflect actual dates of work performed, whereas those areas to the right of the data date represent the planned unfinished work activities.

2. Areas for Fitted Curve Functions of Schedule Density – Each histogram generated by the time-CDR data can be fitted with a mathematical function. Use of a function in lieu of using the density areas specifically provides additional benefits for analysis, including,
    a. Visual representation of the histogram with curves instead of rectangular spikes allows greater ease in observing changes from schedule update to update;
    b. Mathematical calculation of multiple modes, commonly referred to as "humps" or "peaks," to provide demonstrative comparison of the shapes of data;
    c. Statistical calculation of best fitting curves using method of the sum of squares and R-square values within chosen confidence intervals, which may more easily be transferred and applied to other projects; and
    d. Integration of the function to determine calculated areas to the left or right of the data date for comparative purposes.
3. Change in Centroid (x,y) Coordinates – For each schedule update, an x-coordinate and a y-coordinate of the histogram's centroid can be calculated. The centroid concept applies to the schedule density histogram. The x-coordinate reflects the time resultant for the histogram centroid coordinate value. The y-coordinate represents the average CDR coordinate for the histogram. A centroid may be calculated for the area under the best fitting function too. A single (x,y) coordinate centroid point provides insufficient

information to be useful, however, a comparison of two centroid points allows comparison of how the centroid changed from one update to the next.

a. The cumulative change in the Δx coordinate allows for analysis of the x-coordinate as an independent variable

b. The cumulative change in the Δy coordinate allows for analysis of the y-coordinate as an independent variable

4. Centroid Scalar Vectors – Using analytical algebra, the distance between two coordinate points in a cartesian plane can be represented as a linear vector with a magnitude (length) and direction (angle value in degrees). This same principle can be applied to the centroid (x,y) points calculated in each schedule update. Tracking the magnitude and directions for each vector in succession creates a path in the x-y plane that allows for visual observation of trends. The points for each path can also be represented by mathematical functions, which can be compared statistically to functions of other variables.

5. Labor Hours per Percent Complete – For a given trade on a construction project, a comparative quantum value of labor hours per percent complete (LHPC) can be quantified. This measure is accepted in the construction and forensics industries to demonstrate productivity comparisons for like-trade work. This measure considers the sum total number of labor hours expended to complete one-percent of the overall work scope for that trade. In general, lower LHPC values are favorable to higher values because LHPC is a measure of a contractor's labor productivity. The cumulative trend of LHPC for successive schedule updates allows for observation of how the contractor's labor productivity changes over time.

Several independent variables will be considered. For example, one independent variable to be considered is the delta measurement of a CPM schedule's density measure (in units of CDR's) between its initial state, n, to its updated state, (n+1):

$$CDR_{n+1} - CDR_n = CDR_\Delta$$

Because it is impossible to control perfectly for other variables that are extraneous to this study, this independent variable is classified as an attribute independent variable (Gliner, 2000, p. 49 -50). Direct causal relationships cannot be determined with attribute independent variables, only correlative relationships (Gliner, 2000, p. 63 - 64). This independent variable is continuous, however, the CDR_Δ values will be categorized both individually and in different groups based upon ranges of values measured. For example, two different categories may include high and low values – each grouping representing a group with a similar range of values.

There are two primary dependent variables. The first relates to productivity and the second to critical delay. Both of these variables are presented below.

Dependent Variable – Labor Productivity

The labor productivity variable is defined as the delta measurement of a contractor's field experienced labor productivity (LP) relative to each CPM schedule:

$$LP_{n+1} - LP_n = LP_\Delta$$

The LP_Δ dependent variable is also continuous and will be analyzed both as an individual variable and, depending upon interim correlation results, grouped into low and high values, similarly as with the independent CDR_Δ variable. Where evaluated as individual values, regression analysis is applicable.

The LP values will be calculated using the contractors' actual field records that will allow understanding of the units produced (output) given the number of labor hours expended (input).

The calculations are simple provided the data exists, is available and of relatively good quality. Getting the data, however, can be very difficult, therefore, this study uses data from large construction projects where good data exists to perform a test study.

Acquiring data is difficult, therefore, this study uses available data to perform a test study from four different projects where data was available. Determining causes for productivity losses is likewise difficult. In forensics claims on construction projects, reliance is placed on the contemporaneous project records to establish ‘cause and effect’ relationships for productivity losses. Sometimes, the contemporaneous records fail to provide sufficient detail to draw any concrete conclusions, and often the witness testimony of project field personnel is sketchy. These same challenges may surface in performing this study.

Dependent Variable – Critical Delay

The second continuous dependent variable is the measured critical delay to project Substantial Completion (SC) according to the CPM schedules from its initial state, n, to its updated state, (n+1):

$$SC_{n+1} - SC_n = SC_\Delta = Critical\ Delay$$

Critical delay is measured directly from the construction schedules being analyzed. Provided the schedules are based upon reliable data, no subjectivity exists when quantifying critical delay. Given the dynamic nature of construction projects, schedulers routinely make schedule modifications when updating schedules, particularly when critical delay is experienced. These modifications can have an accelerating effect on the schedule, and therefore, influence the amount of critical delay actually realized. For example, if 10 days of critical delay occurred in a month, at the end of that month the scheduler makes schedule modifications that compress planned future work that is on the longest path that reduces the overall longest path by six days.

The net resulting critical delay is just four days, not the 10 days actually experienced. Thus, evaluating critical delay is not as simple as tracking the forecasted substantial completion date in a CPM schedule from update to update.

Comparing the schedule density relationship with critical delay effectively doubles the scope of this study, which is not be possible given time and monetary constraints. It is listed here as a placeholder for possible expansion beyond just evaluating labor productivity.

Because of varying degrees of detail provided in CPM schedules by different contractors, there are some variables that need control. First, only CDR values taken from schedules with similar levels of detail must be compared. Projects of similar type and trades within those schedules must also be considered. For example, comparisons of electricians performing work on a power plant versus carpenters framing a residential home are not useful. An appropriate comparison would include electricians working on two different building projects of relatively similar size.

For this research, deductive inferences must be supplemented with logical reasoning to address the three possible states of claimed causal results as being either 1) necessary, 2) sufficient, or 3) both necessary and sufficient. For example, a positive correlation was discovered between schedule density and reduced labor productivity for mechanical HVAC work. Neither the schedule itself nor the parameters drawn from it serve as cause(s) for the observed labor productivity losses. The cause(s) reside somewhere in the life world with actual laborers on the jobsite. Whereas the schedule is a project management tool intended to assist the contractor in performing the work efficiently and should be updated periodically to reflect changes and progress, it follows that the schedules would reflect conditions such as sufficient progress, or lack thereof, made in the field. The schedules alone cannot adequately explain the productivity loss despite the positive correlation. Further investigation therefore is mandatory to establish the most likely and probable causes.

Correlation Matrix

Searching for correlation between independent and dependent variables requires iterative and exhaustive evaluation. Utilizing the variables mentioned above, a comparative matrix (see **Figure 4-13**) was prepared for each of the projects evaluated wherein relationships for each of the variables were compared to another and best-fitting curves were created. Whereas all variables except the manhours per percent complete were generated from the schedule data, it follows that strong correlations exist between the schedule data generated variables. To verify this assumption, regression techniques were utilized and summarized in a correlation matrix.

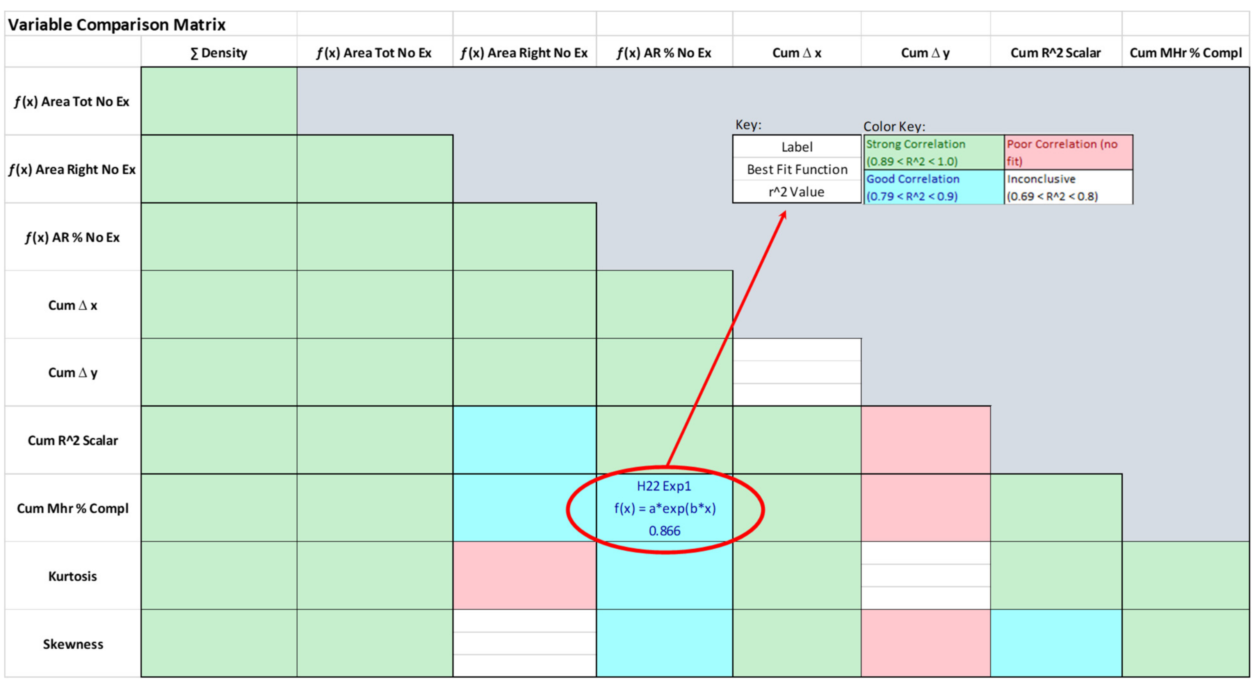


Figure 4-13 Example Variables Correlation Matrix

The correlation matrix compares two variables as indicated by the row header and column header. For each correlation, three primary pieces of information are given in the corresponding cell including:

1. A label with an index number and brief description of the best-fitting equation,
2. The standard form of the best-fitting function, and
3. The r-square value of the fit.

Each cell is then color coded based upon the r-square (r^2) value and defined as follows:

- Green: Strong Correlation ($0.89 < r^2 < 1.0$)
- Blue: Good Correlation ($0.79 < r^2 < 0.90$)
- White: Inconclusive ($0.69 < r^2 < 0.80$)
- Red: Poor Correlation / No Fit ($r^2 < 0.70$)

The completed correlation matrixes for each of the evaluation projects is presented in **Exhibit 4**. As explained in that chapter, the final best-fitting curves were not merely accepted based on mathematical calculations. Reasonableness and calibration with prior research on labor productivity were applied which resulted in selecting a good fitting curve, but not necessarily the best-fitting curve. Still, results confirm a strong correlation between variables.

Variations Considered

This section describes several different variations of the analysis that were performed with intent of finding a correlation between the variables being considered. Each variation considered is described below.

Option 1 – Homogenous Data Approach, Planned and Actual Dates Included

The first option considered all data to be homogenous throughout the entire evaluation time period. This means that as work progressed and some activities were completed and then recorded as actual dates, instead of planned dates, the data points were treated as if all were planned dates. **Figure 4-14** shows the schedule density histogram for electrical work on a condominium high rise project. The corresponding best fitting curve for this histogram is shown in **Figure 4-15**.

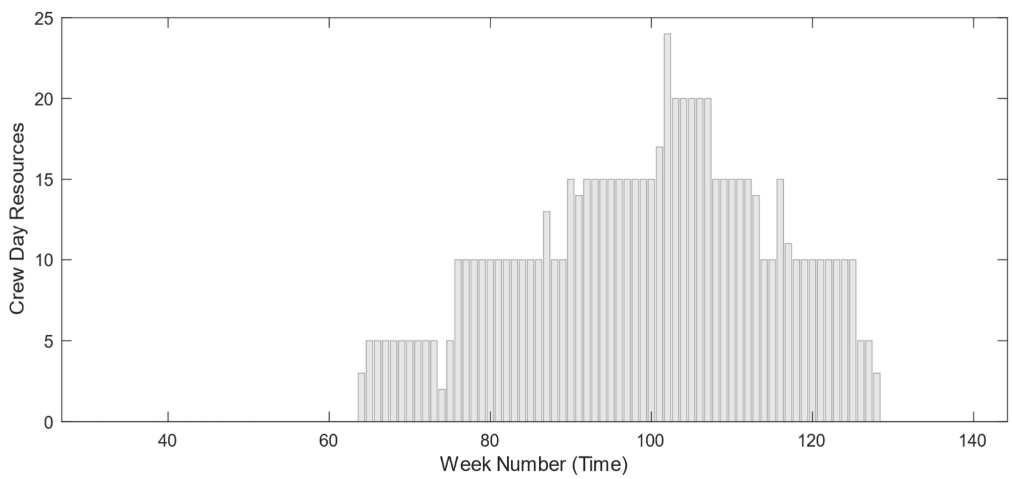


Figure 4-14 CDR Histogram for Electrical Work on Condo High Rise Project

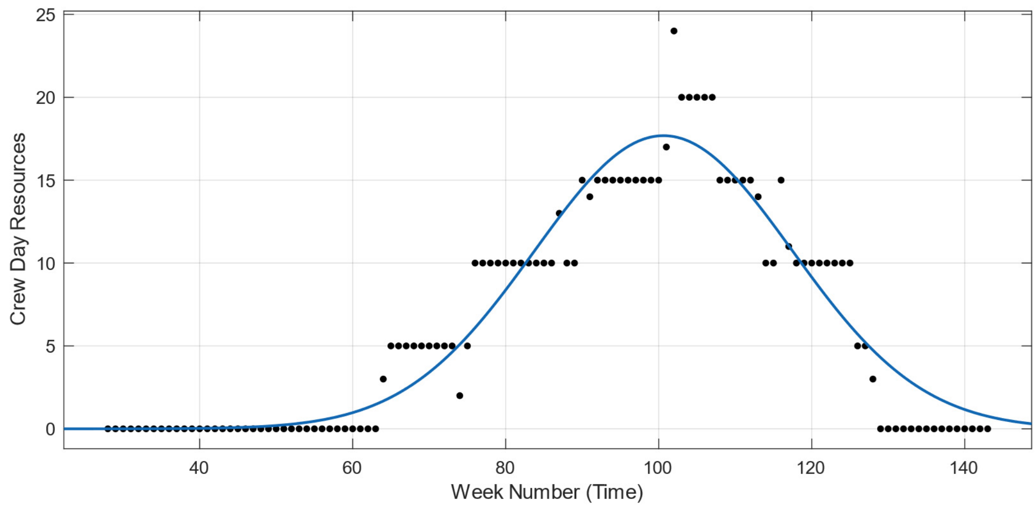


Figure 4-15 Best Fitting Curve for CDR Histogram for Electrical Work on Condo High Rise Project

Because this is the baseline schedule, it represents the planned use of electrical trade workers to complete that work. If work progresses exactly as planned, the histogram and curve remain unchanged throughout the duration of the project.

If the work does not progress as planned, however, and the histogram and its corresponding best fit curve will change with each schedule update. **Figure 4-16** shows the actual CDR's realized (to the left of the data date Week Number 112) and the planned required CDR's going forward. The best fitting curve for this histogram looks dramatically different from the original bell-shaped curve as shown in **Figure 4-17**.

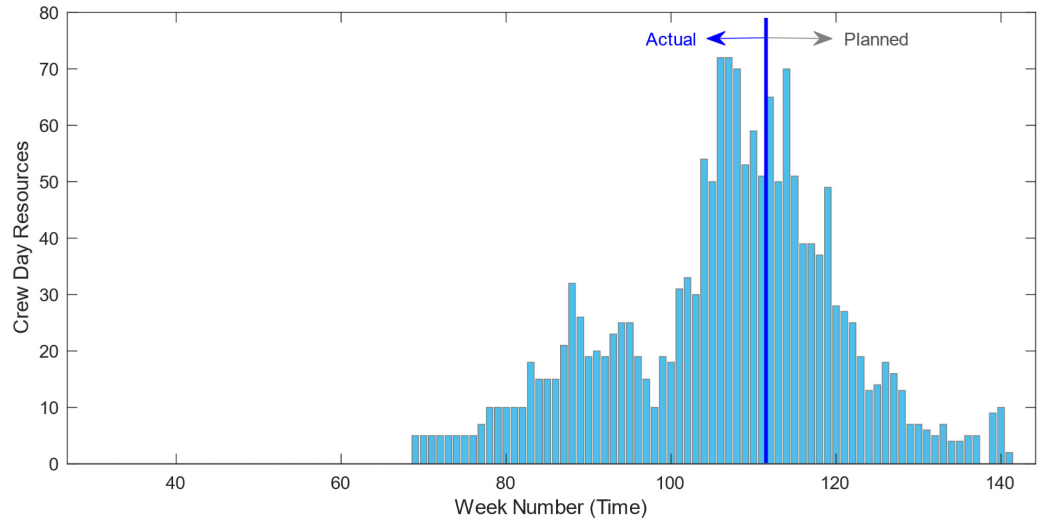


Figure 4-16 CDR Histogram with Data Date at Week No. 112

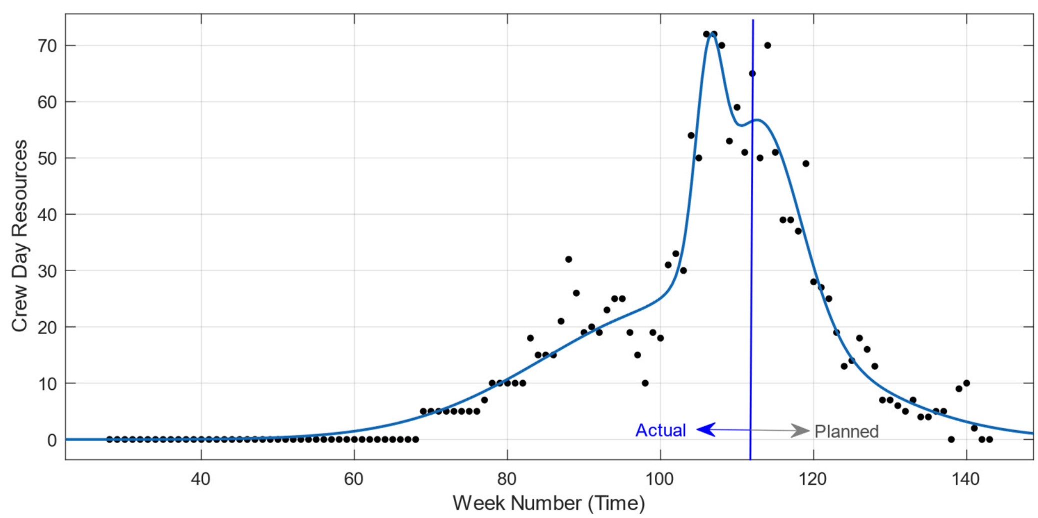


Figure 4-17 CDR Best-Fitting Curve with Data Date at Week No. 112

Because contractors frequently experience differences between its planned original work plan and its actual performance, an argument exists to treat the actual and planned data homogenously, which Option 1 does. Additionally, the contractor's past performance will certainly influence its ability to perform future work and Option 1 presumes this to be true. Each of the variables included in this study were evaluated under the Option 1 scenario.

Option 2 – Planned Dates Only

Option 2 evaluated just planned work going forward and excludes actual performance data. Rationale for this option stems from the original concept that if a contractor performs according to its plan, then the planned condition will not change with each schedule update. If the contractor fails to perform according to plan, however, then certainly the planned data will change from update to update.

From **Figure 4-15** above, the electrical work was originally planned to complete at about Week Number 127. In **Figure 4-16**, however, we see that as of a schedule update at Week Number 112, the planned completion has been pushed out to Week Number 141. Thus, there appears to be a forecasted 14-week delay to electrical work completion which is a clear indication of a changed planned condition with respect to the original baseline schedule. When evaluating the schedules, as the work nears completion, the number of planned activities diminishes and likewise, the number of data points to evaluate in this analysis gets smaller. When performing the analysis using just the planned dates, i.e., data to the right side of the data date, because of this diminishing data, evaluation became meaningless when fewer than six data points remained. For this reason, utilizing this Option 2 approach was abandoned.

Use of Early Dates

The schedule densities were evaluated with respect to the early dates in the CPM schedule. An activity may have float and use of the early dates accounts for the float. In the author's experience, contractors and owners alike work to the early dates. Results of the Delphi Study in Chapter 7 confirms the author's experience.

Use of Late Dates

The schedule densities were also evaluated with respect to the late dates in the CPM schedule. Using the late dates means that every activity included in the density measure has no float. In some instances where the finish milestone was constrained, the late dates in the schedule preceded the early dates, which made no sense because obviously the contractor would not be able to meet late dates with large negative float values. Because of the large differences between early and late dates with the sample projects evaluated and finding no useful correlations using the late dates, further evaluation of the late dates was abandoned.

5 Technique Applied Step by Step

This chapter presents a detailed application of the application technique mentioned in the prior chapter. The intent is to provide a "cook book" approach whereby others may reproduce the results and apply it to their own projects. The technique is demonstrated by applying it to the high rise hotel project mentioned in Chapter 1.

Selection of this project and the others for this research stemmed in part from an initial screening of the criteria shown in **Figure 5-4**. Acquiring usable data for each project proved challenging. Contractors generally tend to construct well, but are not as adept at comprehensive record keeping. Scores of projects were considered, but only the five utilized herein were selected based upon available and useable CPM schedules, labor productivity, and trade progress data.

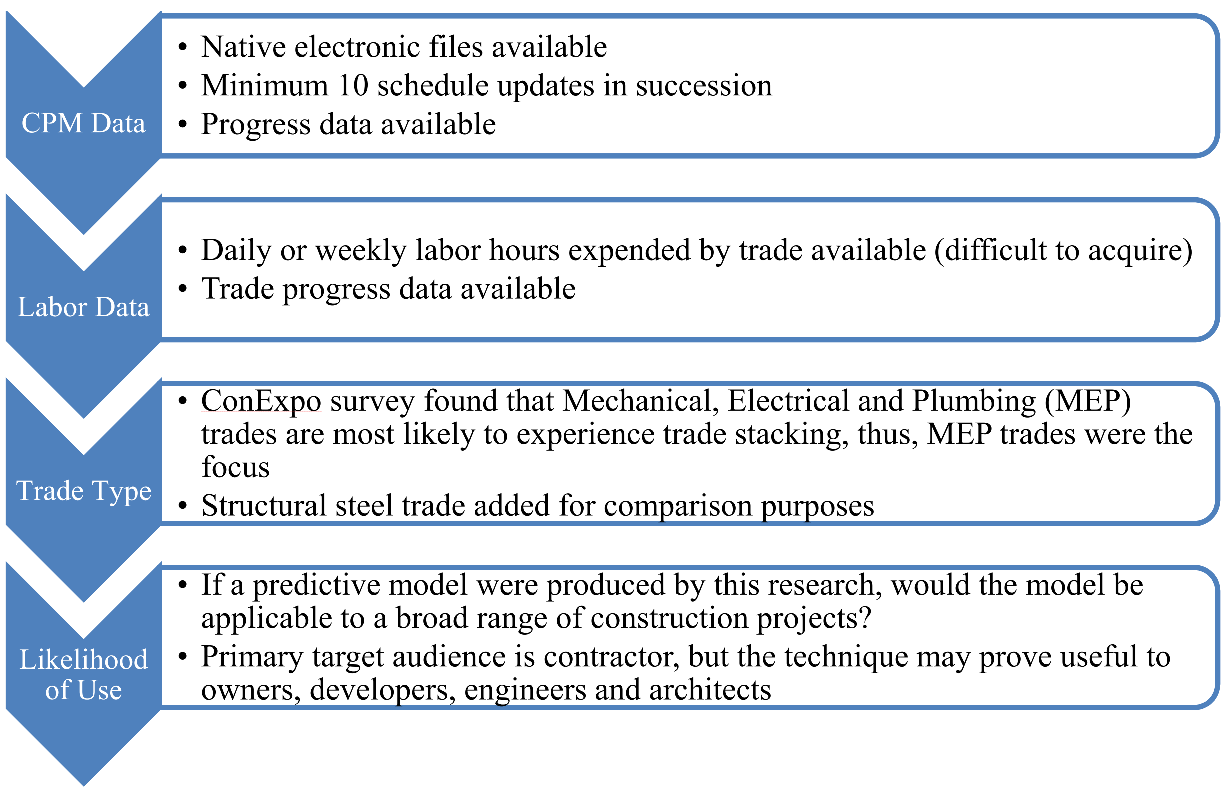


Figure 0-1 Selection Criteria for Project Selection

Because of the proprietary nature of data being utilized, specific names of contractors and the respective projects are withheld. Instead, general information is provided – enough to give the reader a clear understanding of the scope of work. The projects analyzed include:

1. High Rise Hotel (20-stories with three levels of underground parking)
2. Condominium Towers (two 26-story buildings that are alike each with three levels of underground parking)
3. Large Bore Piping on a Combined Cycle Power Plant
4. Steel Structure (used as a cover for maritime maintenance of ships)
5. Resort Hotel (7-stories with one level of underground parking)

Application of the technique for the high rise hotel project is described in detail in this Chapter 5. Chapter 6 presents results of the other projects except that the Resort Hotel project was used for empirical validation of findings generated from results of the other four projects.

High Rise Hotel

The first project considered mechanical trade work on a 20-story high rise hotel in Washington state (see **Figure 5-2**). The contract followed the American Institute of Architect's Document A133, "Guaranteed Maximum Price Amendment." The guaranteed maximum price was not to exceed $60 million. The hotel includes about 400 guest suites, multiple meeting and conference rooms, two ballrooms, two prefunction areas, underground parking, an indoor pool, a restaurant and lounge, and a self-contained housekeeping function. Construction work was to complete within an established contract time of 19 months.

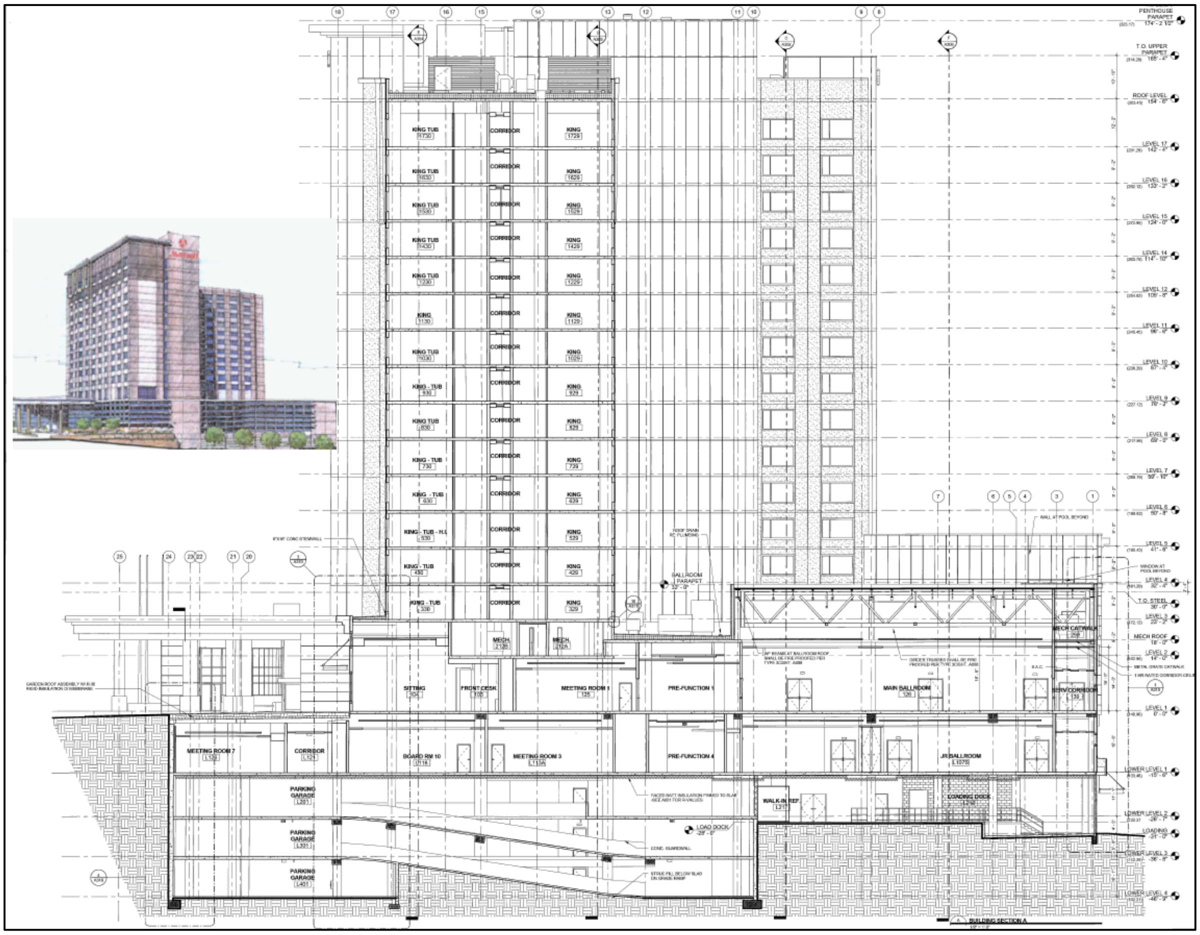


Figure 5-2 High Rise Hotel Sample Project

The project experienced delays due to several factors including design changes, time required to acquire approvals, modifications to permits, restricted spatial logistical issues in working within a downtown area, and alleged subcontractor productivity delays. Collectively, these issues created a stacked MEP trade condition. No time extensions were granted during the project.

The contractor was responsible for preparing the CPM schedule and all schedule updates. In total, including its baseline schedule, the contractor prepared 47 schedule updates over a 26-month total project duration. On average, the schedule contained approximately 3500 activities and contained no resource loading. For this sample project, 18 schedules (issued almost monthly from the seventh month to completion) were evaluated, spanning 27 months.

Specific Steps in Performing the Technique

Figure 0-3 presents a flowchart that shows the summary steps in applying the technique. Detailed explanation for these steps follows below.

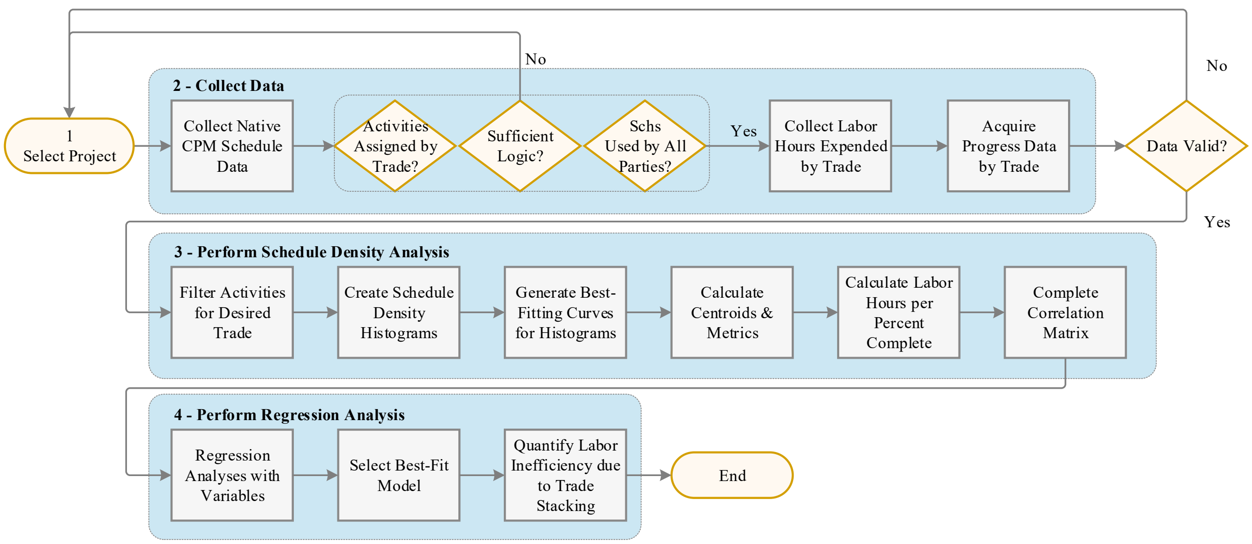


Figure 0-3 Summary Flow Chart for Technique Application

Select Project

The first step was to choose a potential project to analyze. The general criteria for selection was presented earlier in **Figure 0-1**.

Collect Data

Collecting the necessary data to perform the analysis is next. Electronic data was preferred, but not necessary. Specifically, the following data was collected:

- *Executed contract and related specifications* – In every project, CPM scheduling was required by specification, including submittal of monthly schedule updates to the owner.

- *Native electronic CPM schedules* – CPM schedules can contain a significant amount of information, and therefore, become large data sets to manage. Acquiring electronic data saved time in preventing to re-enter data and eliminated likelihood of human error in transcription. Oracle's P6 software files were used for the High Rise Hotel project. Hardcopies of the project schedules are provided in **Appendix 5A**. Once the files were received, the schedules were checked as follows:
    1. Verify activities are distinguishable or assigned by trade. In this instance, mechanical and plumbing trades were sought.
    2. Verify sufficient logic exists to be able to identify a critical path and float. Because the analysis is performed on early and late dates from the schedule, the logic must be sufficiently constructed to allow the software to calculate the early and late dates for each activity.
    3. Verify the schedule was recognized by both the owner and contractor as being used to manage the field work. If a predictive model is to be prepared, it follows that the parties must each recognize the 'official' schedule being utilized by the contractor to manage the work.
- *Labor hours expended by trade* – The analysis compares the productivity actually achieved by the trade in question. Productivity measures were calculated at similar intervals as the schedule updates. Source of this data included daily and/or weekly timesheets for the workers.
- *Progress data* – In order to estimate the percent of work completed by a given trade for each month, monthly progress reports and other contemporaneous project records were used. Productivity was measured in units "labor hours per percent complete," or rather, a

calculation was made to find how many labor hours (on average) were actually expended by the subcontractor to achieve one percent of its work scope for that month.

Perform Schedule Density Analysis

For the trade in question and beginning with the baseline schedule and all subsequent schedule updates, schedule density histograms were generated. First, using the native electronic file and from within P6 software, prepare a filter that selects only those activities for the desired trade from the CPM schedule. Work activities optimally should be as homogenous as possible and filtering by a specific trade facilitates this similarity. Using the filter capabilities of P6, activities related to mechanical and plumbing trades were identified as provided in **Appendix 5B**. Specific data required as extracted from the native P6 schedule included the Activity ID, Activity Name / Description, Original Duration (in work days), Calendar ID, Early Start, Early Finish, Late Start, and Late Finish. Next, copy the filtered data from P6 to a spreadsheet software, such as Microsoft Excel. Using the early dates only, calculate the number of CDR's per work day for the entire filtered set of data. Use of the spreadsheet software eases the process. Because the process is repetitive when using many different data sets for each schedule update, the author derived macro applications using Visual Basic to save time when processing the data within Excel.

Once the sum of CDR's is calculated per work day, group the daily totals into weekly totals. Based upon the author's experience, data received and results of this analysis, findings show that using weekly tallies align best with typically available labor data, which can then be summarize with monthly updates and pay applications. Use of daily CDR's proved to be too microscopic given the weekly summarized data availability.

Using the weekly summed CDR values, create a histogram of the data for each schedule. For this High Rise Hotel project, a histogram of the baseline schedule is shown in **Figure 5-4**. The histogram can be created using the chart features of Excel, or other software such as a MatLAB. **Appendix 5C** contains data for all of the schedule density histograms for the High Rise Hotel project.

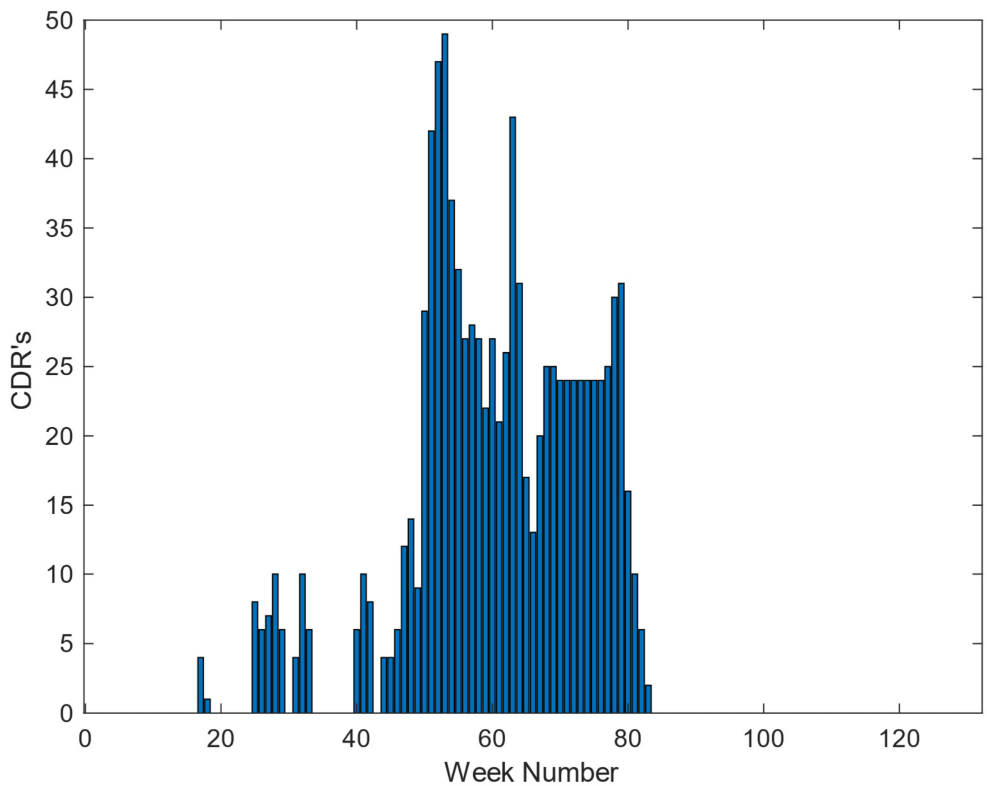


Figure 5-4 Hotel Baseline Schedule CDR Histogram for Mechanical Trade Work (Data Date at Week 0)

From the points that define the histogram, the best-fitting curve for these points was then generated. MatLAB software was used to find the best fitting mathematical function for each histogram using the Curve Fitting application. **Figure 5-5**Error! Reference source not found. shows the best fitting curve for the hotel's baseline schedule histogram presented in **Figure 5-4**.

Instead of columns, however, **Figure 5-5** displays the max weekly CDR value as a single point – one point for every week – instead of displaying it as a column as presented in **Figure 5-4**. Selection of the best fitting curve was made based upon goodness of fit using estimation using least squares regression (Chatterjee, 2013) within MatLAB software. The difference between an observed value and the fitted value is referred to as the residual amount. The smaller the sum of the residual values, the better the fit. This measure coupled with an R-square value that is closer to 1.0 identified the best fitting function for each histogram.

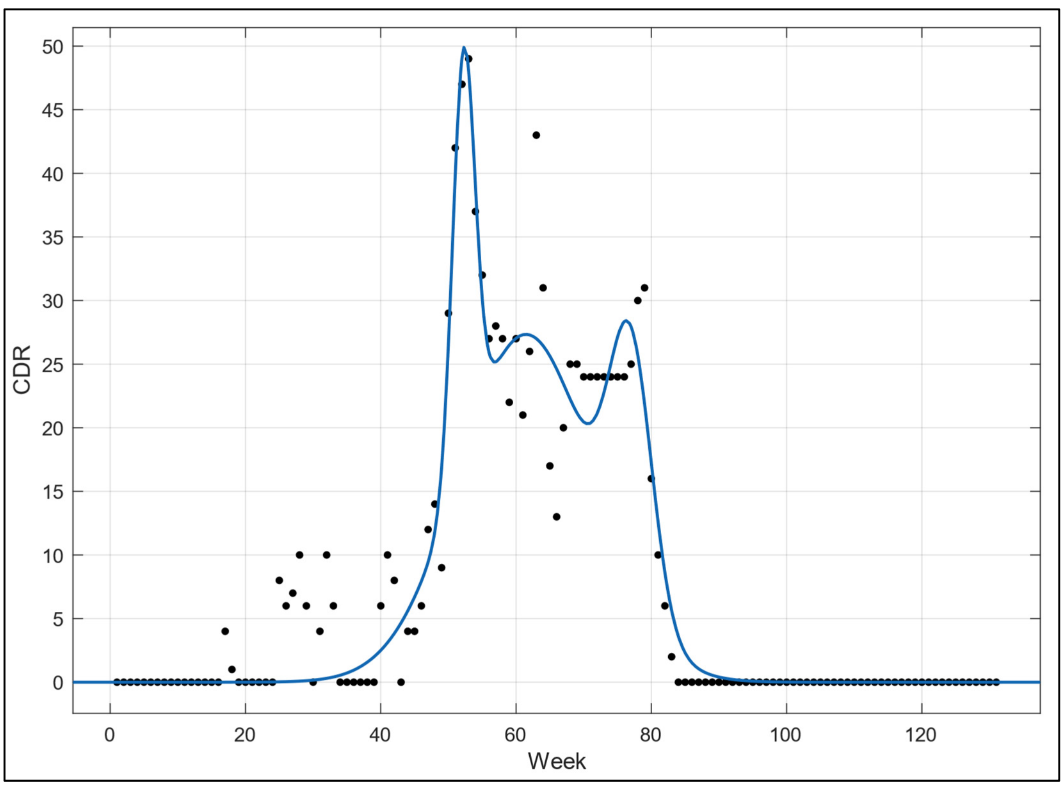


Figure 5-5 Best-Fitting Curve for Hotel Baseline Schedule Histogram (Data Date at Week 0)

Note that the best-fitting curve in **Figure 5-5** does not mimic exactly the high points of the histogram. The curve represents an approximation. Whereas this research attempts to predict estimated construction labor productivity inefficiencies, use of an approximation method for the general shape of the histogram suffices and produced similar results as if exact use of the histogram column values were used. Additionally, use of curve fitting via MatLAB allowed for automating the analysis and evaluating the different variables more quickly and thoroughly using scripts.

Utilizing the best fitting function, the area under the curve can be calculated. This calculated area is one variable that is included in the analysis to determine whether a correlation between the area under the curve and reported productivity exists. Area calculations considered in the analysis included the full area under the curve, and the area to either the right or left of the data date. Areas to the left of the data date reflect actual dates, or rather, the number of activities that were worked on concurrently. Areas to the right represent planned days of concurrent work activities. Area calculations can be made using the schedule density histogram data itself too. Use of best fitted curves allows easier comparison of histogram shapes from update to update.

Following the approach presented earlier in **Chapter 4**, calculate the centroid of the histogram area. In this case, because the data date is at Week Number zero, all of the data is planned future work. The x-coordinate of the centroid is calculated by multiplying each weekly sum of CDR's by the time distance from the data date Week Number for each CDR sum value. The sum total is then divided by the total number of CDR's, which results in a Week Number. The y-coordinate of the centroid is simply the average number of CDR's planned for each week. When comparing how the centroid changes from schedule update to update, a vector and its magnitude (scalar value) was calculated using basic linear geometry principles as explained earlier in **Chapter 4** and summarized graphically in **Figure 0-6** below. The resulting findings for the centroid calculations listed above for each schedule update are included in **Appendix 5D**.

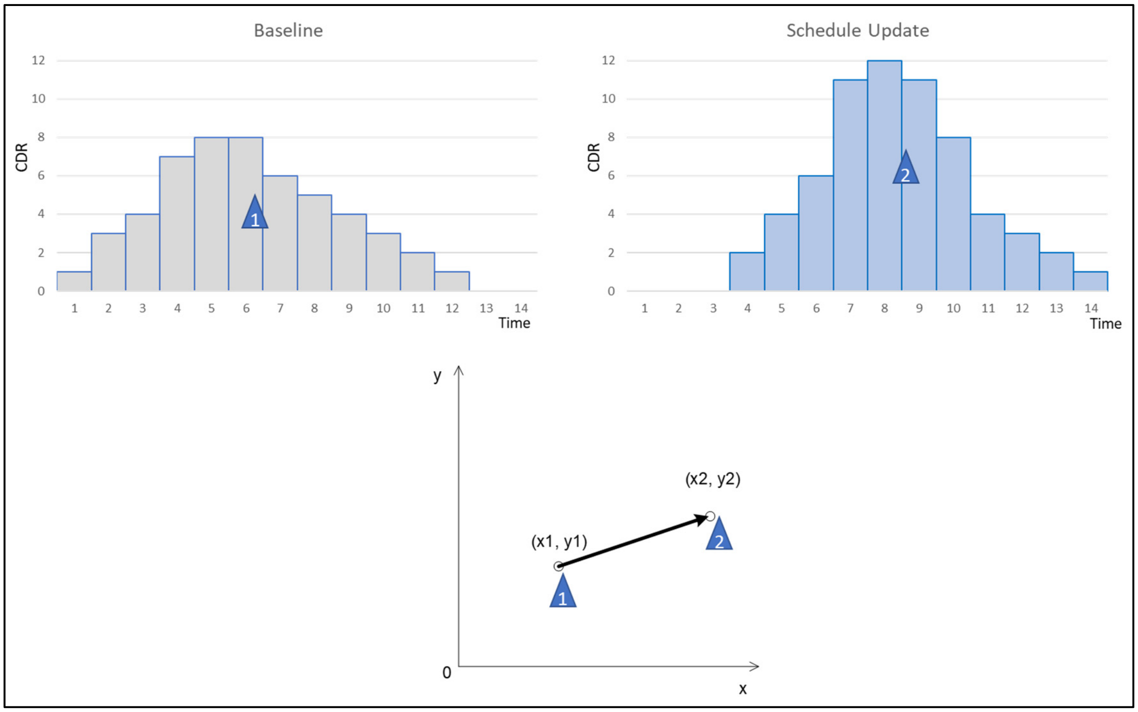


Figure 0-6 Resultant Vector from Two Schedule Density Histogram Centroids

With the data for successive updates compiled, next, calculate the incremental actual labor productivity achieved on the project for the trade under investigation. The unit for this measure is in labor hours expended per each percent complete achieved. Assume that a total of 100 hours were budgeted to complete a given task. It may be simply estimated that it requires 1 hour to achieve 1 percent of the total work; this is the target, or desired productivity. If for example, 10 hours were expended, but just 5-percent of the work was completed, the actual productivity would be 10 hrs divided by 5-percent equals 2 labor hours per percent complete, which is just half of the target productivity. Stated another way, the contractor only achieves 50-percent of the actual progress for each labor hour expended, which is an indicator or inefficiency.

Productivity rates on construction projects do not remain constant throughout the job. The first few periods typically experience poorer than optimal productivity due to a learning curve, and the last periods likewise experience lesser productivity due to rework and basic close-out work (Peles, 1977). These data points are outliers, or anomalies, that can skew observed correlations (Gupta, 2014). For this reason, the outlier data points are removed before deriving a best-fit correlative model. Actual labor hours expended for the mechanical and plumbing trades are presented in **Appendix 5E**.

Once the incremental labor productivity tallies are completed, the search for correlation between each of the variables ensues. This step includes comparing variables described in Chapter 4 and determining whether a correlation exists between them and the labor productivity measures. Comparisons were made using regression analysis within MatLAB software. These comparisons were documented in a correlation matrix such as that shown earlier in **Figure 4-13**. Ultimately, the goal is to find which measures drawn from the CPM schedule data (i.e., independent variables) are strongly correlated with the actual labor productivity data (i.e., the dependent variable).

Perform Regression Analysis

Utilizing the correlation matrix as a guide, where strong correlation exists between an independent variable and the dependent variable, further regression analysis was performed where various forms of the best-fitting curve type were further evaluated. For example, a log normal function closely resembles an exponential function in shape and fit, although not identically. Selecting the better of two or more functions that show strong correlation is determined in part by ease of use if a predictive model were able to be produced. Additionally, use of similar function types for each project would be desirable to better facilitate industry acceptance.

Finally, after a best-fitting model function is selected, calculation of the experienced labor productivity loss due to trade stacking may be estimated using that model. Results presented below demonstrate strong correlation between the cumulative centroid scaler and expended labor hours per percent complete.

Results

This section presents results of the analysis for the hotel sample project. **Figure 5-7** and **Figure 5-8** show the best fitted curves for the High Rise Hotel project based on its early dates. The axes for each schedule update are identical with time (in weeks) on the x-axis and the CDR's on the y-axis. The status date, referred to as the "data date" in P6, is listed below each curve and represented by the vertical line in each update.

Tracking how the curves change from update to update allows identification of trends in how the work actually progressed. For example, the High Rise Hotel's original curve shows a tri-modal gaussian function beginning with its baseline schedule (data date 06-Mar-13). The bulk of this mechanical work was planned to occur over an approximate 50-week time period. Six months later (data date 06-Oct-13), this tri-modal shape is still present, however, the middle mode became the greatest in terms of the number of overlapping CDR's. At this time, the bulk of the mechanical work was then planned to occur over an approximate 30-week time period. Thus, in comparing these two schedule updates, the planned mechanical work had been compressed, meaning that a like amount of planned future mechanical work would need to be completed within 30 weeks instead of the original planned 50 weeks in the baseline schedule. A primary assumption here is that the number of activities representing the mechanical work in the baseline is the same as those in the 06-Oct-13 update.

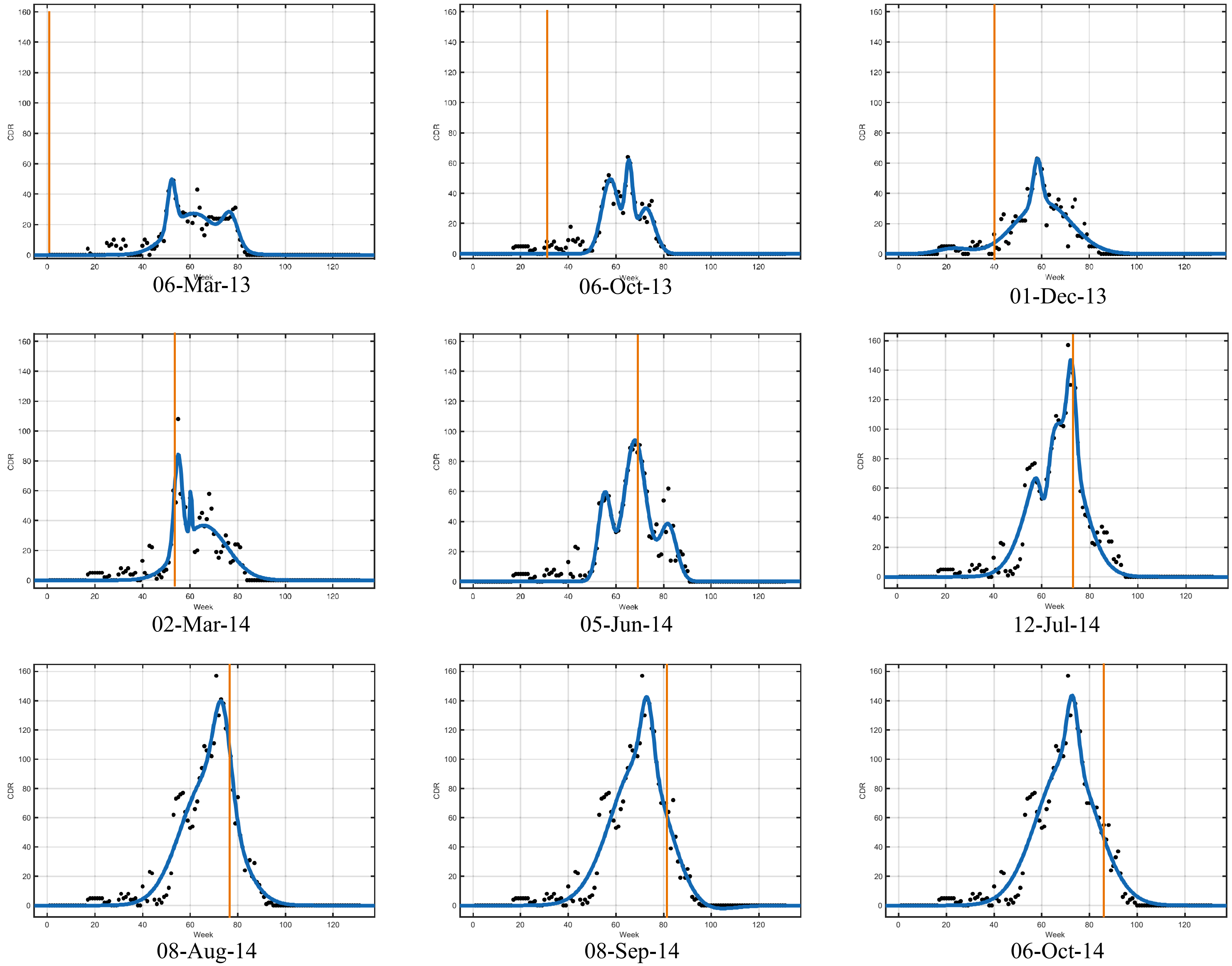


Figure 5-7 Hotel Project Best-Fitted Curves for Schedule Data Date Shown (March 2013 to October 2014)

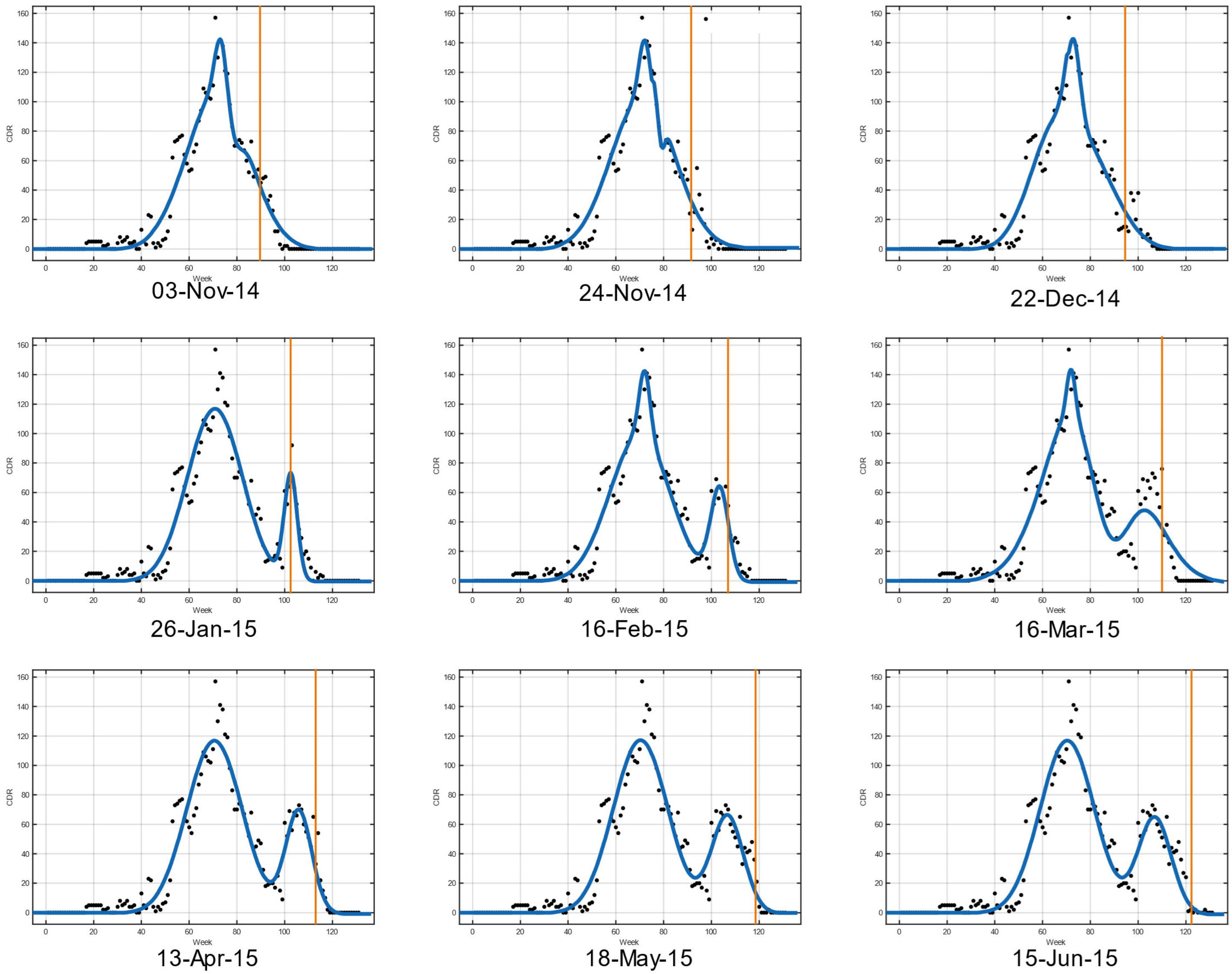


Figure 5-8 Hotel Project Best-Fitting Curves for Schedule Data Dates Shown (November 2014 to June 2015)

The change in shapes between these two updates is due to actual progress realized (or not) on the project. As work progresses, the scheduler makes changes to the schedule. AACE's Recommended Practice RP 53R-06 "Schedule Update Review – As Applied in Engineering, Procurement, and Construction" provides "guidelines for the project scheduler to create a professional schedule update or assess the reasonableness of changes to be made in a schedule due to a change of project status and progress." Recommended types of information that are updated and reported in the schedule for the reporting period include,

- Significant activities started or completed including status of material and equipment procurement activities;
- Changes to critical path activities in comparison to the critical path shown in the prior reporting period;
- Identification of any delays and change orders that may affect the work;
- Changes made to the logic or to activities' planned durations; and
- Explanation of any schedule changes, including changes to the logic sequence or to activity durations and the impacts to the overall project.

The net effect of the implemented schedule modifications causes the schedule's density histogram to change shapes from update to update. If few or no changes are made and the contractor is performing work according to plan, then the schedule density histogram shape remains unchanged even though the data date will change as time advances. In the case of this high rise hotel project, the planned work obviously changed between the March 6, 2013 and October 6, 2013 schedule updates as indicated by the difference in the best fitting curves for each update. A possible cause for the change is delayed progress on predecessor work to the mechanical work. Absent a granted time extension, the start dates of mechanical work would necessarily be pushed to later start dates, but would need to finish on or close to the finish date in the baseline schedule. Consequently, the same amount of work needed to be accomplished, but in a shorter duration, which may explain why the original 50-week duration was reduced to 30-weeks in the first schedule update, and why the second mode value is so much greater in comparison to the baseline schedule.

By the 01-Dec-13 schedule update, the tri-modal shaped curve changed dramatically. Instead of seeing definitive peaks, the shape appears to be a single mode gaussian function. Again, the changed shape is linked to schedule modifications made by the scheduler. The tri-modal function reappears in the 02-Mar-14 schedule update, but note how the CDR values are twice that amount shown in the baseline schedule. This observation supports the trade stacking scenario this analysis seeks to measure.

This model approach accounts for the additional detail the scheduler may include in the schedule. The addition of detail to a CPM schedule as more information becomes available is sometimes referred to as a “rolling wave” approach to updating the schedule. For example, say that three similar trade activities each with seven calendar days duration were planned to occur in series. The schedule density histogram for this scenario would be a single CDR planned for each day over 21 calendar days. Assume now that upon receipt of additional information, the scheduler added more detail to represent these three activities with say four activities each (now 12 activities are used to represent the same prior three activities), and some of those activities overlapped. According to the model proposed herein, trade stacking increased. Arguably, the trade stacking existed beforehand using just the three activities but was only measured by the model when the additional detail was added to the schedule. Whereas many schedulers do add detail as more information becomes available, it follows that the CDR measure alone may not be as strong as a predictor for productivity loss as initially anticipated.

For each of the schedule updates shown in **Figure 5-7** and **Figure 5-8**, the area totals were calculated using integral capabilities within MatLAB. **Table 5-1** shows results of the early date calculations in determining the centroids for each schedule update. **Table 5-2** presents the metric results from each update. These data were used to determine correlation between variables. The labor hours per percent complete measure is also included in this table.

Correlation Between Variables

The following variables were evaluated in comparison to each other:

1. Total Density ("∑ Density" - this value is the sum total of the area histogram generated by the planned activities in the CPM schedule)
2. Area Total ("f(x) Area Tot No Ex" – calculated integral of the fitted mathematical function for the schedule density histogram with no data excluded)
3. Area Right of Data Date ("f(x) Area Right No Ex" - integral of the fitted mathematical function for the schedule density histogram from the data date to the right with no data excluded)
4. Area Right of Data Date as a Percentage of the Area Total ("f(x) AR % No Ex" - ratio of item 3 divided by item 2 above)
5. Cumulative sum of the change in the centroid x-coordinate ("Cum Δx")
6. Cumulative sum of the change in the centroid y-coordinate ("Cum Δy")
7. Cumulative sum of the vector scalar values from the change in centroid coordinates ("Cum R^2 Scalar")

Table 5-1 High Rise Hotel Project - Centroid Results Based on Early Dates

Data Date	∑ Density	∑ Work Days	x Coord Date	Centroid x-Coord	Centroid y-Coord	Dates	Δ Data Date (cd)	Δ x (cd)	Cum Δ x	Δ y (CDR)	Cum Δ y	R^2 Scaler	Cum R^2 Scaler
06-Mar-13	1,011	236	12-Apr-14	402.8	4.3	Early	0	0	0	0.0000	0.000	0	0.00
06-Oct-13	1,085	264	11-Apr-14	187.3	4.1	Early	214	-1.5	-1.5	-0.1740	-0.174	-1.48	-1.48
01-Dec-13	1,167	288	03-Apr-14	123.8	4.1	Early	56	-7.5	-9.0	-0.0578	-0.232	-7.51	-8.99
02-Mar-14	1,301	277	27-Apr-14	56.8	4.7	Early	91	24.0	15.0	0.6447	0.413	24.02	15.03
05-Jun-14	1,976	312	29-Jun-14	24.2	6.3	Early	95	62.3	77.4	1.6366	2.049	62.37	77.40
12-Jul-14	2,802	329	24-Jul-14	12.2	8.5	Early	37	25.0	102.4	2.1834	4.233	25.12	102.52
08-Aug-14	3,038	322	13-Aug-14	5.6	9.4	Early	27	20.3	122.8	0.9181	5.151	20.36	122.89
08-Sep-14	3,224	330	11-Sep-14	3.3	9.8	Early	31	28.8	151.5	0.3349	5.486	28.77	151.65
06-Oct-14	3,415	343	08-Oct-14	2.6	10.0	Early	28	27.3	178.8	0.1866	5.672	27.27	178.93
03-Nov-14	3,595	351	04-Nov-14	1.6	10.2	Early	28	27.0	205.8	0.2859	5.958	27.02	205.94
24-Nov-14	3,598	361	25-Nov-14	1.0	10.0	Early	21	20.4	226.2	-0.2754	5.683	20.39	226.34
22-Dec-14	3,646	382	22-Dec-14	0.9	9.5	Early	28	27.9	254.0	-0.4223	5.261	27.85	254.19
26-Jan-15	4,021	423	27-Jan-15	1.9	9.5	Early	35	36.0	290.1	-0.0386	5.222	36.01	290.20
16-Feb-15	4,116	432	17-Feb-15	1.3	9.5	Early	21	20.5	310.5	0.0219	5.244	20.48	310.68
16-Mar-15	4,345	434	16-Mar-15	0.6	10.0	Early	28	27.3	337.8	0.4837	5.728	27.27	337.95
13-Apr-15	4,462	441	13-Apr-15	0.2	10.1	Early	28	27.6	365.4	0.1064	5.834	27.59	365.54
18-May-15	4,597	458	18-May-15	0.0	10.0	Early	35	34.8	400.2	-0.0808	5.753	34.83	400.37
15-Jun-15	4,628	464	15-Jun-15	0.0	10.0	Early	28	28.0	428.2	-0.0630	5.690	27.98	428.35

Table 5-2 Hotel Project Best-Fitting Curve Descriptive Values and Area Calculations for Early Dates

Data Date	Fit Adj R-Sq	Fit RMSE	Fit # Coeff	Data Date Week	First Plan Week	Last Plan Week	Area Tot	Area Left of DD	Area Right of DD	AR as % of ATot	CumMHrs / % Compl	Kurtosis	Skewness
06-Mar-13	0.92	3.48	9	1	25	83	956	0	956	100%	n/a	4.262	1.508
06-Oct-13	0.93	4.40	9	32	17	81	936	0	936	100%	n/a	5.983	1.984
01-Dec-13	0.91	5.06	6	40	17	84	1159	88	1071	92%	n/a	5.765	1.854
02-Mar-14	0.90	6.74	6	54	17	83	1178	185	993	84%	388	10.153	2.451
05-Jun-14	0.94	6.51	6	68	17	90	1808	933	875	48%	188	4.905	1.729
12-Jul-14	0.99	3.21	9	73	17	94	2671	1956	716	27%	263	5.616	1.866
08-Aug-14	0.98	4.06	3	76	17	94	2984	2343	641	21%	307	4.745	1.702
08-Sep-14	0.93	4.96	3	81	17	95	3176	2760	416	13%	338	4.295	1.566
06-Oct-14	0.93	4.16	3	85	17	99	3375	3018	357	11%	371	4.017	1.457
03-Nov-14	0.98	2.18	3	89	17	101	3556	3249	308	9%	406	3.744	1.351
24-Nov-14	0.94	2.92	3	92	17	104	3561	3371	191	5%	425	3.780	1.366
22-Dec-14	0.84	4.23	3	96	17	107	3574	3448	126	4%	447	3.839	1.379
26-Jan-15	0.95	5.30	3	102	17	116	3893	3558	336	9%	472	3.480	1.222
16-Feb-15	0.96	3.69	3	105	17	116	4058	3788	270	7%	487	3.451	1.182
16-Mar-15	0.91	6.17	3	109	17	116	4260	4006	254	6%	n/a	3.173	1.058
13-Apr-15	0.93	3.76	3	113	17	118	4376	4264	113	3%	n/a	3.109	1.009
18-May-15	1.00	0.61	3	118	17	120	4492	4448	45	1%	n/a	3.105	0.972
15-Jun-15	-	-	-	122	17	122	4528	4520	8	0%	n/a	3.117	0.970

8. Cumulative Manhours per Percent Complete ("Cum Mhr % Compl" – cumulative sum of the ratio of labor hours expended to complete one percent of work for each schedule evaluated)
9. Kurtosis (a measure of how tall and skinny, or short and wide a distribution under consideration is relative to a typical normal distribution)
10. Skewness (a measure of how asymmetric a distribution function is)

Figure 5-9 presents the resulting correlations for the comparisons of these variables. Any correlation with an R-square value of 0.895 or greater was considered a strong correlation. The simplest mathematical fit was sought for each comparison with a linear relationship deemed to be a benchmark for ease of use. A simple linear equation takes the form

$$f(x) = y = mx + b$$

where m is the slope of the line and b is the y-axis intercept value. Where a linear relationship represented the best fit, the slope value is provided in **Figure 5-9**. Where other mathematical functions were used, a simplified function "f(x)" is shown as is a small graphic that shows the relative shape of the curve. Any Gaussian function is based upon the normal distribution, i.e., a typical bell-shaped curve, although, the varying coefficients cause the typical bell-shape to change. Detailed backup information for each best-fitting correlation related to the cumulative manhours per percent complete calculation is provided in **Appendix 5F**.

	∑ Density	*f*(x) Area Tot No Ex	*f*(x) Area Right No Ex	*f*(x) AR % No Ex	Cum Δ x	Cum Δ y	Cum R^2 Scalar	Cum MHr % Compl
***f*(x) Area Tot No Ex**	H01 Linear m = 1.00 0.999							
***f*(x) Area Right No Ex**	H02 Linear m = -0.272 0.920	H08 Linear m = -0.271 0.924						
***f*(x) AR % No Ex**	H03 Linear m = -0.00028 0.915	H09 Linear m = -.00028 0.917	H14 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.998					
Cum Δ x	H04 Exp1 f(x) = a*exp(b*x) 0.978	H10 Exp1 f(x) = a*exp(b*x) 0.976	H15 Linear m = -.378 0.894	H19 Exp1 f(x) = a*exp(b*x) 0.927				
Cum Δ y	H05 Poly2 f(x) = p1*x^2 + p2*x + p3 0.980	H11 Poly2 f(x) = p1*x^2 + p2*x + p3 0.982	H16 Exp2 f(x) = a*exp(b*x) 0.947	H20 Linear m = -6.368 0.976	H23 Sine4 f(x) = a1*sin(b1*x+c1) 0.925			
Cum R^2 Scalar	H06 Exp1 f(x) = a*exp(b*x) 0.978	H12 Exp1 f(x) = a*exp(b*x) 0.976	H17 Exp1 f(x) = a*exp(b*x) 0.884	H21 Exp1 f(x) = a*exp(b*x) 0.927	H24 Linear m = 1.00 1.000	H26 Exp1 f(x) = a*exp(b*x) 0.696		
Cum Mhr % Compl	H07 Linear m = 0.151 0.963	H13 Linear m = 0.144 0.956	H18 Linear m = -.367 0.8465	H22 Exp1 f(x) = a*exp(b*x) 0.866	H25 Exp2 f(x) = a*exp(b*x) 0.998	H27 Linear m = 63.81 0.561	H28 Exp2 f(x) = a*exp(b*x) 0.998	
Kurtosis	H30 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.936	H32 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.926	H34 Linear m = 3.13 0.44	H36 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.828	H38 Gauss3 f(x) = a1*exp(-((x-b1)/c1)^2) 0.924	H40 Gauss3 = a1*exp(-((x-b1)/c1 0.787	H42 Gauss3 f(x) = a1*exp(-((x-b1)/c1)^2) 0.924	H44 Exp2 f(x) = a*exp(b*x) 0.893
Skewness	H31 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.939	H33 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.916	H35 Sqrt(x) f(x) = a*sqrt(x)^b 0.691	H37 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.820	H39 Gauss3 f(x) = a1*exp(-((x-b1)/c1)^2) 0.911	H41 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.585	H43 Linear m = -.0024 0.794	H45 Exp2 f(x) = a*exp(b*x) 0.957

Key

Strong Correlation (0.89 < R^2 < 1.0)	Poor Correlation (no fit)
Good Correlation (0.79 < R^2 < 0.9)	Inconclusive (0.69 < R^2 < 0.8)

Figure 5-9 High Rise Hotel Sample Project Mechanical Trade Work Correlation Results

For the hotel, as the shape of the schedule density curve changes with respect to its skewness and kurtosis, an exponential relationship is observed with the cumulative labor hours per percent complete. This finding supports that the schedule density measurements presented herein may be used to prepare a predictive model of anticipated productivity loss. Increasing trends in how the centroid changes from update to update, and the general shape changes of the area histogram functions can serve as warnings for potential future productivity inefficiencies. Contractors and owners alike may find this tool useful.

Results in **Figure 5-9** show the exponential function as having the best-fit (r-square = 0.998). However, a simpler log normal function was chosen instead because of its more commonly known shape within the mathematics and scientific communities, simplicity with just two coefficients instead of four, and because its fit was nearly identical to the exponential function (r-square = 0.983). The two models are compared in **Table 5-2**.

Table 5-2 Best-Fitting Model v Chosen Model

Coefficient	Best-Fit Exponential f(x) = a*exp(b*x) + c*exp(d*x)	Chosen Lognormal Function f(x) = a * ln(x) ^ b
a	301.5	2.588
b	0.00157	3.009
c	-647	-
d	-0.0188	-
R-sq Value	0.998	0.983
RMSE	5.28	12.77

Figure 5-10 presents the selected curve from the regression analysis for the cumulative centroid scalar value versus the cumulative labor hours per percent complete.

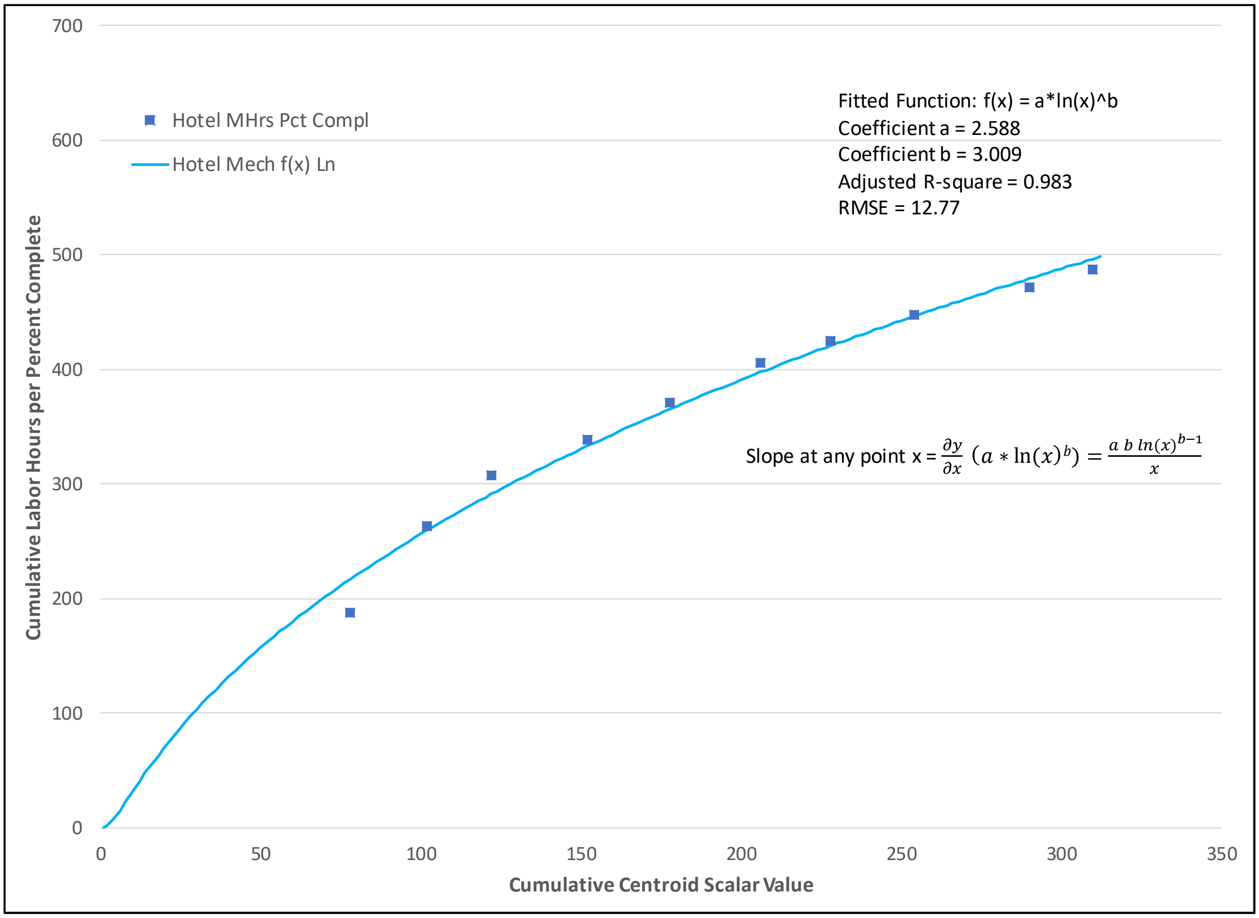


Figure 5-10 Cumulative Centroid Scalar Value v Cumulative Labor Hours per Percent Complete

This figure serves as a starting point for a predictive model wherein a scheduler can track how the centroid scalar value changes from update to update, and if that trend is upward like that shown here, the scheduler may use the function to estimate the potential impact to the amount of labor hours required to complete unfinished work.

Conclusions

Results of this High Rise Hotel project support that strong correlation exists between several variables. Most notably is the fitted function for cumulative centroid scalar value versus cumulative labor hours per percent complete. The centroid value includes both a time component and a resource component. Correlation results support that in isolation, the time element, i.e., delay, has greater influence on productivity than does the increase in just CDR's. However, including the combination of both components in the analysis produces strong correlation and supports that a predictive model for estimating productivity loss is plausible.

Understandability and ease of use are prerequisites to industry acceptance and application of the technique presented here. While execution of each individual step is simple, the numerous iterations performed for each of the variables increase the complexity and time required to perform the technique. Wading through and validating the data also requires some expertise and a knowledge of CPM scheduling. Notwithstanding these potential complications, the results soundly support that the technique works for this project.

6 Summary Results of Technique Applied to Other Sample Projects

In total, five sample projects were evaluated as shown in **Table 6-1.** Two of the projects evaluated are buildings. Another is a combined cycle power plant. The fourth project included erection of a large steel structure. These four projects were used to identify relationships between the schedule density metrics drawn from the CPM schedules. The fifth project, a resort hotel, was used for empirical validation of findings from the analyses and is presented in the next chapter. In effect, use of this validation project sought to answer the question, "Are the results transferable to another project?" Recognizing that the Resort Hotel project is not completely homogenous to the High Rise Hotel and Condo Towers projects, although similar with respect to having MEP trades generally working together, the belief was that there may be some value in seeing how the modeled results from the first four sample projects may be applied.

Table 6-1 List of Sample Projects

Sample Project Type	Year Completed	Number of Native Electronic Schedules	Reliable Labor Hours Data	Progress Percent Complete Data
High Rise Hotel	2015	18	Yes	Yes
Condo Towers	2008	17	Partial	Yes
Large Bore Piping	2010	15	Yes	Yes
Steel Structure	2016	14	Yes	Yes
Resort Hotel (for validation)	2008	15	Yes	Yes

Table 6-1 shows that reliable labor and progress percent complete data were found for all but the Condo Towers project, where labor data was only partially available. For this project, the schedule density and area calculations were useful and therefore, included in the results herein, but any comparison to labor hours per percent complete cannot be made for this project due to lack of complete and reliable data.

Because of the proprietary nature of productivity data being utilized and confidentiality regarding dispute resolution, specific names of contractors and the respective projects are withheld. Instead, general information is provided – enough to give the reader a clear understanding of the scope of work.

Comparison of Results for the Sample Projects

The technique demonstrated in Chapter 5 for the High Rise Hotel was applied similarly to the Piping, Structural Steel and Condominium Towers projects. Results from each analysis were compared to one another to identify common findings or stark differences, if any. Similarly as found in the High Rise Hotel project, both the Structural Steel and Piping projects showed strong statistical correlation between their respective centroid cumulative scalar values and the cumulative labor hours per percent of work scope completed. Error! Reference source not found.**Figure 6-3** presents the correlations for the High Rise Hotel, Piping and Structural Steel projects on the same graph.

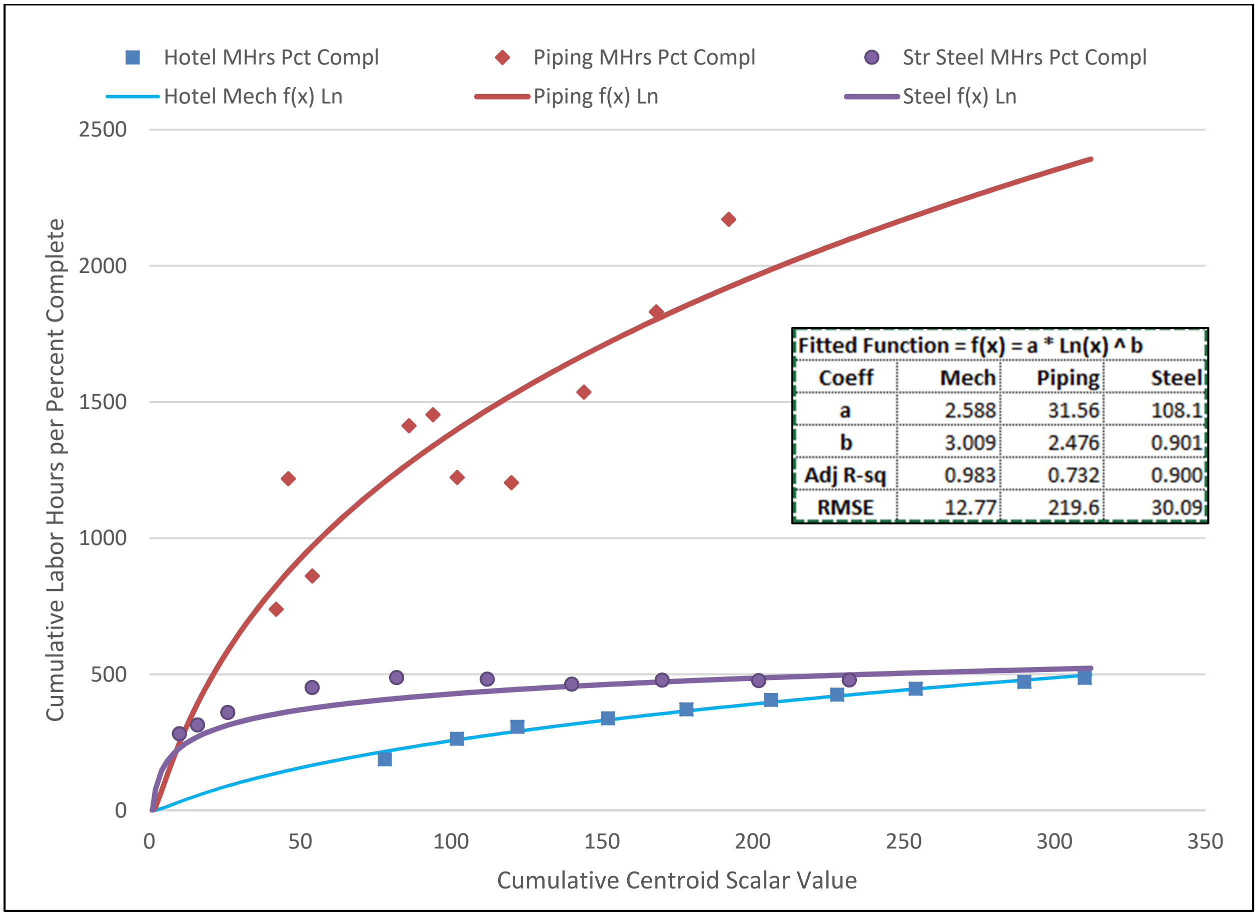


Figure 6-1 Predictive Model Form Using Results of the Schedule Density Analysis

A lognormal equation was found to be a good fit for both the Structural Steel and Piping projects. This function also matches findings from the High Rise Hotel project. Selecting a lognormal function, derived from a lognormal distribution, is the correct choice when modeling something affected by random variation as indicated by Limpert and Stahel, “Empirical evidence suggests the log-normal distribution should be selected as a first choice when “amounts” are modelled – these being quantities that can only take positive values” (Limpert & Stahel, 2017). They continue,

There is also a theoretical justification for using the log-normal distribution: whereas the well-known central limit theorem, in its classical form, says that the *addition of many random "effects" has approximately a Gaussian distribution, the less well-known version ascertains that the multiplication of many positive random variables creates a distribution that is approximately log-normal.*

The 'multiplication of many positive random variables' applies to this study because of the many variables that affect labor productivity.

The lognormal function has a sharp slope when the values start at zero and then flattens out with increasing cumulative centroid scalar values. The coefficients "a" and "b" as shown in the figure define the steepness of the slope of the line at point zero and in how quickly the slope of the function levels out with increasing cumulative centroid scalar values. The actual slope of the line at any point can be calculated by using the derivative of the lognormal equation in question as follows:

$$slope\ at\ any\ point\ x = \frac{\partial}{\partial x} f(x) = ab\left[\frac{\ln{(x)}^{(b-1)}}{x}\right]$$

Results from these three projects show that the slope of the line lessens with greater values of the cumulative centroid scalar value. Interpretation of this graphic indicates that as the schedule density (derived directly from the CPM schedules) changes over time where both the x-coordinate (a function of time and delay) and y-coordinate (an indicator of stacked activities for a given trade) are increasing, the number of labor hours to complete the work likewise increases.

The cumulative sum of each scalar plotted sequentially compared with the calculated labor hours per percent complete reveals this lognormal correlation between these two variables. The strongest correlation identified lies in the High Rise Hotel project's mechanical trade as indicated by the r-square value of 0.983. This finding aligns with the literature review, the ConExpo survey results, and the expert panelists' expectations (presented in Chapter 7) wherein all indicated the greatest likelihood for trade stacking exists in the MEP trades, particularly for multi-story building projects.

Interestingly, the Structural Steel project also had a strong correlation (r-square value of 0.900). With this project, construction progress was largely governed by the availability of two large cranes that were required to hoist larger structural steel members into place. When delay caused a crane to remain stationary longer than planned, this increased the overlapping of planned future work activities in the CPM schedules. Thus, the erection of roofing steel, purlins and siding occurred simultaneously rather than more in series, which according to results of this study, caused labor inefficiencies.

The Piping project showed good, although the lowest (r-square value of 0.732), correlation of the three projects shown in **Figure 6-1**. The lower r-square value and the higher root-mean-square (RMS) value indicates greater variability in the data. Thus, in comparison, the Piping project had the greatest variability in its data. The large bore piping required on a combined cycle power plant is extensive and requires thousands of man-days of labor to complete. The sheer magnitude of these labor hours greatly exceeds those labor hours required to complete the mechanical work on the High Rise Hotel project, for example, and therefore, the curve for the Piping project extends to much higher values on the y-axis. One of the expert panelists indicated that this large variability in labor productivity for piping is explained by a shortage of skilled piping welders in the US market. He opined that if a consistently skilled labor force of piping welders existed, the correlation between the variables in **Figure 6-1** would be greater.

Measurement of labor inefficiency may be estimated by comparing the differences between two values on the x-axis as depicted graphically in **Figure 6-2**. This figure shows that an increase of 50 units on the cumulative centroid scalar value equates to approximately a 70 unit increase in the cumulative labor hours required to complete one percent of the work. Thus, quite literally, the model results may be used to measure labor inefficiency. Creation of a predictive model would utilize the same lognormal function and could be used similarly if, for example, an increasing trend of values to the cumulative centroid scalar values were observed.

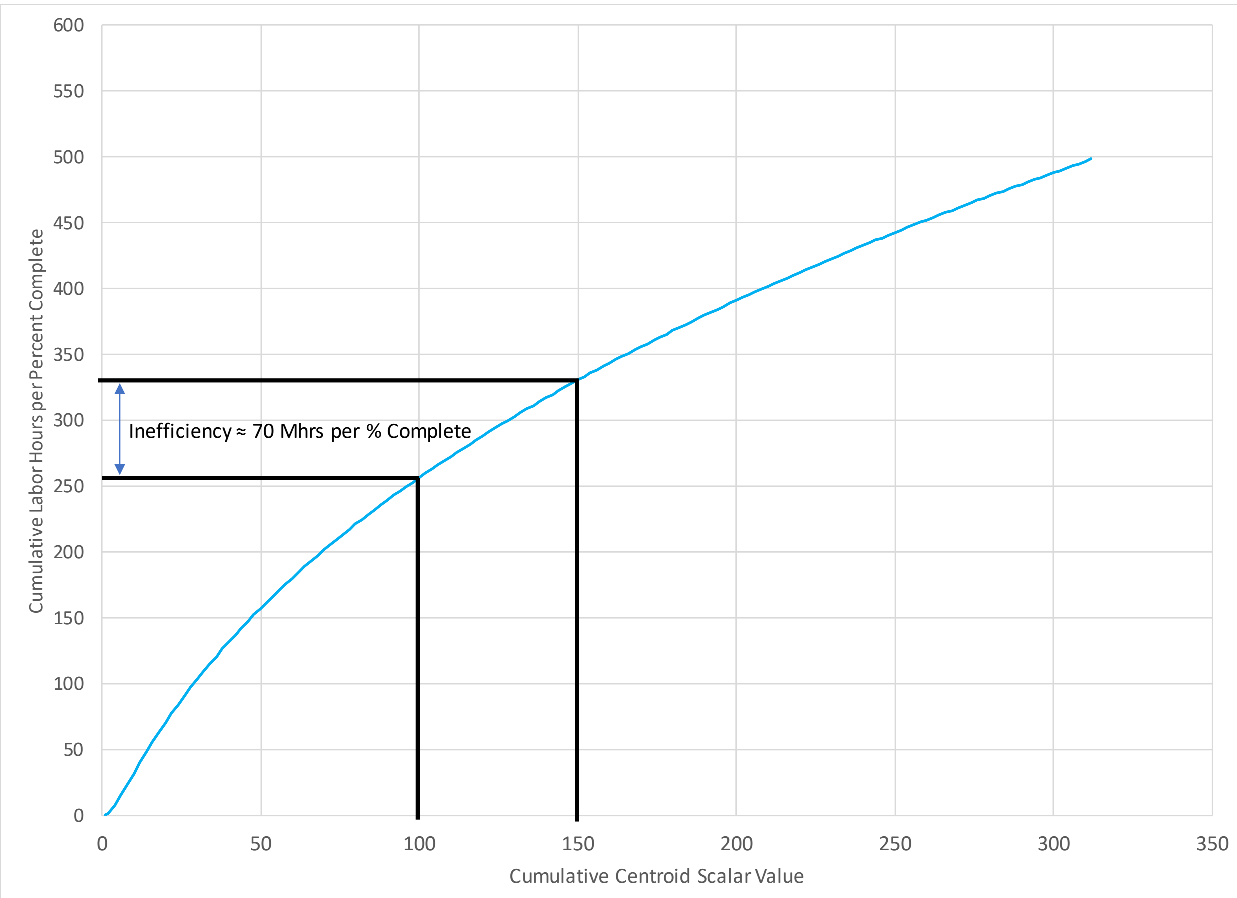


Figure 6-2 Use of Model to Measure Productivity Inefficiency

That each best fitting relationship for three of the sample projects follows a log normal function suggests that this function may be used in a predictive manner for estimating productivity inefficiencies. The function is the same, however, the coefficients are unique to each project. In retrospective analysis, use of the actual histograms to calculate the changes in centroids from schedule update to update would be adequate and simplify the application by foregoing the need to use the lognormal function. In either application, additional research and evaluation of larger sample sizes are warranted to derive a methodology for better understanding variables that affect the coefficients based on project type, trade type, available labor, etc.

Further evaluation in comparing the results collectively shows that the change in the centroid x-coordinate variable has a greater effect on the shape and resulting correlation of the lognormal function than does any other variable evaluated. The centroid x-coordinate is directly related to a contractor's inability to meet its planned dates. When delay occurs and the contractual completion date remains unchanged, the unfinished work activities are pushed forward. Thus, in the succeeding schedule update, the centroid x-coordinate will likewise shift to the right.

Surprisingly, the change in the centroid y-coordinate alone did not consistently show strong correlation or effect on the model. This variable effect may be attributed to several reasons. First, often in times of delay a contractor will reduce planned durations in its schedule update so as to not show delay – particularly if the contractor is responsible for the delay. The reduced duration would necessarily reduce the likelihood of overlapping activities in the schedule. Second, there may be float in the CPM schedule with the trade activities being evaluated. The delayed progress will cause the unfinished work activities to shift to the right, but not result in any measurable change in CDR's. Finally, a contractor may choose to work overtime within the same planned activity duration to recover delay. This approach likewise would not be reflected in the CDR value derived from the schedule update.

Whereas the centroid value itself represents both time and trade stacking, it makes sense that this variable was found to have strong correlation with the other metrics observed and with labor productivity.

The following subsections present the results for the respective project listed.

Condominium Towers Sample Project – Electrical Trade Work

Two nearly identical 22-story condominium towers were constructed under the same contract in Washington State (see **Figure 6-3**). Parking was provided under the towers, the first four floors were used for retail and lease business space, and the remaining floors were used for condominium dwellings. Total construction cost was approximately $100 million. Given a volatile market which resulted in frequent pricing changes downward for condo sales, the contractor was held to a strict completion date. When performance fell behind schedule, the MEP trades stacked up. Labor hour data was kept on the project for the first year, but when the job fell behind schedule, the prime contractor stopped tracking actual labor hours expended by subcontractors each month.

Figure 6-3 Condo Project Photo

Given the similarities between this project and the hotel high rise, the analyses for all of the variables were performed, except the labor hours because this data was found to be incomplete. Results of the condo sample project are presented in **Table 6-2** and **Table 6-3**. Progression of the best-fitting curves for the condo project schedule density histograms are shown in **Figure 6-4** and **Figure 6-5**. The variable correlation matrix is presented in **Figure 6-6**.

Table 6-2 Condo Project - Centroid Results Based on Early Dates

Data Date	∑ Density	∑ Work Days	Centroid x Coord	Centroid y Coord	Δ Data Date	Δ x	Cum Δx	Δ y	Cum Δy	R^2 Scalar	CumR^2 Scalar
17-Feb-06	731	318	495.32	2.30	0	0	0	0.000	0.000	0.00	0.00
01-Mar-06	741	328	550.33	2.26	12	67.0	67.0	-0.017	-0.017	67.01	67.01
10-Apr-06	731	318	443.27	2.30	40	-67.1	0.0	0.018	0.000	-67.05	-0.04
16-May-06	731	318	444.97	2.30	36	37.7	37.7	0.000	0.000	37.70	37.65
01-Aug-06	739	289	367.17	2.56	77	-0.8	36.9	0.112	0.113	-0.81	36.85
01-Nov-06	726	282	276.05	2.57	92	0.9	37.7	0.007	0.119	0.88	37.73
29-Dec-06	800	309	199.53	2.59	58	-18.5	19.2	0.006	0.125	-18.53	19.20
23-Mar-07	997	312	146.25	3.20	84	30.7	49.9	0.234	0.359	30.72	49.92
06-Apr-07	1,029	300	124.27	3.43	14	-8.0	41.9	0.073	0.433	-7.98	41.94
01-May-07	1,180	329	90.46	3.59	25	-8.8	33.1	0.046	0.478	-8.81	33.13
15-Jun-07	1,279	331	67.39	3.86	45	21.9	55.1	0.077	0.556	21.93	55.06
06-Aug-07	1,455	347	39.82	4.19	52	24.4	79.5	0.085	0.641	24.43	79.50
31-Aug-07	1,612	341	25.88	4.73	25	11.1	90.6	0.127	0.768	11.06	90.55
24-Sep-07	1,670	353	21.16	4.73	24	19.3	109.8	0.001	0.769	19.29	109.84
31-Oct-07	1,841	346	12.77	5.32	37	28.6	138.4	0.125	0.894	28.60	138.44
27-Nov-07	2,017	350	8.59	5.76	27	22.8	161.3	0.083	0.977	22.83	161.27
13-Dec-07	1,555	327	6.12	4.76	16	13.5	174.8	-0.175	0.802	13.53	174.80

Table 6-3 Condo Project Best-Fitting Curve Descriptive Values and Area Calculations for Early Dates

Data Date	Fit Adj R-sq	Fit RMSE	Fit # Coeff	Data_ Date Week No	First Plan Week No	Last Plan Week No	AreaTot E NoEx	Area Left DD	Area Right DD	Area Rt DD Pct of AT	CumMHrs / % Compl	Kurtosis	Skewness
17-Feb-06	0.97	1.26	18	28	64	128	704	-10	713	100%	n/a	2.062	0.572
01-Mar-06	0.95	1.47	18	30	66	140	707	-2	709	100%	n/a	1.896	0.506
10-Apr-06	0.94	1.68	9	36	64	128	704	-10	713	100%	n/a	2.050	0.568
16-May-06	0.94	1.66	9	41	70	133	698	-7	705	100%	n/a	2.422	0.744
01-Aug-06	0.95	1.69	6	52	77	133	723	-5	728	100%	n/a	1.880	0.608
01-Nov-06	0.89	2.60	6	65	76	133	701	-25	726	100%	n/a	2.378	0.838
29-Dec-06	0.92	2.18	6	73	69	130	786	9	777	99%	n/a	1.717	0.494
23-Mar-07	0.91	2.82	9	85	76	140	980	96	885	90%	n/a	1.593	0.488
06-Apr-07	0.95	2.17	9	87	76	129	991	199	792	80%	n/a	1.513	0.411
01-May-07	0.96	2.25	9	91	69	134	1169	383	786	67%	n/a	2.365	0.817
15-Jun-07	0.95	2.77	9	97	69	136	1251	403	848	68%	n/a	5.442	1.612
06-Aug-07	0.94	3.84	9	105	69	139	1421	646	775	55%	n/a	4.527	1.538
31-Aug-07	0.94	4.63	6	108	69	141	1613	880	734	45%	n/a	5.369	1.688
24-Sep-07	0.95	4.33	9	112	69	141	1659	1058	601	36%	n/a	3.707	1.415
31-Oct-07	0.95	4.90	6	117	69	142	1818	1313	505	28%	n/a	3.080	1.251
27-Nov-07	0.93	6.12	9	121	69	139	1870	1383	487	26%	n/a	5.444	1.547
13-Dec-07	0.93	4.67	12	123	69	137	1551	1234	317	20%	n/a	1.718	0.570

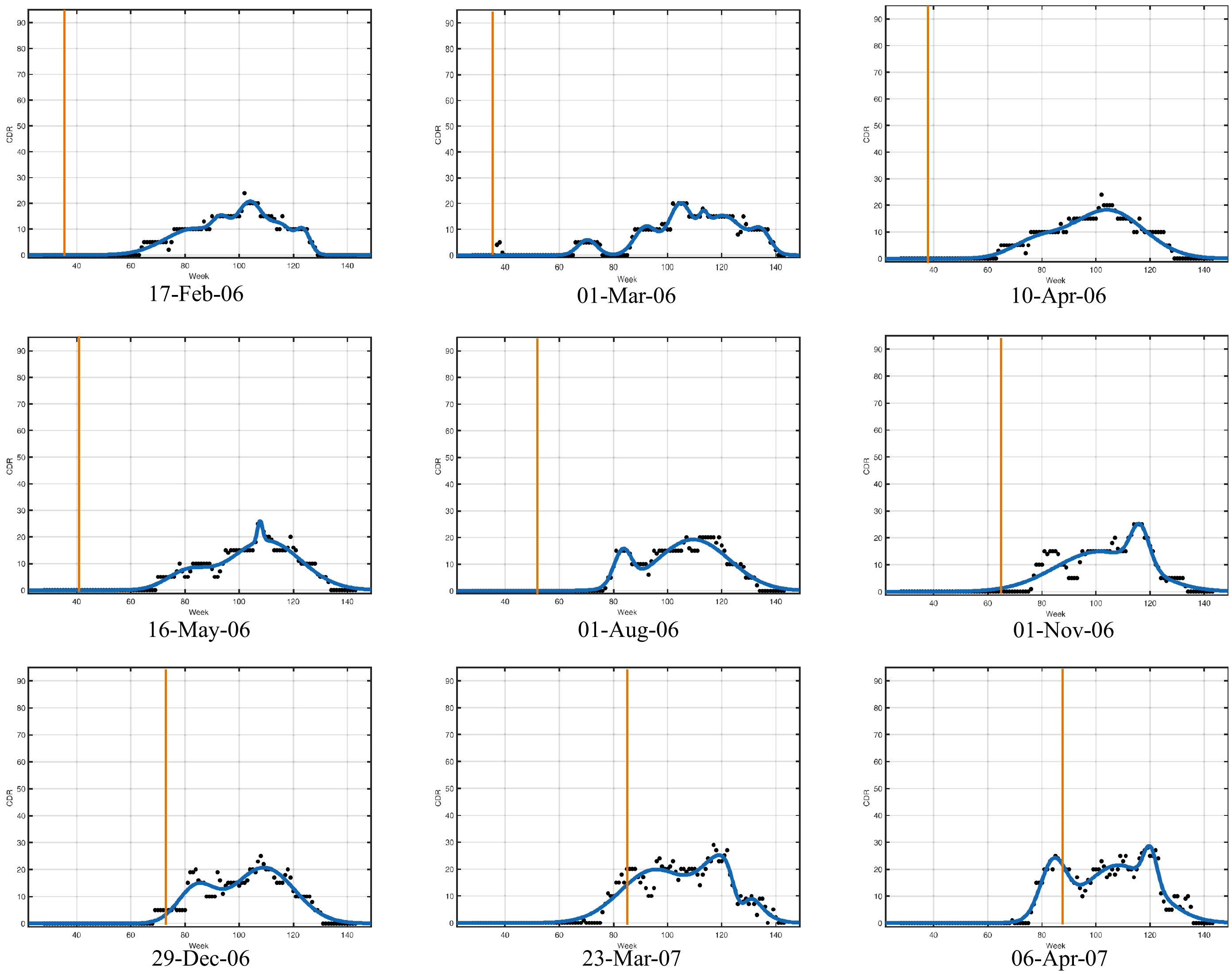


Figure 6-4 Condo Project Best-Fitting Curves for Schedule Data Dates Shown (February 2006 to April 2007)

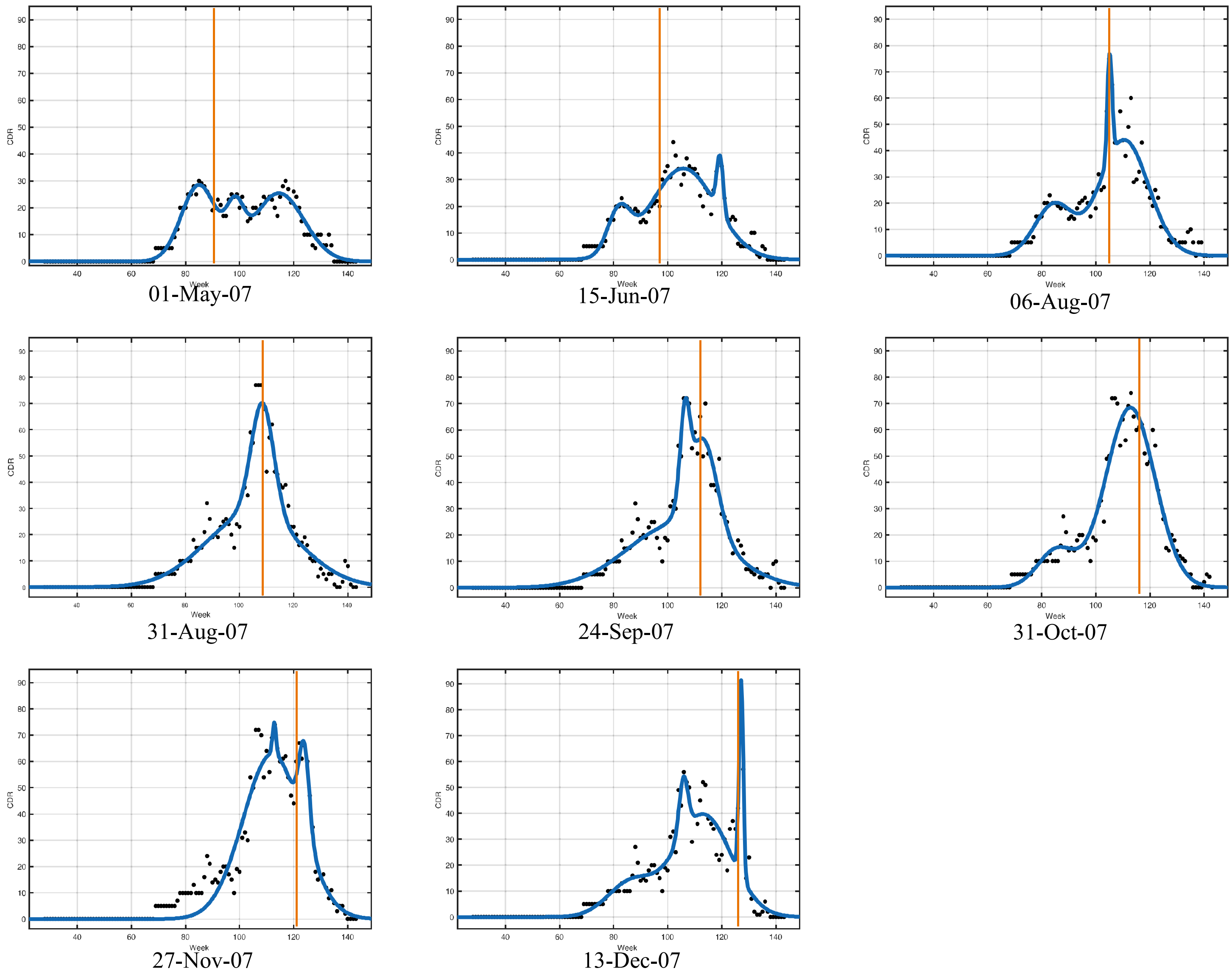


Figure 6-5 Condo Project Best-Fitting Curves for Schedule Data Dates Shown (May 2007 to December 2007)

	∑ Density	*f*(x) Area Tot No Ex	*f*(x) Area Right No Ex	*f*(x) AR % No Ex	Cum Δ x	Cum Δ y	Cum R^2 Scalar
_f_(x) Area Tot No Ex	C01 Linear m = 0.976 0.995						
_f_(x) Area Right No Ex	C02 Guass2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.589	C08 Guass2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.604					
_f_(x) AR % No Ex	C03 Linear m = -0.00066 0.941	C09 Linear m = -.00068 0.953	C14 Linear m = .00145 0.461				
Cum Δ x	C04 Linear m = 0.102 0.749	C10 Linear m = 0.104 0.741	C15 Linear m = -0.292 0.628	C19 Exp1 f(x) = a*exp(b*x) 0.896			
Cum Δ y	C05 Linear m = 0.00077 0.941	C11 Linear m = 0.00079 0.968	C16 Linear m = -0.0012 0.254	C20 Linear m = -1.117 0.934	C23 Sine3 f(x) = a1*sin(b1*x+c1) 0.845		
Cum R^2 Scalar	C06 Linear m = 0.102 0.749	C12 Exp1 f(x) = a*exp(b*x) 0.767	C17 Linear m = -0.292 0.628	C21 Exp1 f(x) = a*exp(b*x) 0.896	C24 Linear m = 1.00 1.000	C26 Exp1 f(x) = a*exp(b*x) 0.813	
Cum Mhr % Compl	C07 incomplete data	C13 incomplete data	C18 incomplete data	C22 incomplete data	C25 incomplete data	C27 incomplete data	C28 incomplete data

Key

Strong Correlation (0.89 < R^2 < 1.0)	Poor Correlation (no fit)
Good Correlation (0.79 < R^2 < 0.9)	Inconclusive (0.69 < R^2 < 0.8)

Figure 6-6 Condo Project Variables Correlation Matrix Results

Observation of the condo project's best-fitting curves shows that as time progressed, and as the electrical trade work was not completed according to plan, the CDR value increases with each successive schedule update. The increasing CDR value represents increased trade stacking. The correlation between the manhours per percent complete and the increasing value of the centroid scaler value supports that increased trade stacking adversely affects labor productivity.

Large Bore Piping – Power Plant

Power, processing and industrial plants typically require significant amounts of mechanical piping work. The second sample project considered large bore (> 2.5" in diameter) piping on a power plant located in the southeast United States (see **Figure 6-7**). Total construction cost exceeded $100 million. Piping work included layout, welding and setting of carbon steel and stainless steel piping in and related to the turbine and boiler areas. The piping work required coordinated efforts between the steel erection and pipe rack constructors. This project experienced delays that caused planned piping work to stack up. Absent any appreciable time extensions, the prime contractor was required to maintain schedule despite the increased schedule density for large bore piping.

To illustrate these principles in a real-world scenario, consider the construction of a large plant for a public utility. The construction includes significant site civil work, piping (both above and below ground), structural steel, mechanical, electrical and instrumentation work. CPM schedules were prepared monthly by the contractor, but were never formally resource loaded.

Figure 6-7 Piping Project Power Plant

The project was impacted by three force majeure events including two hurricanes within two weeks of each other, and a bomb threat that shut the job down for another day. There is a direct impact caused by the force majeure events where the project was shut down or significantly disrupted, and a ripple effect where it takes time for the workers to return to site and ramp back up to full productivity.   The direct time impacts of such events are generally easy to determine. But the contractor struggled to identify the point in time when the ripple effect of the force majeure events had subsided. Consider a still pond where a stone is suddenly dropped into the water. The initial wave of the impact is significant and then travels radially outward. The resulting waves dissipate proportionally to the distance traveled, until ultimately there is a return to calm. Similarly, these force majeure events act like the stone and the ripple effect is the impacts caused by those events, which dissipate over time until no lingering impact remains. The challenge lies in measuring the duration of the impact period with the contemporaneous CPM schedule data.

Results of the piping sample project are presented in **Table 6-4** and **Table 6-5**. Progression of the best-fitting curves for the condo project schedule density histograms are shown in **Figure 6-8** and **Figure 6-9**. The variable correlation matrix is presented in **Figure 6-10**.

Table 6-4 Piping Project - Centroid Results Based on Early Dates

Data Date	∑ Density	∑ Work Days	x Coord Date	Centroid x Coord	Centroid y Coord	Δ Data Date	Δ x	Cum Δx	Δ y	Cum Δy	R^2 Scaler	Cum R^2 Scaler
01-Jan-07	3,684	347	23-Dec-07	356.4	10.6	0	0	0	0.000	0.000	0.0	0.0
26-Feb-07	7,557	383	28-Dec-07	305.6	19.7	56	5.2	5.2	9.114	9.114	10.5	10.5
26-Mar-07	7,498	374	12-Jan-08	292.7	20.0	28	15.1	20.3	0.317	9.431	15.1	25.6
30-Apr-07	7,471	309	29-Jan-08	274.0	24.2	35	16.3	36.6	4.130	13.561	16.8	42.4
04-Jun-07	7,420	309	02-Feb-08	243.3	24.0	35	4.3	40.9	-0.165	13.396	4.3	46.7
02-Jul-07	7,555	333	29-Jan-08	211.1	22.7	28	-4.2	36.6	-1.325	12.071	-4.4	42.2
30-Jul-07	7,329	394	09-Feb-08	194.6	18.6	28	11.5	48.1	-4.086	7.985	12.2	54.4
27-Aug-07	7,345	406	01-Feb-08	158.5	18.1	28	-8.0	40.1	-0.510	7.474	-8.0	46.4
31-Dec-07	6,376	392	19-Mar-08	79.8	16.3	126	47.2	87.3	-1.826	5.649	47.3	93.7
28-Jan-08	4,482	318	11-Mar-08	44.0	14.1	28	-7.8	79.6	-2.171	3.478	-8.1	85.6
25-Feb-08	4,831	403	28-Mar-08	32.8	12.0	28	16.8	96.4	-2.107	1.371	16.9	102.5
24-Mar-08	5,020	416	15-Apr-08	22.9	12.1	28	18.1	114.5	0.080	1.451	18.1	120.7
28-Apr-08	4,843	342	08-May-08	10.5	14.2	35	22.6	137.0	2.094	3.544	22.7	143.3
26-May-08	5,553	342	31-May-08	5.7	16.2	28	23.2	160.3	2.076	5.620	23.3	166.7
23-Jun-08	6,021	339	26-Jun-08	3.4	17.8	28	25.7	185.9	1.524	7.144	25.7	192.4

Table 6-5 Piping Project Best-Fitting Curve Descriptive Values and Area Calculations for Early Dates

Data Date	Fit Adj R-Sq	Fit RMSE	Fit # Coeff	Data_Date Week No	First Plan Week No	Last Plan Week No	Area Tot	Area Left of DD	Area Right of DD	AR % of AT	MHrs / % Compl
01-Jan-07	0.96	8.75	3	1	4	73	3625	-2	3627	100%	n/a
26-Feb-07	0.99	5.93	6	1	1	77	7578	0	7578	100%	n/a
26-Mar-07	0.98	10.46	3	1	3	77	7563	-1	7565	100%	n/a
30-Apr-07	0.99	6.63	3	5	16	77	7532	-33	7565	100%	n/a
28-May-07	1.00	4.35	6	10	16	77	7402	-15	7417	100%	n/a
02-Jul-07	1.00	4.71	6	14	11	77	7520	22	7498	100%	739
30-Jul-07	1.00	4.70	9	18	7	85	7307	140	7167	98%	861
27-Aug-07	1.00	4.89	9	22	7	88	7245	230	7015	97%	1218
31-Dec-07	0.99	5.02	9	40	9	89	6356	1396	4960	78%	1454
28-Jan-08	0.99	5.39	9	44	9	74	4459	1656	2804	63%	1413
25-Feb-08	1.00	3.20	12	48	1	77	4812	2444	2368	49%	1223
24-Mar-08	0.99	3.92	15	52	1	84	5023	3099	1924	38%	1204
28-Apr-08	0.99	4.21	12	57	9	79	4838	3614	1224	25%	1536
26-May-08	0.99	4.31	15	61	9	79	5556	4516	1040	19%	1831
23-Jun-08	1.00	4.25	15	65	9	78	6017	5225	792	13%	2171

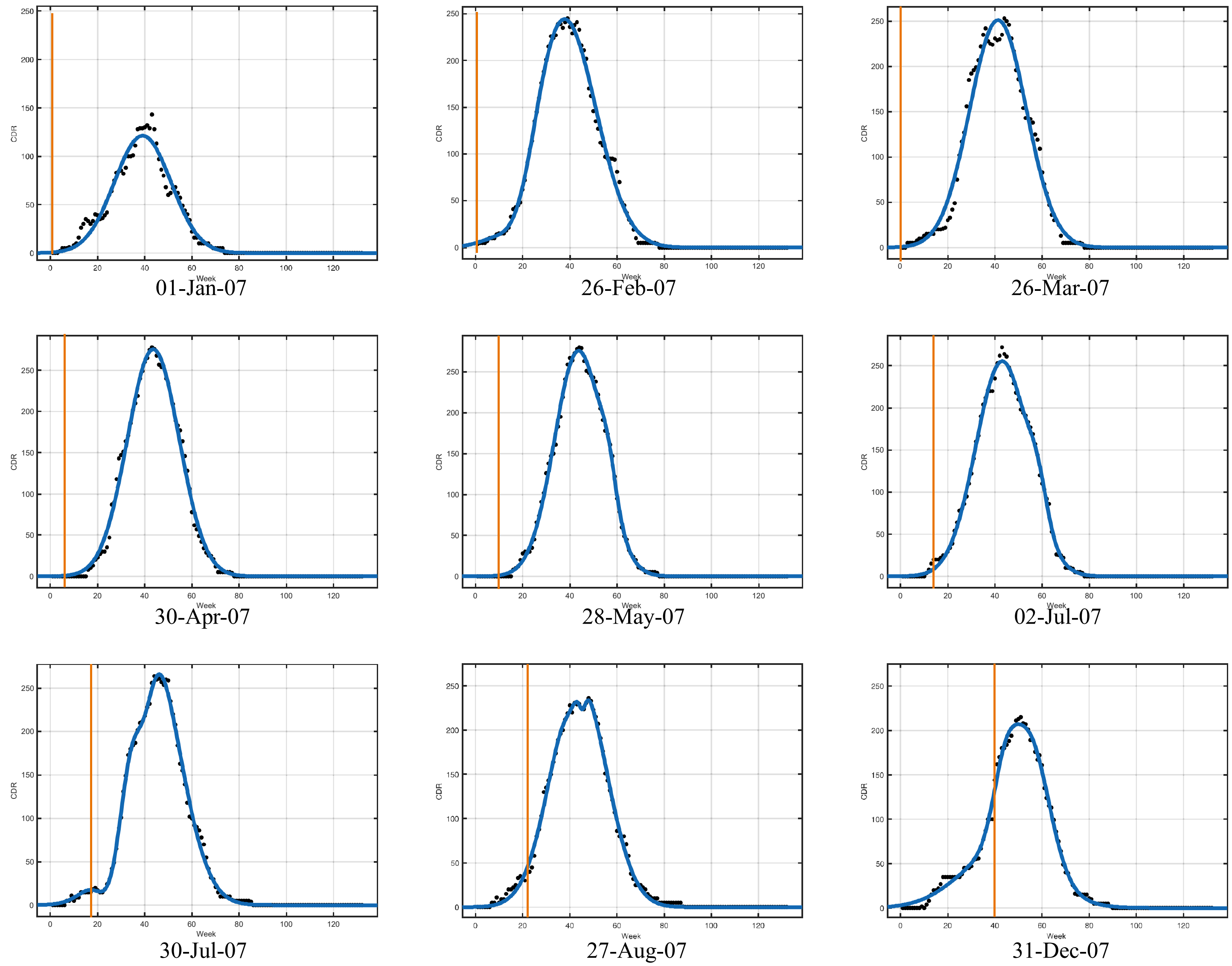


Figure 6-8 Piping Project Best-Fitting Curves for Schedule Data Dates Shown (January 2007 to December 2007)

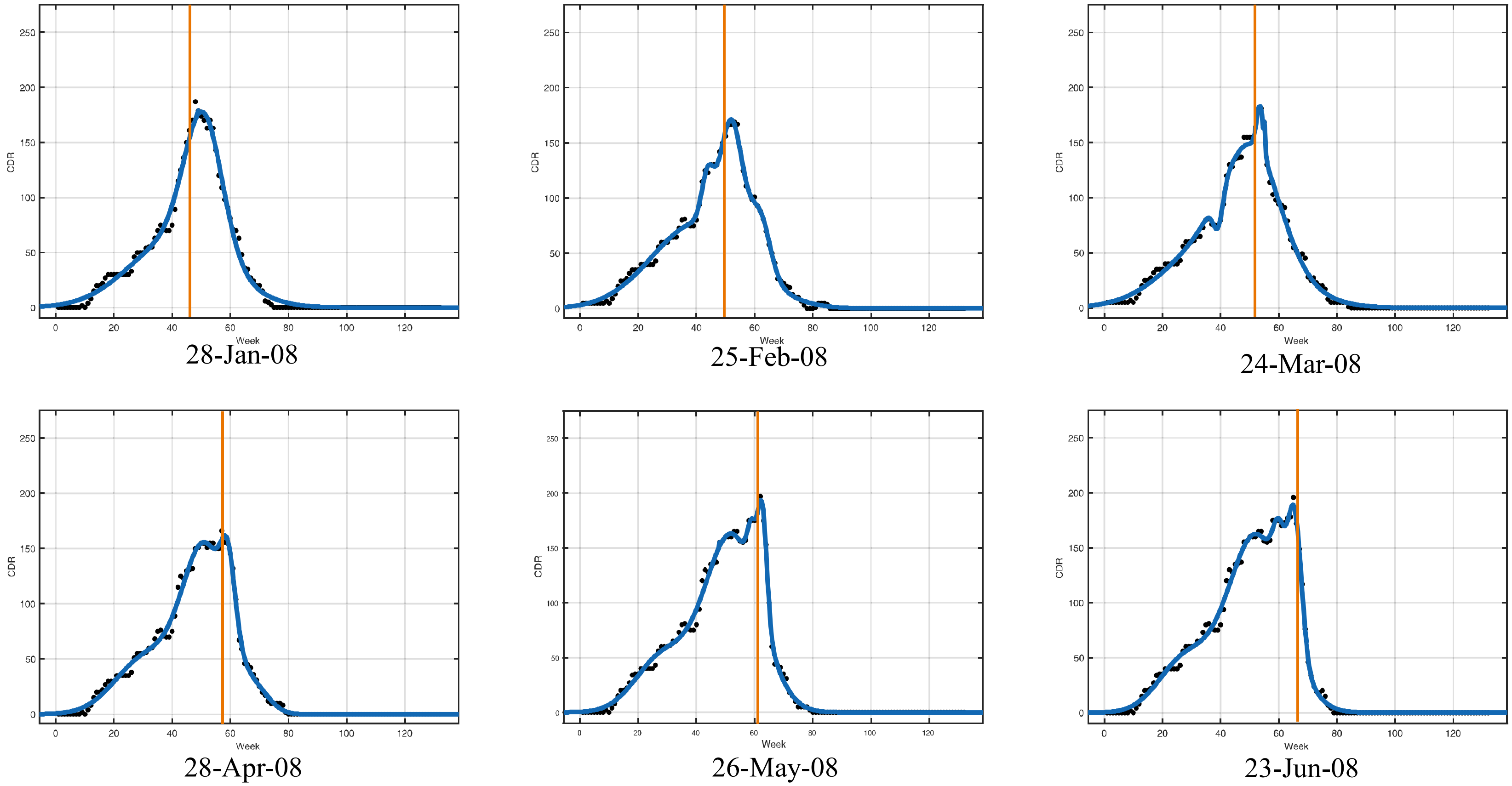


Figure 6-9 Piping Project Best-Fitting Curves for Schedule Data Dates Shown (January 2008 to June 2008)

	∑ Density	ƒ(x) Area Tot No Ex	ƒ(x) Area Right No Ex	ƒ(x) AR % No Ex	Cum Δ x	Cum Δ y	Cum R^2 Scalar	Cum MHr % Compl
ƒ(x) Area Tot No Ex	P01 Linear m = 1.00 0.999							
ƒ(x) Area Right No Ex	P02 Exp1 f(x) = a*exp(b*x) 0.850	P08 Exp1 f(x) = a*exp(b*x) 0.845						
ƒ(x) AR % No Ex	P03 Exp1 f(x) = a*exp(b*x) 0.654	P09 Exp1 f(x) = a*exp(b*x) 0.645	P14 Linear m = 0.00012 0.958					
Cum Δ x	P04 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.894	P10 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.895	P15 Exp1 f(x) = a*exp(b*x) 0.910	P19 Exp1 f(x) = a*exp(b*x) 0.966				
Cum Δ y	P05 Linear m = 0.0029 0.811	P11 Linear m = 0.0028 0.816	P16 Exp2 f(x) = a*exp(b*x) 0.873	P20 Exp2 f(x) = a*exp(b*x) 0.871	P23 Sine2 f(x) = a1*sin(b1*x+c1) 0.754			
Cum R^2 Scalar	P06 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.892	P12 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.893	P17 Exp1 f(x) = a*exp(b*x) 0.906	P21 Linear m = -144.9 0.942	P24 Linear m = 1.01 0.999	P26 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.545		
Cum Mhr % Compl	P07 Exp2 f(x) = a*exp(b*x) + c*exp(d*x) 0.683	P13 Exp2 f(x) = a*exp(b*x) + c*exp(d*x) 0.703	P18 Exp2 f(x) = a*exp(b*x) 0.824	P22 Exp2 f(x) = a*exp(b*x) 0.800	P22 Exp2 f(x) = a*exp(b*x) 0.827	P27 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.456	P28 Exp2 f(x) = a*exp(b*x) 0.828	
Kurtosis	P29 Linear m = -0.00019 0.345	P31 Linear m = -0.00018 0.365	No Fit	No Fit	No Fit	No Fit	No Fit	No Fit
Skewness	P30 Linear m = -0.00002 0.084	P32 Linear m = -0.00002 0.085	No Fit	No Fit	No Fit	No Fit	No Fit	No Fit

Key

Strong Correlation (0.89 < R^2 < 1.0)	Poor Correlation (no fit)
Good Correlation (0.79 < R^2 < 0.9)	Inconclusive (0.69 < R^2 < 0.8)

Figure 6-10 Piping Project Variables Correlation Matrix Results

Tracking the change in best-fitting curves for the schedule density histograms shows that as delay occurs, the planned number of overlapping activities likewise increases. This same trend is observed in the High Rise Hotel and Condo Tower projects.

Steel Structure

The steel structure project comprised construction of a government steel structure approximately 100-feet tall and 300-feet in length. Total construction cost exceeded $100 million. The prime contractor experienced delays to concrete work – work that preceded the steel erection activities. Without a time extension, the prime contractor had to maintain schedule despite stacked planned structural steel erection work. Because this work involved construction of a structure with heavy cranes and equipment, the stacking of planned erection work only carried so far.

Results of the Structural Steel sample project are presented in **Table 6-6** and **Table 6-7**. Progression of the best-fitting curves for the Structural Steel project schedule density histograms are shown in **Figure 6-11** and **Figure 6-12**. The variable correlation matrix is presented in **Figure 6-13**.

Figure 6-11 Structural Steel Project (Source: Daily Journal of Commerce, Seattle, WA January 23, 2017)

Table 6-6 Structural Steel Project

Data Date	∑ Density	∑ Work Days	x Coord Date	Centroid x Coord	Centroid y Coord	Δ Data Date	Δ x	Cum Δx	Δ y	Cum Δy	ℝ Scalar	Cum ℝ Scalar
01-Oct-14	274	159	11-Feb-15	133.61	1.72	0	0	0	0.000	0.00	0.0	0.0
01-Nov-14	264	163	28-Feb-15	119.31	1.62	31	16.7	16.7	-0.104	-0.10	16.69	16.7
01-Dec-14	248	140	05-Mar-15	94.48	1.77	30	5.2	21.9	0.152	0.05	5.17	21.9
01-Jan-15	194	123	24-Feb-15	54.75	1.58	31	-8.7	13.1	-0.194	-0.15	-8.73	13.1
01-Feb-15	445	149	22-Feb-15	21.29	2.99	31	-2.5	10.7	1.409	1.26	-2.84	10.3
01-Mar-15	813	172	10-Mar-15	9.04	4.73	28	15.7	26.4	1.740	3.00	15.84	26.1
01-Apr-15	999	184	06-Apr-15	5.59	5.43	31	27.6	54.0	0.703	3.71	27.57	53.7
01-May-15	1,327	198	04-May-15	3.55	6.70	30	28.0	81.9	1.273	4.98	27.99	81.7
01-Jun-15	1,392	205	03-Jun-15	2.17	6.79	31	29.6	111.6	0.088	5.07	29.62	111.3
01-Jul-15	1,431	203	01-Jul-15	0.92	7.05	30	28.8	140.3	0.259	5.33	28.76	140.1
01-Aug-15	1,491	213	01-Aug-15	0.67	7.00	31	30.8	171.1	-0.049	5.28	30.75	170.8
01-Sep-15	1,530	231	01-Sep-15	0.28	6.62	31	30.6	201.7	-0.377	4.90	30.61	201.4
01-Oct-15	1,553	249	01-Oct-15	0.03	6.24	30	29.8	231.4	-0.386	4.51	29.75	231.2
01-Nov-15	1,594	264	01-Nov-15	0.00	6.04	31	31.0	262.4	-0.199	4.31	30.97	262.2

Table 6-7 Structural Steel Project Best-Fitting Curve Descriptive Values and Area Calculations for Early Dates

Data Date	Fit Adj R-Sq	Fit RMSE	Fit # Coeff	Data_Date Bi-Week No	First Plan Bi-Week No	Last Plan Bi-Week No	Area Tot	Area Left DD	Area Right DD	Area Rt DD Pct of AT	Cum MHrs per % Compl
01-Oct-14	0.88	3.01	15	1	1	21	291	4	287	100%	256
01-Nov-14	0.92	2.34	18	3	1	23	283	6	277	100%	314
01-Dec-14	0.92	2.44	24	5	1	21	300	10	290	100%	166
01-Jan-15	0.79	3.43	24	8	1	21	178	38	140	79%	193
01-Feb-15	0.97	4.17	21	10	1	23	431	312	120	28%	281
01-Mar-15	0.98	5.82	24	12	1	23	807	703	103	13%	360
01-Apr-15	0.98	6.56	9	14	1	24	993	896	97	10%	451
01-May-15	0.97	9.18	15	16	1	25	1316	1233	82	6%	487
01-Jun-15	0.96	11.35	21	18	1	25	1389	1309	80	6%	482
01-Jul-15	0.99	5.73	21	20	1	25	1433	1379	54	4%	463
01-Aug-15	0.99	5.92	24	23	1	27	1491	1470	21	1%	478
01-Sep-15	0.96	11.05	18	25	1	29	1520	1505	15	1%	476
01-Oct-15	0.97	8.38	21	27	1	28	1553	1546	7	0%	479
01-Nov-15	0.96	10.03	24	29	1	29	1592	1584	8	1%	n/a

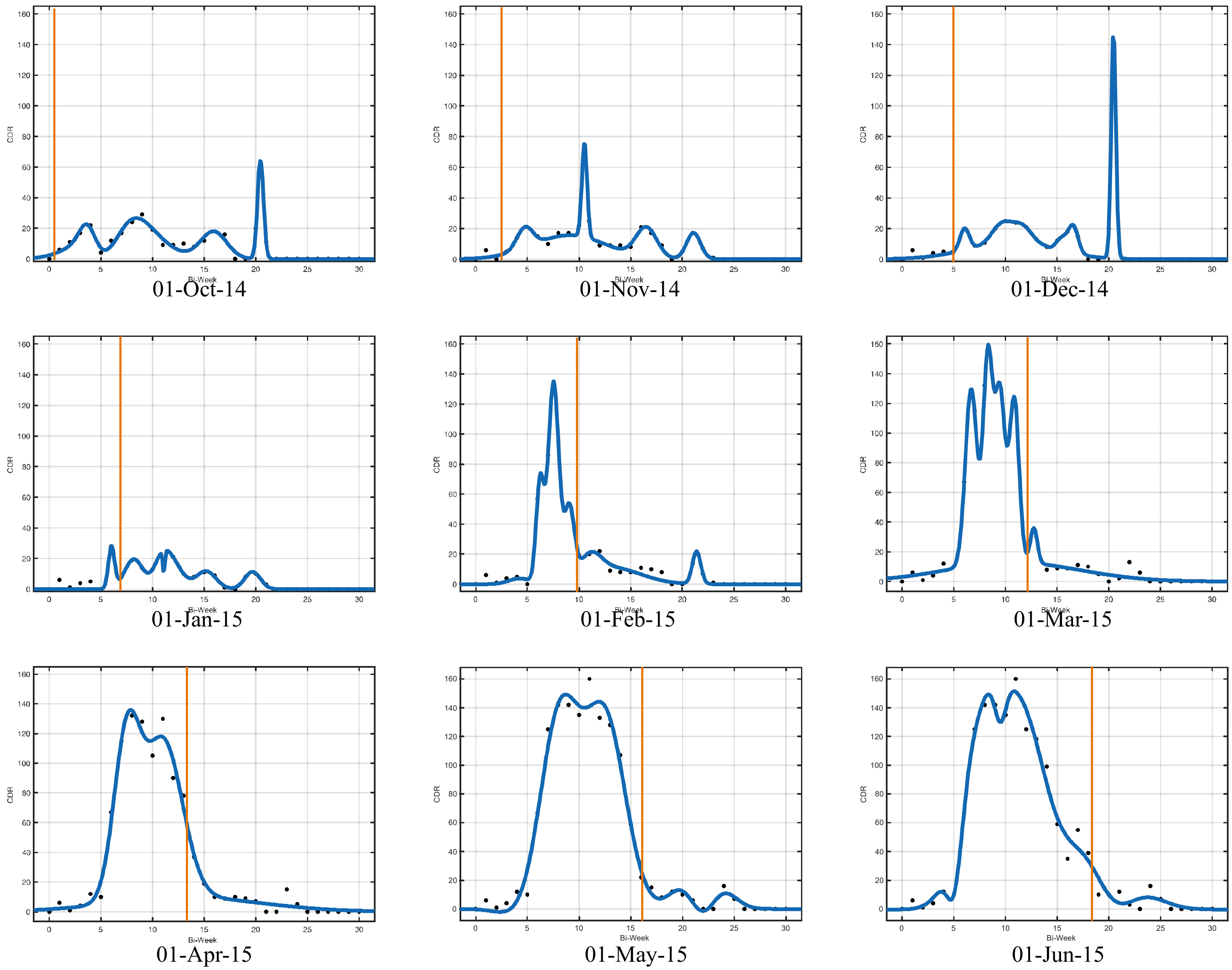


Figure 6-12 Structural Steel Project Best-Fitting Curves for Schedule Data Dates Shown (October 2014 to June 2015)

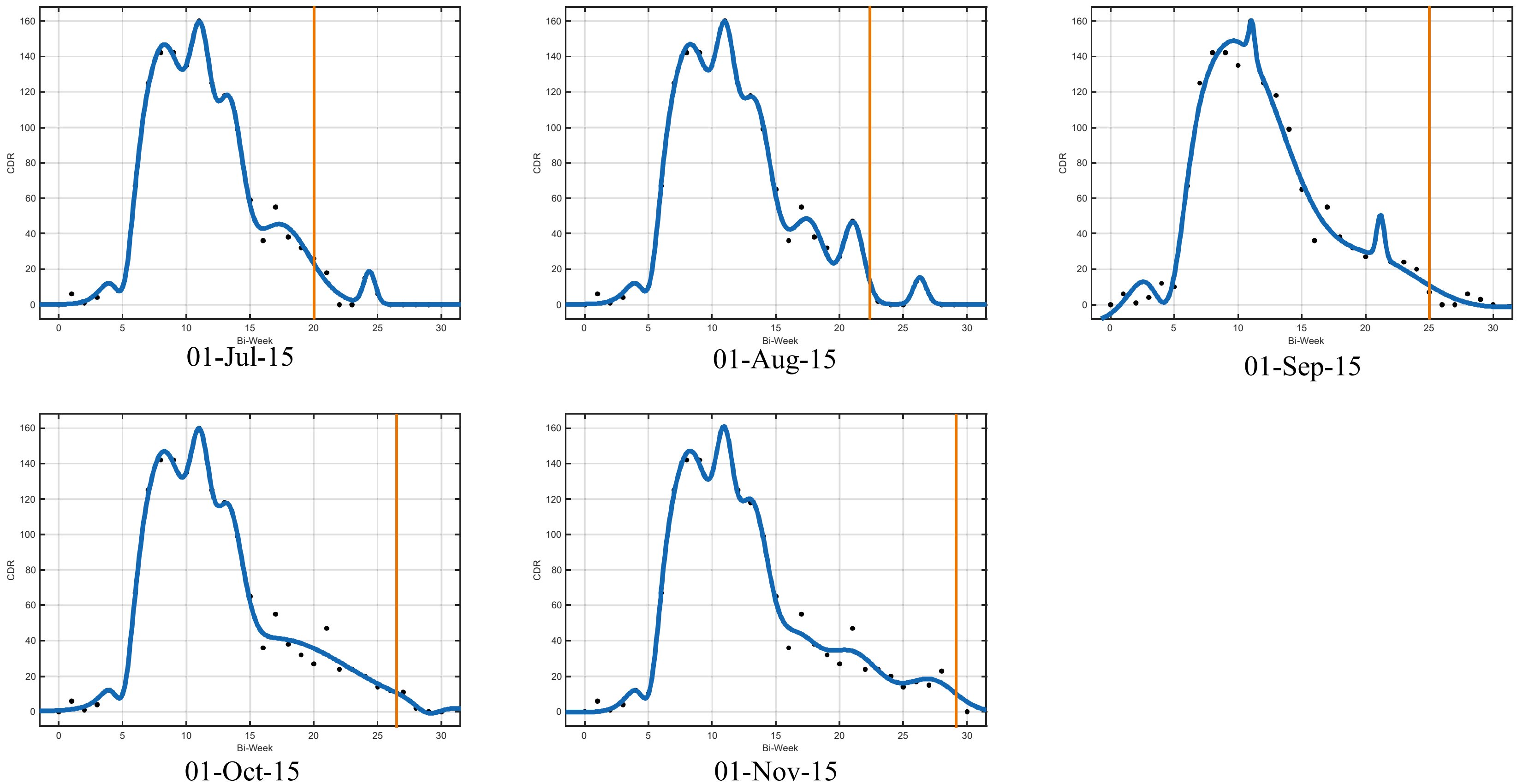


Figure 6-13 Structural Steel Project Best-Fitting Curves for Schedule Data Dates Shown (July 2015 to November 2015)

	∑ Density	ƒ(x) Area Tot No Ex	ƒ(x) Area Right No Ex	ƒ(x) AR % No Ex	Cum Δ x	Cum Δ y	Cum R^2 Scalar	Cum MHr % Compl
ƒ(x) Area Tot No Ex	W01 Linear m = 0.987 0.999							
ƒ(x) Area Right No Ex	W02 Linear m = -0.158 0.782	W08 Linear m = -0.00006 0.763						
ƒ(x) AR % No Ex	W03 Exp1 f(x) = a*exp(b*x) 0.920	W09 Exp1 f(x) = a*exp(b*x) 0.873	W14 Linear m = 0.0039 0.890					
Cum Δ x	W04 Exp1 f(x) = a*exp(b*x) 0.981	W10 Exp1 f(x) = a*exp(b*x) 0.982	W15 Exp1 f(x) = a*exp(b*x) 0.946	W19 Exp1 f(x) = a*exp(b*x) 0.970				
Cum Δ y	W05 Linear m = 0.0039 0.943	W11 Linear m = 0.0039 0.939	W16 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.968	W20 Exp1 f(x) = a*exp(b*x) 0.943	W23 Sine2 f(x) = a1*sin(b1*x+W1) 0.910			
Cum R^2 Scalar	W06 Exp1 f(x) = a*exp(b*x) 0.981	W12 Exp1 f(x) = a*exp(b*x) 0.982	W17 Exp1 f(x) = a*exp(b*x) 0.946	W21 Exp1 f(x) = a*exp(b*x) 0.970	W24 Linear m = 1.00 1.000	W26 Exp1 f(x) = a*exp(b*x) 0.556		
Cum Mhr % Compl	W07 Linear m = 0.201 0.896	W13 Linear m = 0.203 0.890	W18 Linear m = -0.946 0.640	W22 Exp1 f(x) = a*exp(b*x) 0.800	W25 Exp2 f(x) = a*exp(b*x) 0.800	W27 Linear m = 48.75 0.898	W28 Exp2 f(x) = a*exp(b*x) 0.795	
Kurtosis	No Fit	No Fit	W29 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.997	W31 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.867	W33 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.779	W35 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.746	W37 Gauss3 f(x) = a1*exp(-((x-b1)/c1)^2) 0.996	No Fit
Skewness	No Fit	No Fit	W30 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.986	W32 Gauss1 f(x) = a1*exp(-((x-b1)/c1)^2) 0.932	W34 Gauss3 f(x) = a1*exp(-((x-b1)/c1)^2) 0.930	W36 Gauss2 f(x) = a1*exp(-((x-b1)/c1)^2) 0.766	W38 Gauss4 f(x) = a1*exp(-((x-b1)/c1)^2) 0.986	No Fit

Key

Strong Correlation (0.89 < R^2 < 1.0)	Poor Correlation (no fit)
Good Correlation (0.79 < R^2 < 0.9)	Inconclusive (0.69 < R^2 < 0.8)

Figure 6-14 Structural Steel Project Variables Correlation Matrix Results

Overall Correlation Synthesized

Considering the results of the first three sample projects, the synthesized results are shown in

Figure 6-15Error! Reference source not found.. The lognormal function that joins the cumulative centroid scaler value and cumulative manhours per percent complete represents good correlation overall. Results in this figure, however, represent the joining of mechanical, piping and structural steel trades. Thus, caution is warranted when interpreting these results. The lower r-square value found in applying the methodology to the Resort Hotel sample project presented in Chapter 7 supports this warning. More research and a larger sample size may help resolve the differences.

	∑ Density	*f*(x) Area Tot No Ex	*f*(x) Area Right No Ex	*f*(x) AR % No Ex	Cum Δ x	Cum Δ y	Cum R^2 Scalar
f(x) Area Tot No Ex	Strong Linear						
f(x) Area Right No Ex	Inconclusive	Inconclusive					
f(x) AR % No Ex	Good Linear	Good Linear	Inconclusive				
Cum Δ x	Strong Exponential	Strong Exponential	Inconclusive	Strong Exponential			
Cum Δ y	Good Linear	Good Linear	Inconclusive	Good Linear	Inconclusive		
Cum R^2 Scalar	Strong Exponential	Strong Exponential	Inconclusive	Strong Exponential	Strong Linear	Inconclusive	
Cum Mhr % Compl	Inconclusive Linear	Inconclusive Linear	Inconclusive	Good Lognormal	Good Lognormal	Inconclusive	Good Lognormal
Kurtosis	Project Dependent						
Skewness	Project Dependent						
	Correlation Rating: Strong 0.89 < r-sq < 1.0; Good 0.79 < r-sq < 0.9; Inconclusive 0.69 < r-sq < 0.8						

Figure 6-15 Synthesized Results of the Regression Analyses

7 Empirical Validation of Results

Validation of results was performed in two ways. First, the lognormal function derived from the High Rise Hotel project was applied to the Resort Hotel sample project. There is practical value in being able to take the predictive model derived from this study and have a contractor or other practitioner be able to apply it to their own project. The intent is to see how correlation with an outside project compared when overlaying results of the other four projects upon it. The second validation effort included assembling an expert panel and soliciting opinions of the panelists via a Delphi Study relative to the findings of the research. Because the methodology developed in this study is unique, validation of results via experts and their collective years of experience help to establish credibility. Both of these validation efforts are presented below.

Hotel Resort Validation Project

Observed results from the sample projects evaluated were applied to a resort hotel project located in a mountainous region of central California (see **Figure 7-1**). The hotel is a 6-story building with parking located beneath. Total project cost was approximately $50 million. It is believed that the resulting lognormal functions for the other three sample projects would provide a good fit for the mechanical work of this Resort Hotel project.

Figure 7-1 Resort Hotel

The predictive forecast made prior to evaluation of this resort project included, if the cumulative centroid scaler value for the resort is continuously increasing, then there will be a lognormal relationship between this value and the cumulative manhours per percent complete measure experienced. Regression analysis and derivation of a best-fitting curve were used to vet this forecast.

Figure 7-2 shows the best-fitting curve for the resort project. This curve is an exponential function and differs in general shape from the log normal functions found in the sample projects. The data suggests that productivity actually improved even though the cumulative centroid scalar value continued to increase. The data includes outlier data points, which influence the selection of the best-fitting function. Outlier data here includes early learning curve time for the first month of work and wind down time for the last couple months. By removing the outlier data points as was done for all of the other sample projects, **Figure 7-3** results, which looks similar to the other sample project results.

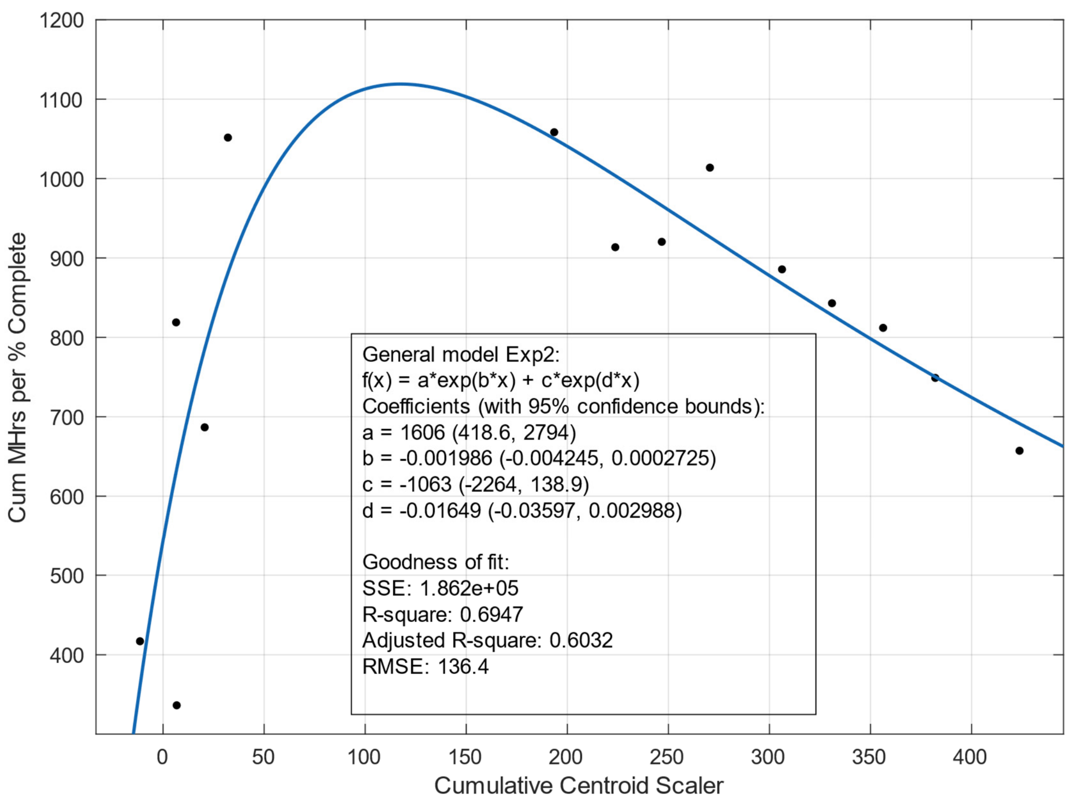


Figure 7-2 Resort Project Best-Fitting Curve with Outlier Data Included

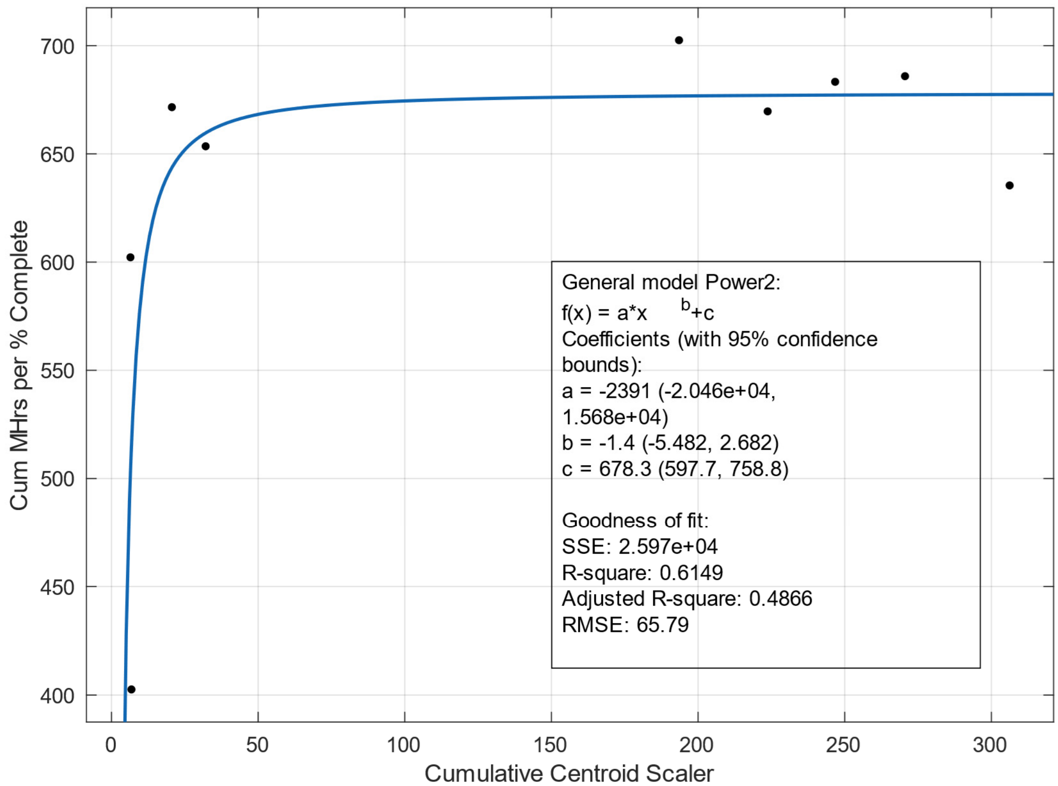


Figure 7-3 Resort Project Best Fitting Curve with Outliers Removed

Removing the outliers results in a best-fitting power function, instead of the exponential function shown in **Figure 7-2**. Additionally, the r-square value is less for the power function.

The lognormal function derived from the sample projects was then applied to the resort project as shown in Error! Reference source not found.. The r-square value was just 0.50, which shows some correlation, but is not as strong as the correlations found in the sample projects.

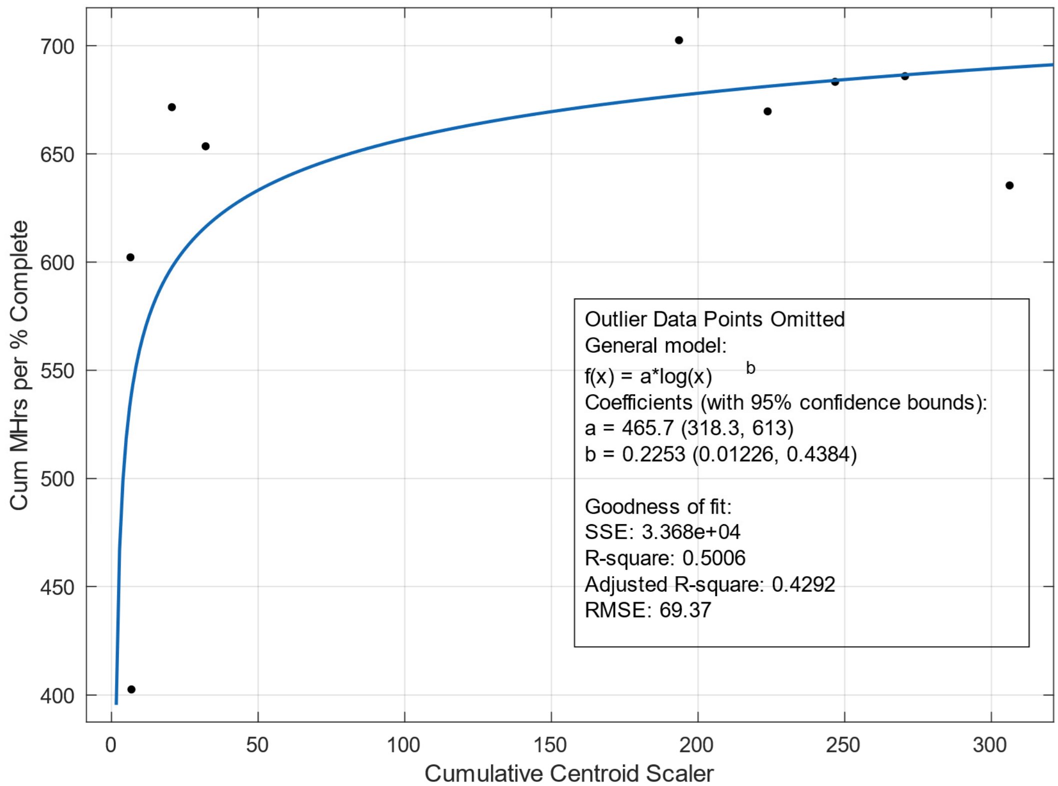


Figure 7-4 Resort Project Log Normal Function Applied to Outliers Removed Data Se

Several reasons may explain the lesser correlation:

1. The resort project occurred at a non-urban location where the supply of skilled laborers originates from outside locations and may be less available than in an urban environment;
2. The resort is only 6-stories tall and by fire code is not classified as a high-rise structure. In effect, the resort is not as large or complex a project in comparison to the hotel and condo high rises; and
3. The resort project is located in the mountains and subject to seasonal weather conditions. While the weather is good, contractors typically spend as many hours as

are necessary to finish ahead of snowy/bad weather days, and pay less attention to productivity.

Results from the calculations for the Resort Hotel sample project are presented in **Table 7-1**.

Table 7-1 Resort Project Centroid Results Based on Early Dates

Data Date	∑ Density	∑ Work Days	x Coord Date	Centroid x Coord	Centroid y Coord	Δ Data Date	Δ x	Cum Δx	Δ y	Cum Δy	R^2 Scaler	Cum R^2 Scaler	Cum MHrs / % Compl
17-Apr-06	493	176	14-Sep-06	150.9	2.8	0	0	0	0.000	0.000	0.0	0.0	0
02-Jun-06	523	222	21-Sep-06	111.7	2.4	46	6.7	6.7	-0.445	-0.445	6.8	6.8	403
07-Jul-06	680	197	03-Sep-06	58.5	3.5	35	-18.1	-11.4	1.096	0.651	-18.2	-11.4	443
25-Aug-06	1110	232	21-Sep-06	27.3	4.8	49	17.8	6.4	1.333	1.983	17.9	6.5	602
18-Sep-06	1030	217	05-Oct-06	17.5	4.7	24	14.1	20.6	-0.038	1.945	14.1	20.6	672
06-Oct-06	1726	228	16-Oct-06	10.6	7.6	18	11.2	31.7	2.824	4.769	11.5	32.1	654
29-Jan-07	416	132	26-Mar-07	57.0	3.2	115	161.3	193.1	-4.419	0.350	161.4	193.5	703
07-Apr-07	493	113	26-Apr-07	19.2	4.4	68	30.2	223.3	1.211	1.562	30.2	223.7	670
05-May-07	622	129	19-May-07	14.2	4.8	28	23.0	246.2	0.459	2.021	23.0	246.7	683
31-May-07	625	140	11-Jun-07	12.0	4.5	26	23.8	270.1	-0.357	1.663	23.8	270.5	686
07-Jul-07	657	156	17-Jul-07	10.7	4.2	37	35.7	305.7	-0.253	1.410	35.7	306.2	635
06-Aug-07	834	174	11-Aug-07	5.4	4.8	30	24.7	330.5	0.582	1.992	24.7	330.9	594
04-Sep-07	971	175	05-Sep-07	1.6	5.5	29	25.3	355.7	0.755	2.747	25.3	356.2	589
01-Oct-07	1288	180	01-Oct-07	0.4	7.2	27	25.7	381.5	1.607	4.354	25.8	382.0	0
12-Nov-07	1326	197	12-Nov-07	0.1	6.7	42	41.7	423.2	-0.425	3.930	41.7	423.7	0

Delphi Study

Pursuant to validating results of the sample study analysis findings, a Delphi Survey was performed. Results of this study must be tested and validated for logical soundness and general understandability. In addition to the causal theory presented above, further validation was sought using a Delphi Study with industry experts.

The Delphi technique is a method of surveying a group of expert panelists systematically with intent to reach consensus on specific questions (Ellis, 1989). Delphi may be characterized as a method for structuring a group communication process. The process is effective in allowing a group of individuals, as a whole, to deal with a complex problem (Linstone & Turoff, 1975) and is useful for situations where individual judgements must be tapped and combined in order to address a lack of agreement or incomplete state of knowledge (Delbecq, 1975). The literature review found that no existing methodology similar to the approach derived herein exists, therefore, the Delphi technique as applied here sought to expand the state of knowledge in validating the results. Linstone & Turoff further explain the Delphi method indicating up to four phases may be required to get consensus,

> *Usually Delphi . . . undergoes four distinct phases. The first phase is characterized by exploration of the subject under discussion, wherein each individual contributes additional information he feels is pertinent to the issue. The second phase involves the process of reaching an understanding of how the group views the issue (i.e., where the members agree or disagree and what they mean by relative terms such as importance, desirability, or feasibility). [I]f there is significant disagreement, then that disagreement is explored in the third phase to*

bring out the underlying reasons for the differences and possibly to evaluate them. The last phase, a final evaluation, occurs when all previously gathered information has been initially analyzed and the evaluations have been fed back for consideration.

The Delphi technique scrutinizes the methodology presented in this research utilizing experts in CPM scheduling, project controls and labor productivity. Questions presented to the panelists were based on logical reasoning to verify that the methodology was sensible and the results were reasonable. Results of the Delphi study required just two phases because consensus was met. Phase 1 served as a pre-qualifying step. Prerequisite qualifications to participate in the survey included a minimum of 5 years of experience in construction or construction project management, a knowledge of CPM scheduling and a having witnessed trade stacking. Phase 2 sought the expert panelists' collective experiences regarding trade stacking and construction labor productivity, and how their experiences correlated with results of this dissertation research. Results of Phase 2 confirmed a general consensus of the results such that a third phase was deemed unnecessary.

In total, 106 potential panel experts were contacted for Phase 1, but just 33 responded of which 31 were qualified to take the Phase 2 survey. For Phase 2, 17 participants completed the survey. Results for each survey are presented below.

Phase 1

The Phase 1 survey consisted of 10 questions. These questions sought general information about the type and depth of experience, employment history and knowledge of CPM and labor productivity. Refer to **Exhibit 7A** for a complete copy of the survey. The survey was administered via QuestionPro software and made available via the internet. Potential participants were identified based on professional business contact lists and via construction industry meetings. Summary results of the Phase 1 survey are presented below. Not every respondent answered every question. Consequently, the count for respondents in the tables below do not always equal the number of participants who completed the Phase 1 survey.

Employer Types and Time

Participants were asked the types of employers they have worked with in their careers. Participants could select more than one employer type. Results show that all employer types are represented, but that general contractor was the most common (see **Table 7-2**).

Table 7-2 Delphi Phase 1 Represented Employer Types

Employer Type	**Employed in Career Count**	**Present Employer Count**
Public Owner (e.g., government agency)	9	4
Military Branch (e.g., U.S. Corps of Engineers, U.S. Navy, etc.)	4	0
Private Owner (e.g., Developer, Corporation, etc.)	14	7
General Contractor	**20**	**11**
Specialty Contractor	9	3
Other (e.g., Consultant, Professor)	6	8

Table 7-3 shows that 19 respondents (more than half) indicated having been more than 10 years with their present employer.

Table 7-3 Delphi Phase 1 Represented Years Experience with Present Employer

Time	**Count**	**Percent**
Less than 1 year	0	0.00%
1 to 5 years	12	36.36%
5 to 10 years	2	6.06%
More than 10 years	**19**	**54.55%**

Project Size

Participants were asked to provide the average estimated value of construction projects they had managed or constructed over the last three years. Results are presented in **Table 7-4** . Twenty-six respondents (approximately 80 percent) indicated having managed or constructed projects valued at more than $50 million in the past three years.

Table 7-4 Delphi Phase 1 Represented Project Sizes Managed or Constructed

Estimated Project Value	Count	Percentage
< $50 Million	7	21.21%
$50 to $250 Million	9	27.27%
$250 to $500 Million	4	12.12%
More than $500 Million	**13**	**39.39%**

Work Experience

Participants were asked how many cumulative years of construction field experience or construction management they possessed. As shown in **Table 7-5** , a total of 29 participants indicated having more than ten years of experience. Participants reporting less than five years of experience were removed from the pool of potential Phase 2 survey participants.

Table 7-5 Delphi Phase 1 Represented Years of Experience per Participant

Experience	Count	Percentage
Less than 5 years	3	9.09%
5 to 10 years	1	3.03%
10 to 15 years	4	12.12%
15 to 20 years	6	18.18%
More than 20 years	**19**	**51.52%**

Participants were asked to describe the type of duties they perform in their present duties. Results are shown in **Table 7-6** . Given the years of experience participants reported, it is not surprising that much of the daily duties performed includes executive and project management functions.

Table 7-6 Delphi Phase 1 Represented Duties Performed per Participant

Position	Count	Percentage
Executive	**14**	**30.43%**
Project Management	11	23.91%
Superintendent (or other field manager)	2	4.35%
Scheduler	7	15.22%
Estimator	3	6.52%
Project Controller / Contract Administrator	3	6.52%
Other (e.g., educator, consulting)	6	13.04%

Respondents were asked to rate their proficiency with CPM scheduling. Results showed that 63 percent of the respondents possessed advanced or expert proficiency (see **Table 7-7**).

Table 7-7 Delphi Phase 1 Reported Proficiency with CPM Scheduling

Proficiency	**Count**	**Percentage**
Fundamental Awareness (basic knowledge)	2	6.67%
Novice (limited experience)	1	3.33%
Intermediate (practical application)	8	26.67%
Advanced (applied theory)	**12**	**40.00%**
Expert (recognized authority)	7	23.33%

Factors That Affect Construction Labor Productivity

Utilizing a Likert scale (McIver, 1981, pp. 23–31) with values ranging from 1 (extremely negative) to 7 (extremely positive), respondents were asked to rate the impact, if any, of factors identified in literature that influence construction labor productivity. Twenty-four different factors were presented. These factors mimicked those identified by Dual and Syal, 2017. Results are presented in **Figure 7-5**. Backup for the calculated Likert averages as shown in the figure are presented in **Exhibit 7A**.

Respondents results show that Dilution of Supervision causes a significantly negative impact on construction labor productivity (average Likert scale equals 2.23). This study focuses primarily on trade stacking, which had an average Likert scale rating of 2.55, which likewise falls into the significantly negative category.

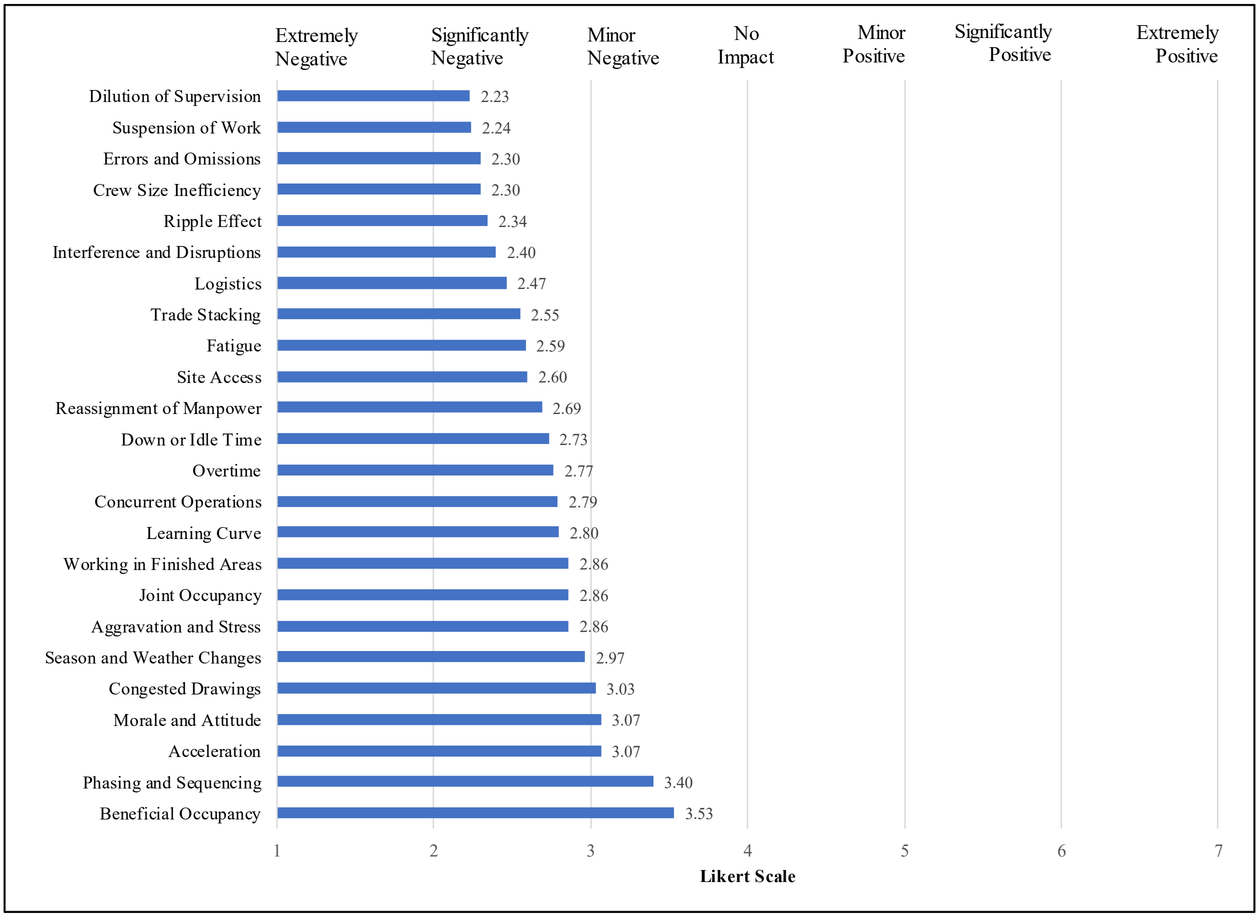


Figure 7-5 Delphi Phase 1 – Likert Ratings for Factors that Influence Labor Productivity

A paired t-test was performed to test the hypothesis that the difference between these two means equal zero, i.e., H_o: $\mu_1 - \mu_2 = 0$. (Ott, 1993, p. 154) Rejection of this hypothesis follows if the calculated t-value is greater than the alpha level of confidence for a t-distribution, or rather, reject H_o if $t > t_{\alpha/2}$. The calculated t-test statistic for a one-tailed test for these two means was found to be 0.44, versus a t-distribution value of 2.462 for $\alpha/2 = 0.01$. Consequently, the null hypothesis was not rejected and it may be reasonably inferred that the means are not significantly different. Stated plainly, the trade stacking variable and its perceived impacts on labor productivity is significant even though trade stacking did not appear with the lowest mean Likert scale.

Respondents were asked to indicate their observed effects of trade stacking on construction labor productivity for mechanical, electrical, plumbing and steel erection trades work. A similar Likert scale was used that ranged from Extremely Negative to Extremely Positive. **Figure 7-6** presents the respondents' results and shows that in the participants' experiences, trade stacking caused significantly negative effects on mechanical piping, electrical, mechanical HVAC, mechanical plumbing and steel erection activities.

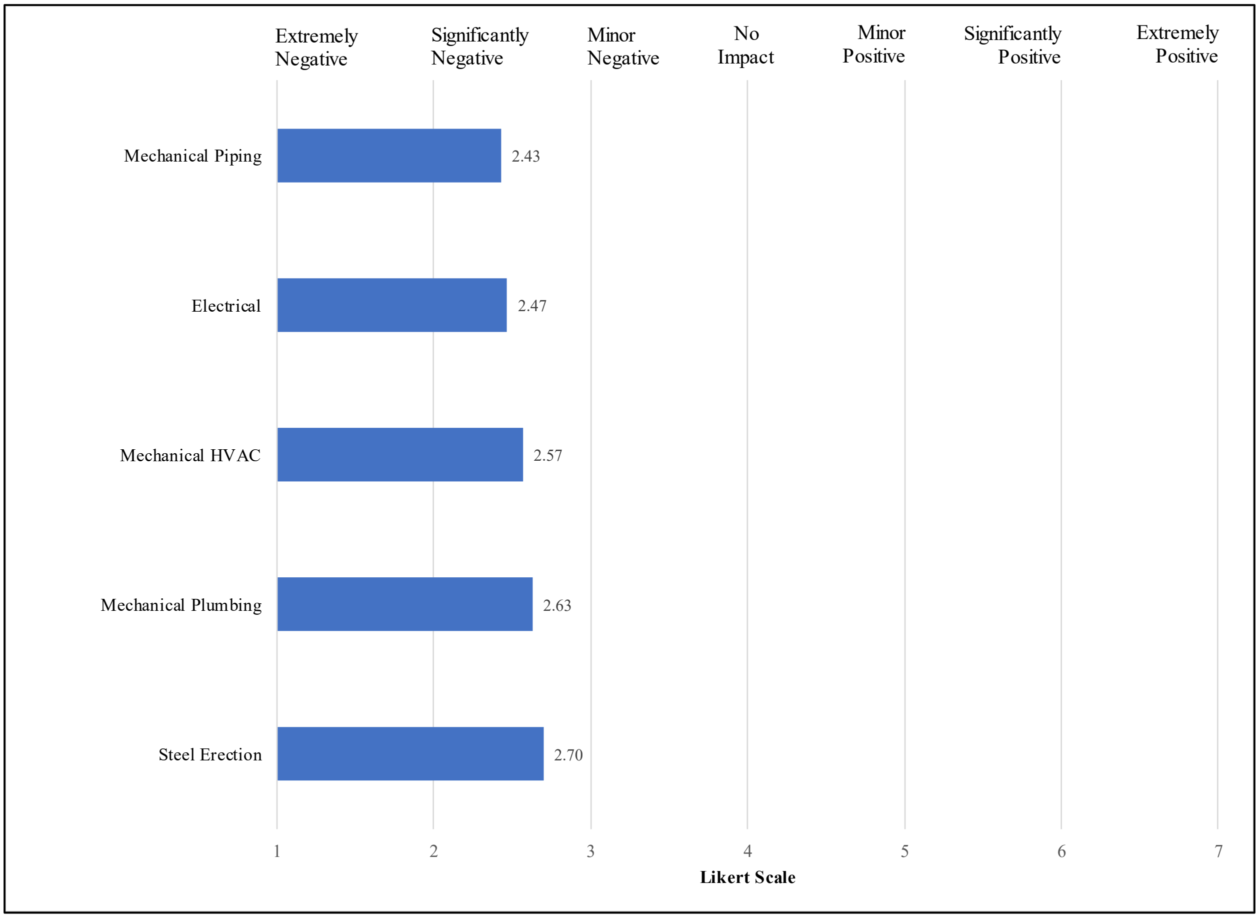


Figure 7-6 Delphi Phase 1 – Respondents Indicated Effects of Trade Stacking on MEP and Steel Erection Trades

Respondents were asked to describe the degree to which they agreed or disagreed with the following statement, "Trade stacking on a construction project always results in labor productivity losses." Results were mixed as depicted in **Table 7-8** . In total, approximately 63% of the respondents agree that an adverse impact results from trade stacking. Follow up questions with participants revealed that in some cases, mostly with tenant improvement projects, trade stacking was viewed as being potentially more productive because it forced the trades to coordinate and work potential field conflicts out together rather than working independently. Overwhelmingly, participants agreed that each situation must be considered based on its own merits and conditions, which can widely vary from project to project.

Table 7-8 Delphi Phase 1 – Respondent Response to the Statement, "Trade stacking on a construction project always results in labor productivity losses."

Response	**Count**	**Percent**
Strongly Disagree	0	0.00%
Disagree	6	20.00%
Neither Agree nor Disagree	5	16.67%
Agree	**12**	**40.00%**
Strongly Agree	7	23.33%

Concluding Phase 1, a total of 31 participants were qualified to complete the Phase 2 survey. Phase 1 also validated that trade stacking caused significantly adverse effects on construction labor productivity.

Phase 2

Phase 2 consisted of 18 questions, however, many questions were used simply to establish an understanding of the methodology and not an opinion from the respondent. Because the research approach presented herein is new, use of the pre-qualified experts from Phase 1 was necessary to validate results. Before actual results were presented to the panelists, however, participants were first asked to offer their opinions regarding what they would expect to see based on a set of conditions from the high rise construction project presented in Chapter 5. Only after recording these expert opinions were the actual results presented. In effect, intent of the survey was to verify that the results of this research align with industry expert experience.

As explained below, results from this Phase 2 survey establish consensus agreement with the results. Consequently, the Delphi study was concluded with just two phases. A complete copy of the Phase 2 survey is included in **Exhibit 7B**.

The Phase 2 survey was performed via a GoToMeeting.com conference call between the researcher and the participant. Every survey was recorded to ensure accurate reporting of a participant's responses. On average, each survey required 37 minutes to complete. In one instance, two participants were able to complete the survey while on the same conference call albeit while using their own computers. In this instance, each participant responded to questions independently and without discussion between themselves before recording their responses. All other participants completed the survey independently in a one-on-one conference call.

Results of the Phase 2 survey are presented below in the order of questions presented to each participant. Results validate the findings of this research and support that further research in expanding the data set for future research is warranted.

Likelihood for Trade Stacking

Participants were asked to identify the likelihood of trade stacking with various construction trades. A Likert scale was applied to responses that varied from Highly Unlikely (score = 1) to Highly Likely (score = 7). **Figure 7-7** shows that mechanical, electrical, plumbing and finishing trades are most likely or highly likely to experience trade stacking. This result comports with the literature review regarding likelihood for trade stacking with these same trades.

Figure 7-7 Delphi Phase 2 Respondents Reported Likelihood for Trade Stacking for Various Trades

CPM Scheduling

Respondents were asked to render an opinion regarding the degree to which they agreed or disagreed with several statements related to CPM scheduling as shown in **Figure 7-8** . A Likert scale of Strongly Disagree (score 1) to Strongly Agree (score 5) was used. Neutral / No Opinion carried a score of 3. Respondents' results show general agreement with every statement. The strongest agreement was found with the statement, "Contractors give critical activities highest priority."

Question	Count	Score
Contractors manage their construction activities using the early dates	17	3.76
Contractors give critical activities highest priority.	17	4.18
With proper scheduling, a change to construction labor productivity may be predicted before it occurs.	17	3.47
Resource loaded schedules serve as better project planning and management tools than schedules without labor resources assigned.	17	3.88
	Average	3.82

Figure 7-8 Delphi Phase 2 Respondents Responses to Statements Regarding CPM Scheduling

Results of the study show that evaluation of the early dates in the schedule updates produces the strongest correlative results when using regression, best-fit analysis. The expert panelists' agreement with the statement, "Contractors manage their construction activities using the early dates," lends credibility to utilizing early dates in a CPM schedule when performing the schedule density analysis.

Participants indicated agreement with the statement, "Resource loaded schedules serve as better project planning and management tools that schedules without labor resources assigned." As established in the literature review, notwithstanding the perception otherwise, few contractors actually do resource load their schedules. If through additional study it can be shown that the schedule density histograms generated serve as surrogate measures for actually resource loading a schedule, the participant's responses to this question support that potential adaptation of the schedule density approach may be used in lieu of or in concert with resource loading a schedule.

Participants also reported general agreement, albeit with the lowest of the four average values, with the statement, "With proper scheduling, a change to construction labor productivity may be predicted before it occurs." Results of this study support that development of a predictive model for forecasting and quantifying productivity loss may be possible.

Expected Productivity Curve

Participants were presented with the background information of the High Rise Hotel sample project that was utilized as a sample project (refer to Chapter 5) and asked to draw the expected productivity rate over time for the mechanical trade. Participants were provided with several examples from which to choose, or they had the option to draw their own curve. Of the 17 respondents, 13 (or 76 percent) selected the adverse log normal or exponential function as shown in **Figure 7-9** . For this function, a productivity value of 1.0 represents 100% of the planned productivity, or rather, the contractor's productivity is on target as planned. Productivity values less than 1.0 indicate inefficiency, with greater inefficiency associated with smaller values. This function mimics the results of this schedule density research that compared the cumulative centroid scaler value as the independent variable and the manhours per percent complete as the dependent variable. Thus, the expert panel's experience validates findings of this research.

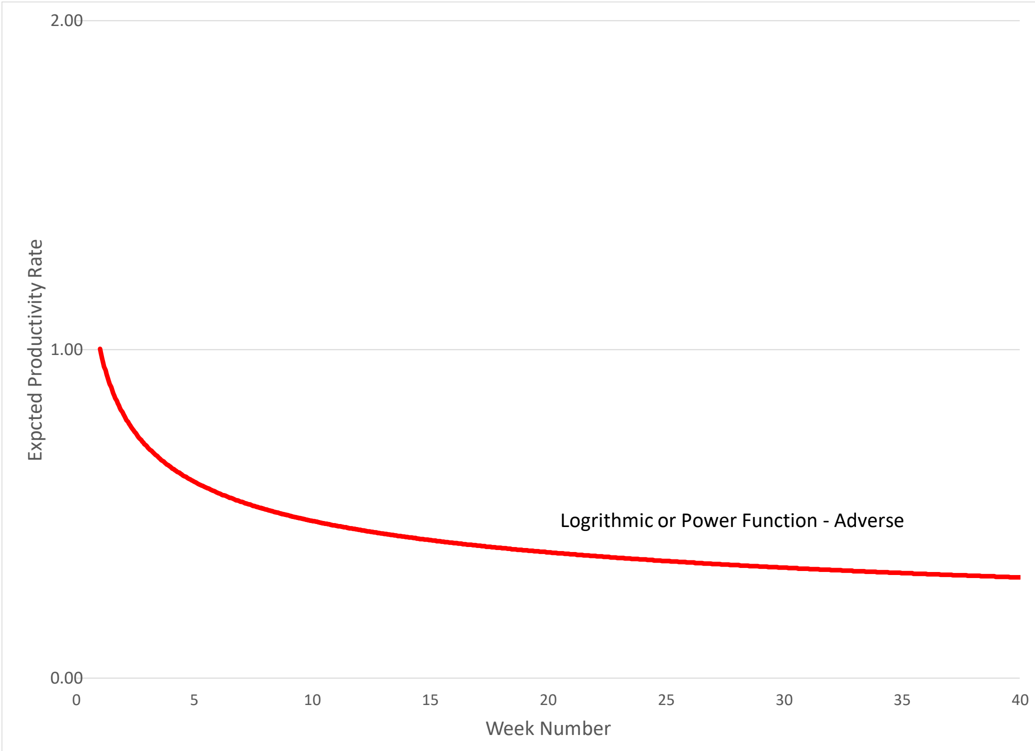


Figure 7-9 Delphi Phase 2 Majority Respondent Expected Labor Productivity Curve for the Mechanical Trade on the High Rise Hotel Sample Project

Generally speaking, the lognormal function shape of the curve in **Figure 7-9** shows an exponential decline in productivity for approximately the first 20 to 25 percent of the impact duration. Then, the curve flattens out indicating an improvement to incremental productivity, but the cumulative productivity rate never returns to the planned rate. This observation was audibly expressed and validated by several of the respondents based on their own experiences.

Two respondents chose a compound linear function as shown in **Figure 7-10** . This function has some commonality to the log normal function shown earlier, the primary difference being a linear decline in cumulative productivity and then leveling out at some point. Also similarly, the cumulative productivity rate never returns to the planned value.

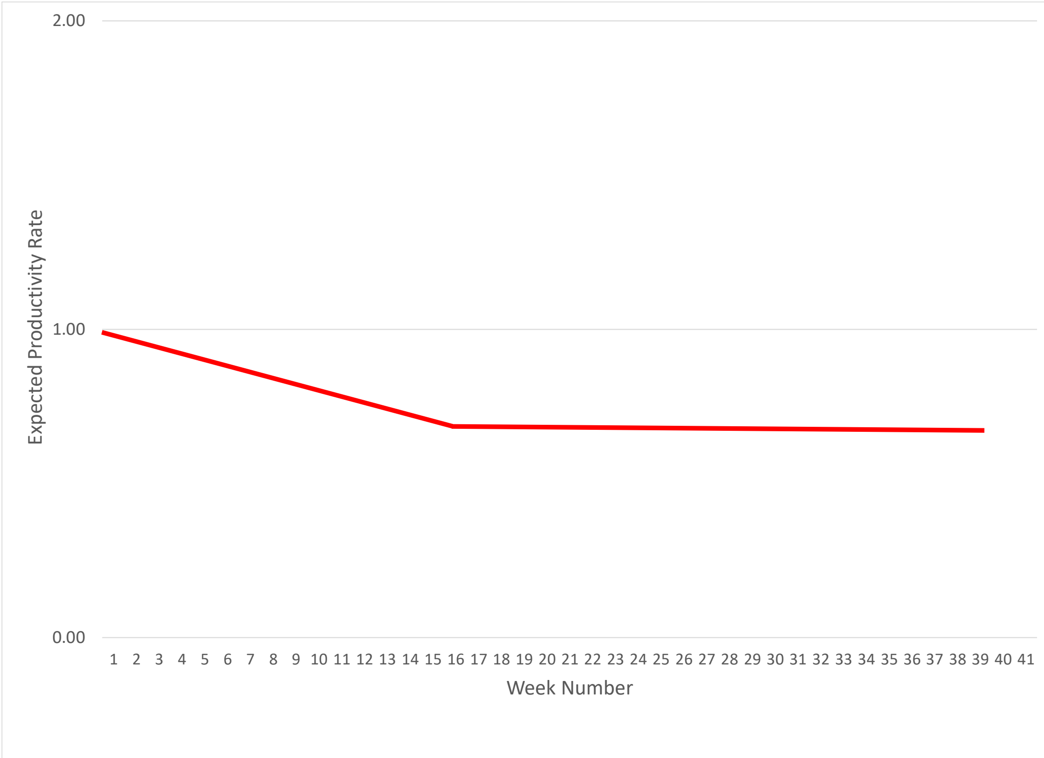


Figure 7-10 Delphi Phase 2 Respondents Selected Compound Linear Function for Expected Mechanical Trade Labor Productivity

Two participants selected a polynomial function as shown in **Figure 7-11** under the assumption that the design changes experienced on the hotel high rise would eventually diminish with progress of the work. One of the two participants then reverted back to the log normal adverse function when considering the curve was a cumulative measure and not an incremental measure. Incrementally, the contractor's productivity would improve as work progressed and fewer design changes occurred, which in fact, may be represented by a polynomial function. However, when the participant was reminded that the curve represented cumulative data, the response was changed to the adverse log normal function. This selection was included in the 13 mentioned earlier.

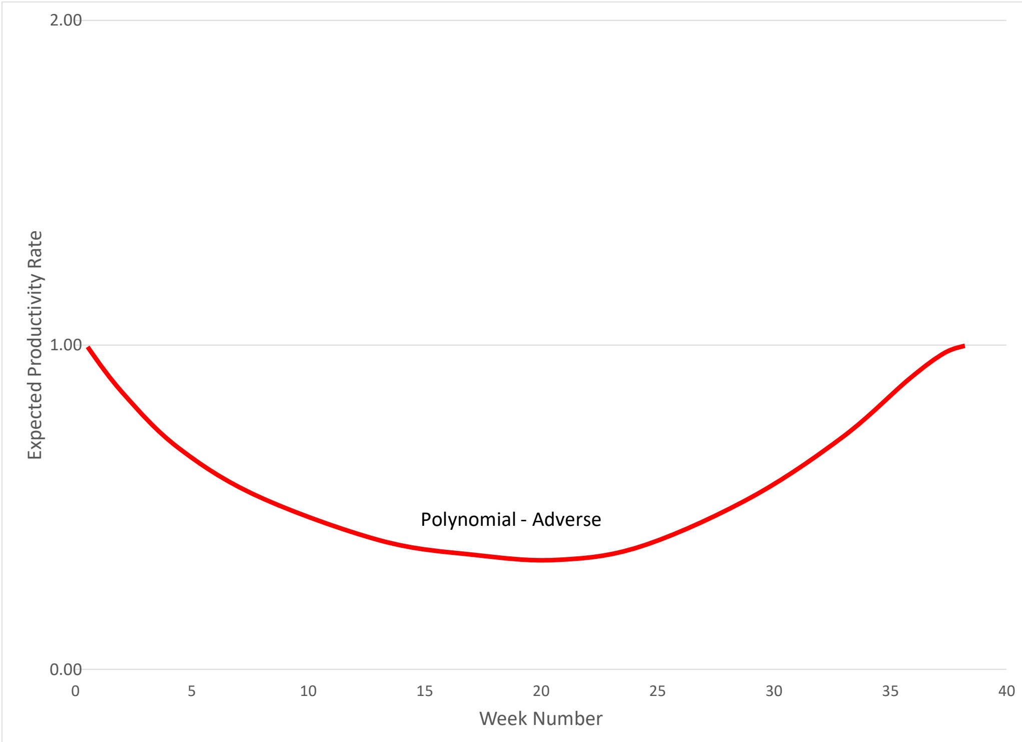
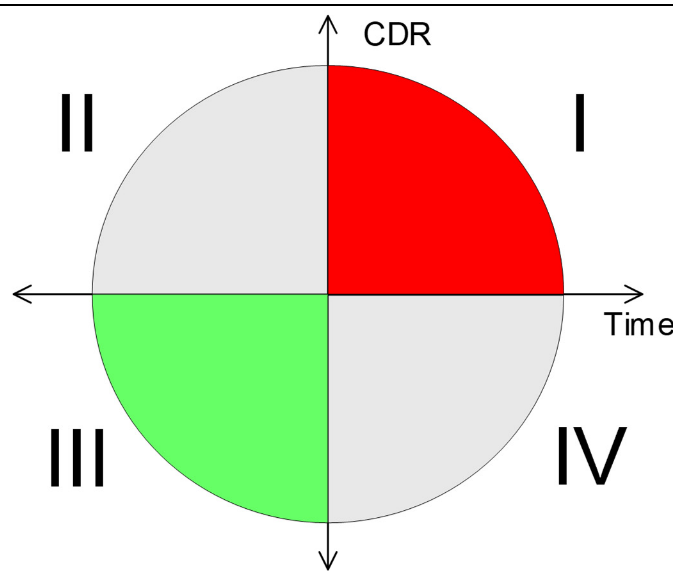


Figure 7-11 Delphi Phase 2 Hypothetical Adverse Polynomial Productivity Curve

Regardless of the expected shape of the function, all 17 experts agreed that for this High Rise Hotel project, productivity becomes worse when trade stacking begins, or soon thereafter. Considering that the general shape of a compound linear function is similar to the log normal function, it may be concluded that 15 of the 17 experts (88 percent) agreed that incremental productivity eventually improves, however, the cumulative productivity curve never returns to the original planned productivity. Both of these findings corroborate results of this research.

Methodology

Participants were asked to opine on the methodology employed for this research regarding generation of a schedule density histogram and its resulting centroid, and then use of the centroid measures to generate vectors connecting two successive schedule density histograms that may be evaluated as explained in Chapter 3. Each respondent indicated orally a clear understanding of the methodology and an acceptance of how the centroids and resulting vectors were prepared and evaluated. Once this understanding and acceptance was established, participants were asked to opine on the use of centroid vectors. Specifically, if a centroid vector was found to exist in one of the standard four quadrants in a cartesian coordinate system, what would the expected impact to the mechanical labor productivity be? A Likert scale was applied where Extremely Adverse was given a score equal to 1 and Extremely Positive was scored as a 7. Results of this question are shown in **Figure 7-12** .



Question	Count	Score	Extremely Adverse / Significantly Adverse / Minor Adverse / No Impact / Minor Positive / Significantly Positive / Extremely Positive / Unsure / No Opinion
Quadrant I	17	2	
Quadrant II	16	3.75	
Quadrant III	17	5.47	
Quadrant IV	17	3.82	
	Average	3.76	

Figure 7-12 Delphi Phase 2 Expected Effect on Labor Productivity If Centroid Vector Was Found to Exist in a Given Quadrant

Participant's responses show that vectors falling in Quadrant 1 would indicate a significantly adverse impact to the mechanical trade's labor productivity. Conversely, where a vector was found to reside in Quadrant 3, positive or better labor productivity would be expected. Quadrants 2 and 4 were perceived to have just minor adverse impacts. Evaluation of the hotel high rise project found that most of its centroid vectors fell in Quadrant 1. Results showed significant productivity inefficiencies for the mechanical trade for these time periods, which is consistent with the expert panelists experiences and expectations. Once these results were shared with the panelists, each was asked what the expected effect on productivity would result for the mechanical trade. All but one participant indicated significantly lower than planned productivity as shown in **Figure 7-13** . Actual results of the research verified that significantly lower or worse than planned productivity resulted for the mechanical trades on all sample projects. Thus, the panelists experience again validates the research findings presented herein.

Answer	Count	Percent
Extremely Lower than Planned	1	5.88%
Significantly Lower than Planned	15	88.24%
Slightly Lower than Planned	0	0%
No Impact	0	0%
Slightly Better than Planned	1	5.88%
Significantly Better than Planned	0	0%
Extremely Better than Planned	0	0%
Unsure / No Opinion	0	0%
Total	**17**	**100 %**

Mean: 2.118 **Variance: 0.610** **Standard Deviation: 0.781** **Standard Error: 0.189** **Confidence Interval: [1.746 - 2.489]**

Figure 7-13 Delphi Phase 2 Respondents Expected Labor Productivity for Mechanical Work on the High Rise Project Given that Centroid Vectors Mostly Fell in Quadrant 1

Participants were then presented with the best fit curves for the schedule density histograms and asked what features of these curves, if any, they thought may be useful (Likert score = 1), unsure (Likert scale =2) or not useful (Likert score = 3) in developing a predictive construction labor productivity loss model. The following variables were presented:

- Total Area Under the Curve

- Total Area Under the Curve for Planned Dates Only
- Centroid of the Total Area Under the Curve
- Shape of the Curve
- Change in Average CDR (y-component of histogram centroid)
- Change in Time (x-component of the histogram centroid)

Results of the participants' responses are shown in **Figure 7-14** .

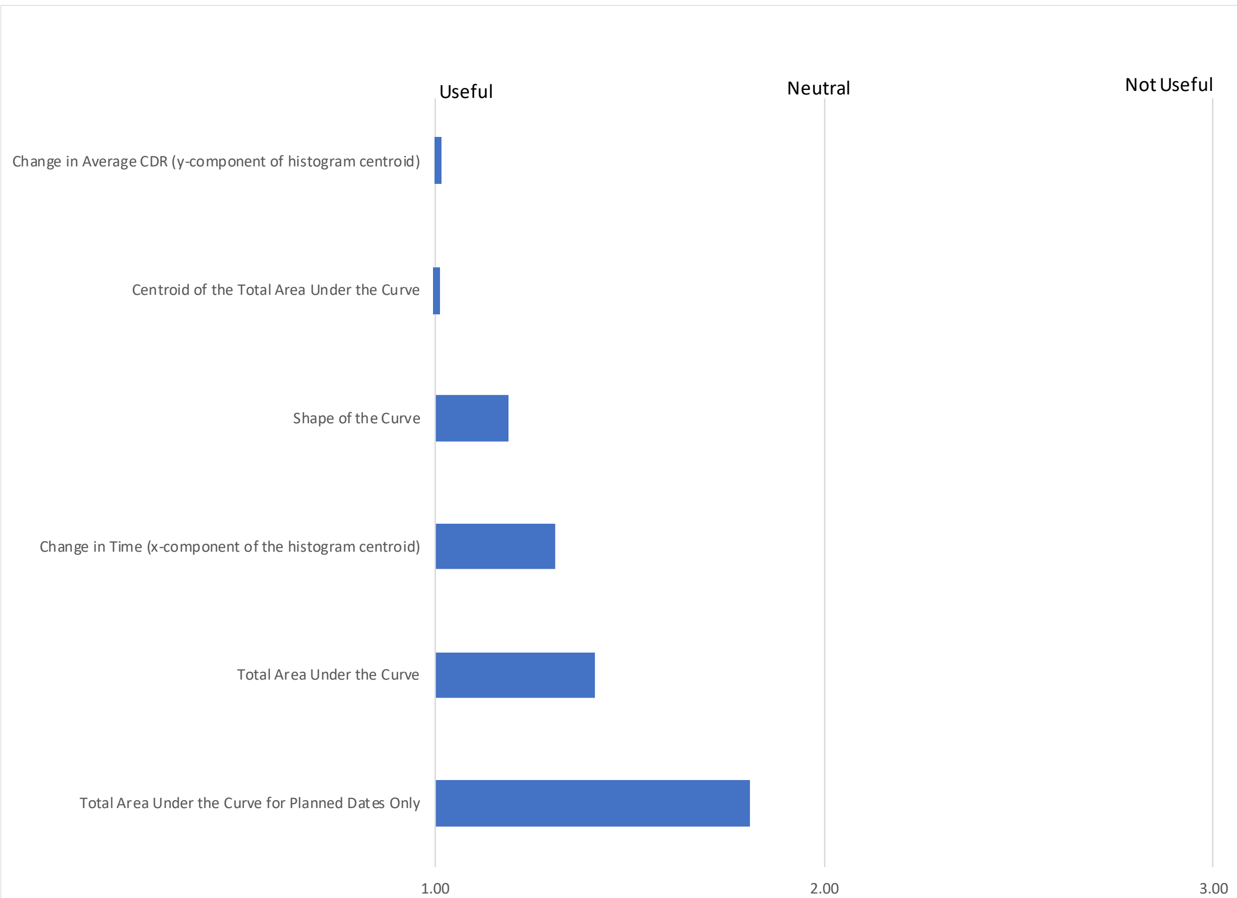


Figure 7-14 Delphi Phase 2 Respondent Responses for Usefulness of Variables Related to Best Fitting Curves for Schedule Density Histograms

Respondents' results show that all of the variables may be useful. Respondents indicated that the Centroid of the Total Area Under the Curve and the Change in Average CDR (y-component of the centroid) were both potentially most useful. The variable rated the least useful, albeit still falling within the useful category, was the Total Area Under the Curve for Planned Dates Only. Both of these findings align with actual results of the study. Results of this schedule density research found that use of the centroid and tracking its cumulative change over time has the strongest correlation with labor productivity, whereas the total area under the curve for just planned dates was found to have the weakest correlation. This is consistent with the panelists' responses.

Panelist Responses to Research Results

Following solicitation of the panelists' responses for all inquiries mentioned above, the results of the research study for the high rise hotel project were presented. The best fitting curve was found to be a log normal function where the independent x-axis variable was the cumulative centroid scaler values and the dependent y-axis variable was the project's cumulative actual productivity for its mechanical trade subcontractor in units of manhours per percent complete. This result is shown graphically in **Figure 7-15** .

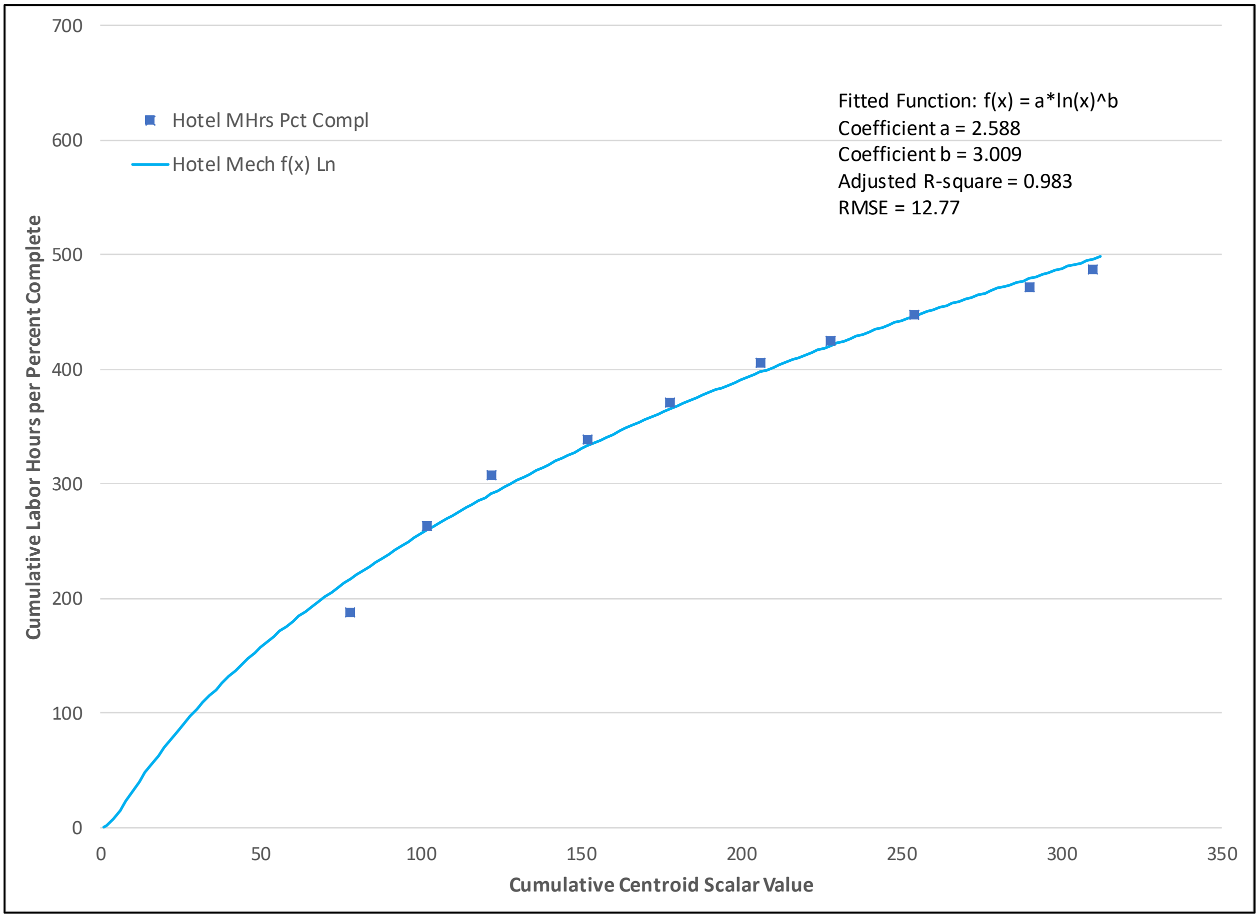


Figure 7-15 Delphi Phase 2 – Log Normal Function Results for the High Rise Project

Results were explained to each of the panelists with respect to the strong correlation as evidenced by the r-square value of 0.983. Respondents were asked to opine on this curve. Specifically, did the correlation between the two variables and shape of the curve make sense based on their professional experience. Overwhelmingly, the responses were favorable in support of the general statement that, 'Yes, this curve makes sense and is what I've experienced in my career.'

For respondents who earlier in the survey chose the log normal function as shown in **Figure 7-9** for the expected productivity curve for the mechanical trade, the author pointed out that the shape of the curve in **Figure 7-15** is the same, but a vertical mirrored image of it due to the y-variable values. For respondents who chose the compound linear function as shown in **Figure 7-10** , their responses were that the compound linear function generally follows the same shape as the log normal, so no change to their responses were made. For the two respondents who chose the polynomial parabolic curve as shown in **Figure 7-11** , the author inquired as to whether the results of this study would cause them to change their response to the earlier question. One respondent did change the response with the clarification that there is a difference between a cumulative curve and an incremental curve, and that the first response was based on the misunderstanding of using incremental values. The second respondent declined to comment indicating more time would be needed to work the math out before responding.

Respondents were then presented with the best fitted curves for the mechanical piping work on the power plant job and the structural steel project (see **Figure 7-16**). Similar questions were asked regarding the reasonableness of the curve and the relationship between the x and y variables. Responses were again overwhelmingly agreeable. In every instance, the log normal function was found to be the best fitting curve. Because the analyses measure different trades on different projects, the coefficients for the best fitting curves are different for each project, but the mathematical function is the same. R-squared values for each curve follow:

- High Rise Hotel Mechanical Trade $r^2 = 0.983$
- Power Plant Mechanical Piping Trade $r^2 = 0.732$
- Structural Steel Ironworkers $r^2 = 0.900$

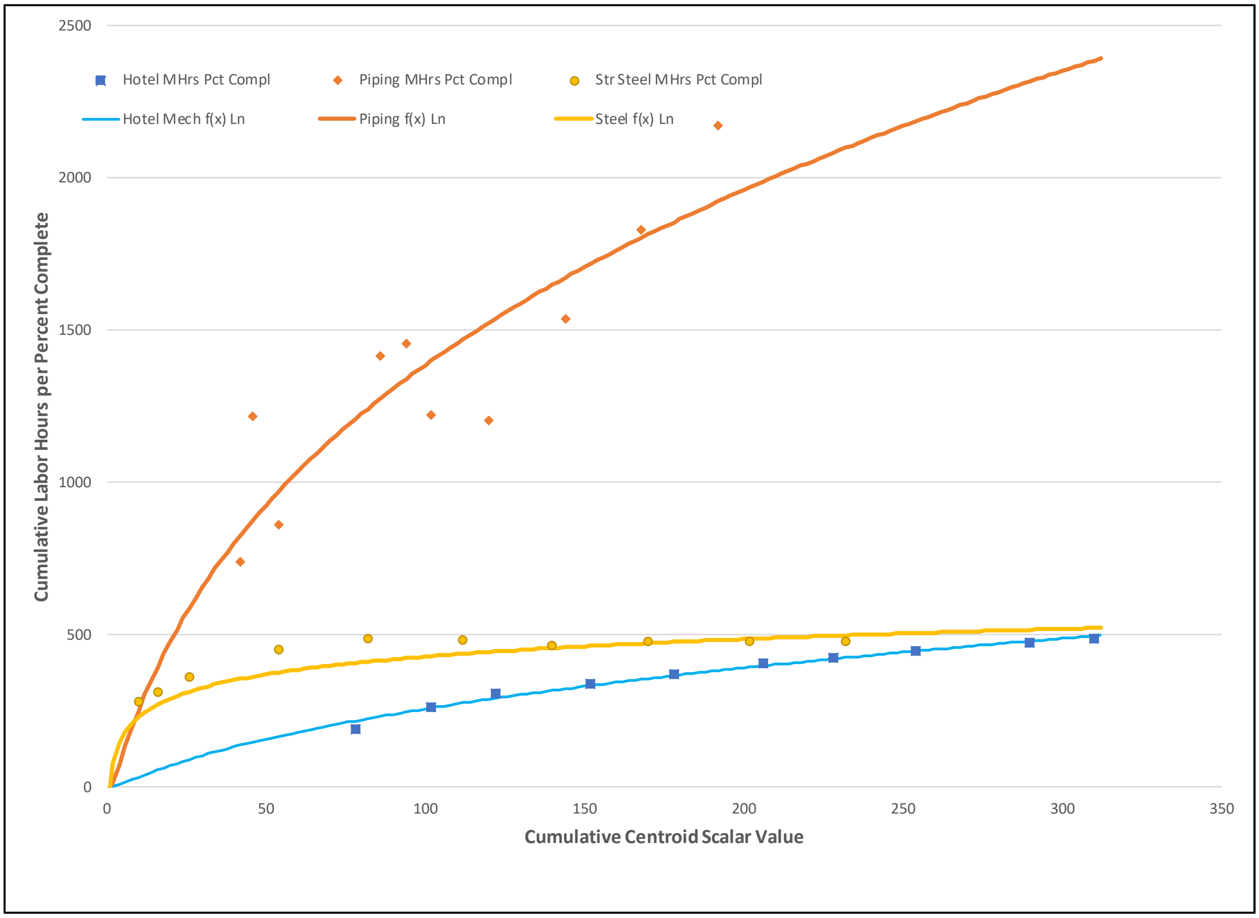


Figure 7-16 Delphi Phase 2 – Research Results Best Fitted Curves for Piping and Structural Steel Projects

One panelist commented on the piping curve indicating that the slope of this curve is much greater today than if this work were performed say two decades ago because there is a shortage of skilled welders to perform the piping work. Once trade stacking begins and productivity losses accumulate, these trade workers never recover. Otherwise, this panelist's belief is that the curve would flatten out similarly as shown for the high rise and structural steel projects.

Strengthening the Model

Panelists were asked how the results of the study could be strengthened. Most respondents indicated that larger project sample size for each trade would be better. Other comments included subdividing sample projects by contract type. This comment stems from how contractors and subcontractors behave under different types of contracts. For example, a lump sum project bears greater risk for a contractor than say a time and materials contract. The contractor operating under a lump sum job must maintain productivity efficiency or face greater risk of financial loss whereas under a time and material contract, the contractor may not feel such a sense of urgency.

Panelists were concerned that the model may be too complex for contractors to understand and implement. Each respondent received a hand-held walk through of the methodology and how the model was developed for this study, but that luxury may not be readily available in the field. Thus, simplification of every aspect of the model must be emphasized.

One panelist felt that this approach was similar conceptually to a costing software called Resource Allocation Cost System (RACS) used by Turner Construction, and that integrating cost into the model may be beneficial. The RACS system is a method of applying dollar values of the various trade contractors onto a chart. The software calculates a targeted dollars per hour measure required for the trade to complete its work timely. When invoicing, the trades' billings are recorded. If a trade is billing at a rate lower than required to utilize the full budget within the allotted time, the software creates a backlog or "wave" of unspent dollars and pushes those dollars forward. This software's utility offers Turner Construction opportunity to tell the owner an order magnitude of cost impacts that a change order or RFI may have on unfinished trade work. The creation of a wave of unspent dollars conceptually is similar to this research where unfinished work durations in the schedule are pushed forward, which also simulates a wave effect. Thus, the possibility of linking unspent dollars to the unfinished work in the schedule may strengthen the model.

Finally, one panelist suggested that the x-axis be presented in a time scale [rather than based on schedule update number] such that results may be correlated to key impacting events that then can explain the change in the slope of the curve. Consideration should also be given to understanding how the various trades affect each other. Plotting curves for the MEP trades on the same chart may help to identify these relationships.

Expansion of Knowledge

In total, 14 of the 17 panelists indicated that they strongly agreed that this research expanded the body of knowledge in construction labor productivity. The remaining three panelists selected agreement that this research expanded the body of knowledge.

Each panelist expressed interest in seeing the final results of the study. Many requested a copy of the final published dissertation. One panelist with more than 40 years of experience as a practitioner, professor and testifying expert indicated that this research was one of the best advancements to quantifying labor inefficiencies he had seen in the past two decades. With such positive feedback, it follows that additional research, development and expansion of the data set is warranted.

Summary Results of Dephi Study

Results of the Delphi surveys clearly support that the schedule density methodology developed in this research is new, viable and potentially useful to the construction industry. This position is supported by responses of 17 experts, each who possess a minimum of 10 years of experience. Responses verify that trade stacking, particularly in the MEP trades, adversely impacts labor productivity. The proposed methodology herein allows contractors a possible means to predict labor inefficiencies early such that mitigation measures may be implemented to minimize those adverse impacts.

8 Conclusions

This study contributes to and expands upon the present body of knowledge related to CPM scheduling and labor resource loading. This chapter summarizes these contributions relative to the resultant predictive model developed, and identifies primary assumptions and limitations related to it.

Expanding the Present Body of Knowledge

This study extends the present body of knowledge in CPM scheduling and resource loading because results herein challenge present industry beliefs indicating that use of resource-loaded schedules are mandatory for contemporaneously managing labor resources on construction projects. This study shows that trends within non-resource loaded schedules may be identified and utilized to predict construction labor productivity loss before it occurs. Nothing in the literature review revealed anything like the technique and resulting model developed and showcased herein. This finding represents a significant contribution to the construction industry and opens possibilities of developing a project management protocol around the model developed herein to predict and avoid labor productivity loss before it occurs.

CPM Alone May Be Sufficient

Construction projects pose significant challenges for all parties involved, but particularly for the contractors who frequently assume tremendous risk in completing the project on time, within budget and of a quality to meet the contract specifications. CPM scheduling was created to identify ways to 'crash' the schedule, i.e., accelerate or save time, when delaying events threatened timely completion of the work. Recovering time almost always involves labor resources and an understanding of the productivity those resources can reasonably achieve. It followed logically that integrating CPM scheduling with resource loading of those schedules would sharpen the accuracy of forecasting a completion date and in more efficiently managing day to day work on the project.

Unfortunately, industry experience shows that few contractors integrate resource loading into its CPM schedules, most commonly because of the laborious nature of collecting, vetting, entering the data into the schedule, and repeating these efforts regularly as conditions on the project dynamically change daily. Acknowledging contractors' reluctance to resource load CPM schedules, while likewise recognizing the potential benefits of linking labor resources to CPM scheduling, this study sought to find a way for CPM scheduling to be used to predict labor productivity absent resource loading of the schedules.

A Predictive Model Was Developed

Following basic tenets of CPM scheduling where activities represent contractual work scope to be performed by a given trade and within a planned time duration, each activity necessarily carries with it a primary assumption that the contractor will provide enough materials, equipment and labor resources to complete that task within the planned activity's time duration. Without resource loading, a reviewer of the schedule does not know exactly how much labor or other resources the contractor plans to allocate to meet that task's planned duration. This study utilizes a new measure called a Crew Day Resource, or CDR to represent the sufficient amount of labor resources for the contractor to achieve one full day of work against a planned activity in its CPM schedule.

CDR's are additive when schedule activities overlap in time. Increased overlap or "stacking" of CDR's occurs in CPM schedule updates when actual progress falls short of meeting planned durations. In these instances, float erosion and/or delay occurs, and the remaining unfinished work tasks drift, or rather, are pushed forward in time in the schedule while the project completion date remains the same. An increase in CDR overlap is an indicator of trade stacking. Both the literature review and the expert panel confirmed that particularly with MEP trades, trade stacking results in adverse impacts on labor construction productivity. The CDR value, therefore, serves as a surrogate measure to physically resource loading a CPM schedule. However, results of this study show that changing values of CDR alone are insufficient to predict labor productivity loss. A contractor's inabilities to meet planned durations likewise contribute to productivity loss.

A measure utilizing the concept of a centroid was developed. This measure contains both a measure of trade stacking via the CDR values and a time element that considers float erosion and delay in observing how planned future work drifts from schedule update to update. Several primary assumptions apply to the technique developed here, including,

1. That the crew's productivity rate remains constant, or nearly so, thereby reflecting a linear distribution of resources over the full duration of the activity;
2. That the resources assigned are similar to those that were estimated to be able to complete the work represented by the schedule activity;
3. That one "crew," represented by one CDR unit measurement will perform the work per each schedule activity, and
4. That field conditions are similar to those experienced when the estimated productivity rate was measured.

Utilizing a standard coordinate x, y cartesian plane, the cumulative change in centroid values generated strong correlations with actual observed labor productivity using a lognormal function.

Findings here show that trends indicating schedule drift, i.e., float erosion and delay, coupled with an increased overlapping of planned work may be modelled using a lognormal distribution function of the form:

$$f(x) = a\ \ln(x)^{b}$$

where,

f(x) = estimated cumulative labor hours per percent complete

a and b = coefficients determined by empirical data and regression analysis

x = cumulative centroid scalar value

A lognormal distribution results when the natural log of a variate stems from a normal distribution and is the result of many random effects acting multiplicatively on the variate. Such is the case here where so many different variables influence labor productivity, and the difficulty that exists in trying to separate and quantify each variable individually.

Validation of Technique and Results

The Delphi portion of the study provided an expert validation of this technique supported by the collective tacit knowledgebase of the panelists, which was composed by professionals with substantial construction management experience. Panelists unanimously agreed that the principles utilized in developing the model technique were sound and that the shape of the resulting lognormal function aligned with their observed field experiences regarding labor productivity coupled with trade stacking and delay. The expert panelists also agreed that a large sample size would strengthen the results, but overwhelmingly all agreed that results of this study indicate that a predictive model for construction labor productivity inefficiencies utilizing non-resource loaded CPM schedules was plausible.

Application of the lognormal model to an outside model showed some correlation, explained by differences between the sample projects used to develop the lognormal functions and the actual Hotel Resort project. A limitation of these findings is that they are based upon a small sample size of projects. Thus, applying the results here to an outside project will likely not result in such a strong correlation between labor productivity and the cumulative centroid scalar value as is demonstrated in Chapter 7 herein. Still, the results drawn from this small sample support that additional study with a larger sample size is warranted. Further study in the interactions between trades, particularly within the MEP trades, is likewise warranted and possible with a larger sample size.

Practical Application

Two practical applications of this model are possible. First, the model can be applied to projects from commencement of construction going forward as a construction management tool that identifies trends that lead to trade stacking and labor productivity inefficiencies. Intent here is to allow managers to mitigate the potential adversities either before they occur, or at least to minimize the impacts of those issues earlier than would otherwise have been possible. Second, the model is useful as a retrospective analysis to demonstrate how trade stacking increased over time thereby leading to labor productivity loss, and to quantify the actual loss in productivity over the life of the project. The retrospective approach may be simplified by using the CDR histograms generated from the schedule updates in lieu of using the lognormal function.

Successful development and implementation of a predictive model for construction labor productivity loss requires simplicity and ease of application. Simply stated, nobody will use the model if it requires too much effort to understand and utilize it. Additional research is required to develop a simple procedure. Perhaps results from a large sample size may be summarized in a simple table or curve graphic whereby a contractor, for example, can easily identify a change in the centroid value for a given trade and associate it with a forecasted change in labor productivity unless some action were taken to reverse the trend. If the parties benefit from use of the model and it's easy to understand, they are more likely to apply it. If functionality were included within existing CPM software that allowed for the centroids of various trades to be tracked from update to update, it follows that a predictive model could likewise be integrated into the software's capabilities. Developing these capabilities present yet another frontier for knowledge expansion in construction, one of the oldest professions on earth.

9 List of Appendices

Appendix No.	Description
5A	High Rise Hotel Sample Project CPM Schedules
5B	High Rise Hotel Sample Project Mechanical and Plumbing Activities
5C	High Rise Hotel Sample Project MatLAB Histograms
5D	High Rise Hotel Sample Project Calculations of Centroids and Other Metrics
5E	High Rise Hotel Sample Project Labor Hours for Mechanical and Plumbing
5F	High Rise Hotel Sample Project Best-Fit Correlations with Manhours per Percent Complete
7A	Delphi Study – Phase 1 Factors that Affect Labor Productivity
7B	Delphi Study – Phase 2 Online Validation of Results Survey

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