

LINEAR SCHEDULING OF
PIPELINE CONSTRUCTION PROJECTS
WITH VARYING PRODUCTION RATES

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Submitted to the Faculty of the
Graduate College of
Oklahoma State University
in Partial Fulfillment of
the Requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2009

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ACKNOWLEDGEMENTS

I would like to thank my research committee for their time and patience during this research effort. Each of you have provided mentoring and assistance at different stages of my studies that is greatly appreciated. Special thanks go to Dr. Oberlender for his support and encouragement throughout both my undergraduate and graduate studies.

I would like to thank my family, especially my mother and father for providing a balanced mix of creative and mathematical influence.

Finally I would like to thank my beautiful wife, Jana, for her support and patience throughout the process. It has been a long journey and I appreciate you being there to keep me sane.

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TERMINOLOGY

Activity: The performance of a task required to complete the project.

Activity Performance Index (API): A percentage that indicates the relationship of the calculated production rate for a given working window versus the desired rate of production.

Activity Sequence List: A list that describes the order in which activities will occur at any location on the project. This is utilized by Harmelink as a precursor to calculating the controlling activity path in the Linear Scheduling Model.

Controlling Activity Path (CAP): This is the path of longest duration through the project that is identified after the downward pass has been completed.

Critical Path: A series of interconnected activities through the network diagram, with each activity having zero, free and total float time. The critical path determines the minimum time to complete the project.

Critical Path Method (CPM): A form of scheduling which uses a network logic diagram to display interdependencies and calculate scheduling information including: early start, late start, early finish, late finish, free float, and total float.

Discrete Activity: An activity consisting of unconnected separate or distinct parts.

These activities are typically best scheduled with bar charts or CPM.

Downward Pass: Beginning with the last activity on the sequence list, identify the critical segment of each activity until the first activity is reached. This is Harmelink's adaptation of the backward pass used in CPM applied to the linear scheduling model.

Duration: The time required to perform an activity.

Early Finish (EF): The earliest time an activity can be finished.

Early Start (ES): The earliest time an activity can be started.

Finish to Finish: An activity relationship which means the successor activity can finish at the same time as or later than the predecessor activity.

Finish to Start: An activity relationship which does not allow the successor activity to start until the predecessor is completed.

Free Float (FF): The amount of time an activity may be delayed without delaying the early start time of the immediately following activity.

Late Finish (LF): The latest time an activity can be finished.

Late Start (LS): The latest time an activity can be started without delaying the completion date of the project.

Least Distance Interval: The shortest distance between any two adjacent activities that lies within the coincident duration and intersects the least time interval.

Least Time Interval: The shortest time interval between any two adjacent (consecutive) activities. The interval will always occur at a vertex of at least one of the activities.

Line of Balance (LOB): A scheduling technique which utilizes three charts: production, objective, and progress. The production chart is the plan to build or process one unit. The objective chart is an overview of the units needed to complete the project or

order. The progress chart depicts the units produced per a unit of time. While originally used for the manufacturing process, many adaptations have been fit to repetitive construction.

Move-Around: Areas in pipeline construction where the equipment and crews are moved from one location to another location out of sequence along the alignment thus disrupting the continuous flow of construction.

Production Variable: Variables which affect the rate at which construction production occurs. There are four types of production variables:

- 1) General Variables – Broad constraints which affect the production but are not related to a specific time or location, e.g. number of welders.
- 2) Time Variables – Variables which change with respect to time only, e.g. holidays per month.
- 3) Location Variables – Variables that change with respect to location only, e.g. terrain.
- 4) Time–Location Variables – Variables that change with respect to both time and location, e.g. weather, environmental windows.

Skip: An area of the construction alignment that must be avoided at the time the construction crews arrive, thus forcing the crews to “skip” the area and come back when appropriate. Skips may be required due to environmental concerns, constructability issues, or other factors affecting the progression of the construction project.

Spread: A segment or portion of a pipeline project. Pipeline projects are typically broken into spreads based on terrain and the ability to complete the spread in a given construction window.

Start to Start: An activity relationship which means the successor activity can start at the same time or later than the predecessor activity.

Total Float (TF): The amount of time an activity may be delayed without delaying the completion date of the project.

Upward Pass: Beginning with the first activity on the sequence list, the least time and least distance intervals and potential controlling segments are identified for each activity until the end of the list is reached. This is Harmelink's adaptation of the forward pass used in CPM applied to the linear scheduling model.

Working Window: A rectangle on the linear scheduling chart with a homogenous set of production variables. The working window has time on the y-axis and location on the x-axis.

NOMENCLATURE

API	Activity Performance Index
AS	Activity Separation
CAP	Controlling Activity Path
CEPRV	Cumulative Effect of Productivity Rate Variations
CFL	Continuous Full Span Linear Activity
CPM	Critical Path Method
CPT	Construction Planning Technique
DOT	Department of Transportation
DR	Distance Remaining
DTTR	Distance Traveled in Time Remaining
DUR	Duration
EF	Early Finish
ES	Early Start
FF	Free Float
FLSP	Florida Linear Scheduling Program
FS	Full-Span Block or Bar
HVLS	Horizontal & Vertical Linear Schedule
IFL	Intermittent Full Span Linear Activity
LCPM	Linear Construction Planning Model

LD	Least Distance Interval
LF	Late Finish
LOB	Line of Balance
LS	Late Start
LSM	Linear Scheduling Method (Johnston 1981)
LSM ^h	Linear Scheduling Model (Harmelink 1995)
LSM _{VPR}	Linear Scheduling Model with Varying Production Rates
LT	Least Time Interval (Harmelink 1995)
LTI	Least Time Interval
ML	Minimum Lead
PPD	Probability of Project Delay
PR	Production Rate
PRV	Productivity Rate Variation
PS	Partial-Span Block or Bar
PV	Production Variable
RASP	Repetitive Activity Scheduling Process
RPM	Repetitive Project Modeling
RSM	Repetitive Scheduling Method
SCAP	Secondary Controlling Activity Path
TII	Time Iteration Interval
TLC	Time Location Chart
TF	Total Float
TR	Time Remaining

TSSM	Time Space Scheduling Method
VLSM	Variable Linear Scheduling Model
VPM	Vertical Production Method
WW	Working Window
WWLE	Working Window Location End
WWTE	Working Window Time End
WWLS	Working Window Location Start
WWTS	Working Window Time Start

CHAPTER I

INTRODUCTION

Background

Pipeline construction projects involve continuous, linear activities performed along the horizontal alignment of the facility. Grading, trenching, and welding are examples of such activities. While bar charts and the critical path method are currently the most common methods of pipeline construction scheduling, these methods lack detail when scheduling linear projects. Linear (time-location) scheduling is a technique that better depicts linear activities, and thus has the potential of enhancing the scheduling of pipeline projects.

Purpose and Scope

The purpose of this research is to develop a framework for linear scheduling which accounts for variance in production rates when and where the variance occurs and to enhance the visual capabilities of linear scheduling. The framework will be supported by empirically derived production equations with the appropriate variables input at the appropriate time and location in the project. For example, production rates of ditching across flat prairie will greatly exceed that of ditching through mountainous terrain. A

given project may consist of both types of terrain; therefore utilizing one production rate or an average production rate for the example would lead to erroneous expectations in the two unique areas. It would therefore be more useful to apply “production variables” at the appropriate changes in conditions. These different production variables would in turn be applied to the production rate of the activity as it moves through the given area and time window. This allows the project team to better understand how and when the production variables affect the construction progress throughout the length of the project. It may be possible to bypass certain drops in production performance simply by understanding the compound effect of the production variables. The specific objectives of the research study are:

1. Determine the variables which affect production rates of pipeline construction (i.e. rainfall, terrain, etc.)
2. Determine which activities are affected by the production variables
3. Determine a method for capturing as-built production rates and developing “production variables” from the data to use for future linear scheduling
4. Develop an algorithm for applying the combined variables to the individual activities base production rate, thereby developing a most likely production rate for all locations and times of construction
5. Develop prototype software for performing the calculations associated with the scheduling algorithm.

The remainder of this Chapter presents basic concepts and terminology related to scheduling of construction projects. Chapter II summarizes the findings of the literature

review regarding linear scheduling, its application to pipeline construction, and a review of existing linear scheduling software. Chapter III provides an explanation of the proposed linear scheduling model. A description of the data collected, the methods used to analyze the data, and the output of the analysis are found in Chapter IV. Chapter V details the use of the prototype software Velocity 1.0 and provides a validation of the model using the software. Chapter VI provides a summary and conclusions of the research, as well as recommendations for future research.

Bar Charts

One of the earliest methods of construction scheduling is the bar chart, developed by Henry Gantt during World War I [36]. As shown in Figure 1, a bar chart consists of bars representing activities with time on the x-axis and the names of activities on the y-axis. Each bar illustrates the start date, duration, and finish date of a particular activity.

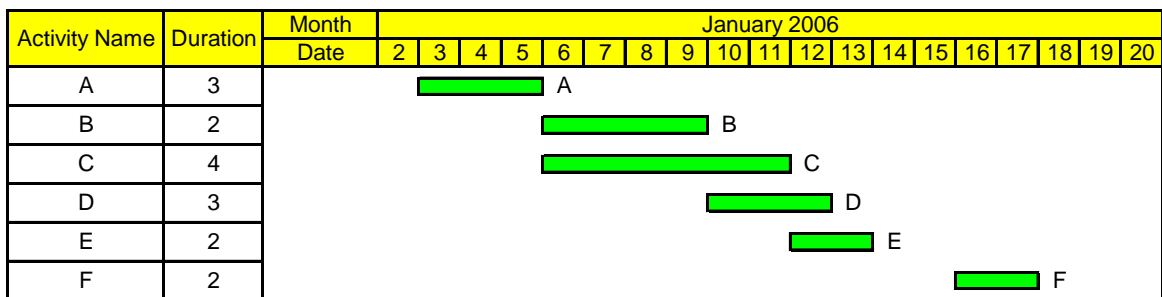


Figure 1 – Bar Chart (Five Day Work Week)

Today, bar charts remain popular because they are simple to develop and easy to understand. Bar charts provide a good overview of the project schedule; however, they lack detailed information that is necessary to effectively manage a project. A bar chart

does not show the float time of activities, the dependencies between activities, and other detailed activity information.

Critical Path Method

Bar charts were the industry standard until 1957, when the DuPont Company developed the Critical Path Method (CPM) for planning and scheduling complex projects in the chemical manufacturing industry. The CPM is especially applicable to projects that have multiple interdependency relationships between succinct activities.

Figure 2 shows a CPM logic diagram with the interrelationship between activities and the sequential flow of work. The project is represented by a network with activities shown as rectangular boxes, called nodes, and the sequential flow logic is depicted by arrows. The early and late start dates (ES, LS), and the early and late finish dates (EF, LF), are shown for each activity. Thus, the CPM provides a range of start and finish dates each activity; whereas, a bar chart simply shows a single start and finish date for each activity.

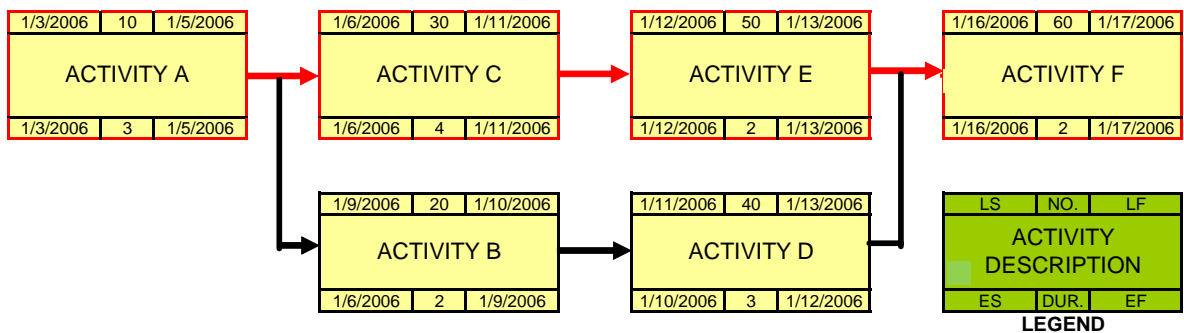


Figure 2 – Critical Path Method (CPM)

The advent of the personal computer spurred a large increase in the usage of the CPM. As a result, several software packages are available for developing CPM schedules including: Primavera[®], Microsoft Project[®], Open Plan[®], and Artemis[®]. These software packages allow rapid calculations of the scheduling information and numerous options for creating graphic output reports. Using software, activities in a CPM schedule can be resource loaded to provide valuable information to project management.

CPM assumes that construction activities can be divided into relatively small discrete activities that can then be sequenced in the order of their performance. Although the CPM is an excellent tool for scheduling projects consisting of discrete activities, it is not a good tool for scheduling linear or repetitive activities. Pipeline projects involve activities continuous along the horizontal alignment such as grading, stringing, bending, welding, coating, etc. Typically the same crew repeats each of these activities from one end of the project to the other. Often the only distinguishing feature for these linear-type activities is their rate of progress. When CPM is used to schedule repetitious activities, the resulting schedules have either a small number of activities (if the durations of the activities are large) or an excessive number of activities (if the durations of the activities are subdivided artificially by physical place or location).

For pipeline construction projects, the sequence of activities is usually not the issue of concern; instead the issue is accurately assessing and achieving the optimum production rates necessary for timely completion. Thus, to effectively schedule pipeline construction it is necessary to focus on repetitive-work activities and the probable production rates rather than the interrelationship of activities.

Scheduling of Projects Involving Repetitive Activities

Projects involving repetitive activities may be grouped into two groups; *point-based projects* and *distance-based (alignment-based) projects*. Examples of point-based projects include multi-unit housing complexes and high-rise building construction, whereas examples of distance-based (alignment-based) projects include pipelines and highways construction projects. As described in the following paragraphs, the Line of Balance (LOB) method of scheduling applies to point-based projects, whereas the Linear Scheduling Method (LSM) applies to distance-based (alignment-based) projects.

For point-based projects, workers perform discrete tasks (e.g. framing, painting, etc.) to complete similar units (e.g. apartment units, levels of a high-rise building, etc.) at one or more points in space. The repetitive activities are scheduled using the Line of Balance (LOB) technique. While originally used by the manufacturing industry, LOB has been adapted for application to point-based repetitive construction projects. Some of the names found in the published literature for these adaptations include: vertical production method [35], time-space scheduling method [44], repetitive activity scheduling process [40], and horizontal and vertical logic scheduling [45].

Figure 3 illustrates the application of LOB to the scheduling of two similar buildings, A and B. Each building contains the same activities: foundation, framing, and interior work as shown by the blue, green, and red lines. The same resources (foundation crew, framing crew, and interior work crew) are used from one building to the next. The LOB schedule allows the scheduler to show the location of each activity in relation to the building unit planned for construction. The diagram also ensures continuous resource usage without delays; by ensuring the activities do not overlap or delay one another.

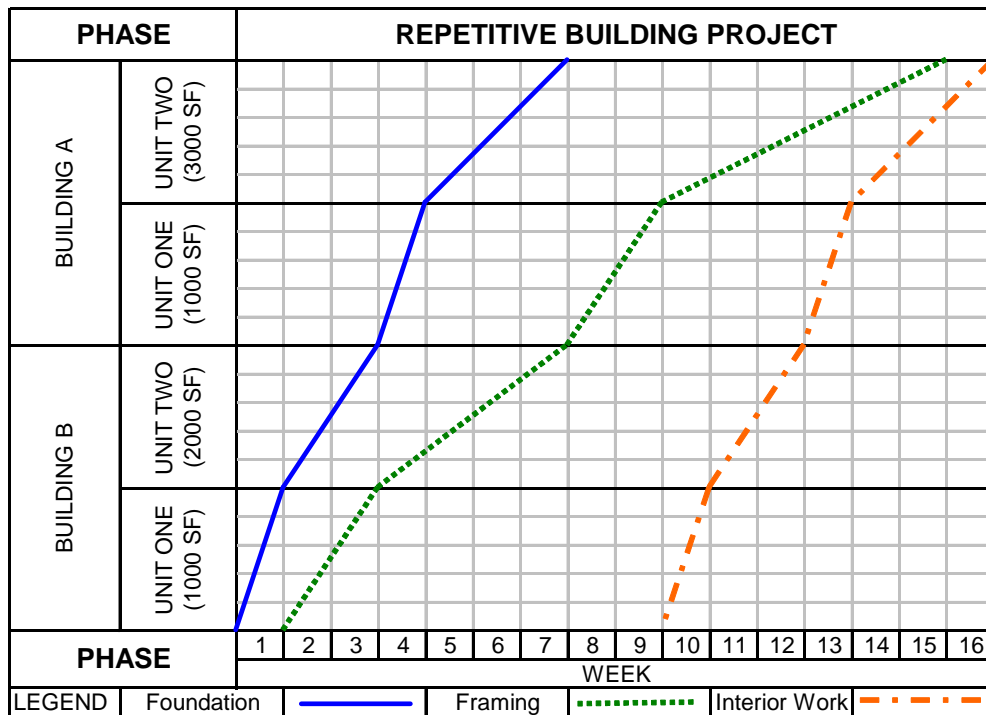


Figure 3 – Line of Balance for Point-based Repetitive Activities

For distance-based (alignment-based) projects, activities are performed continuously along the length of the horizontal alignment of the project. Highways, railroads, tunnels and pipelines are examples of such projects. The Linear Scheduling Method (LSM) is a very useful and informative tool for scheduling alignment-based projects. As shown in Figure 4, a linear schedule is developed with time on the y-axis and distance, or stationing, on the x-axis. The blue, red, and green activities represent grading, paving, and striping respectively. The progression of each of these activities in relation to location and time is plotted on the chart. Users can determine activities in progress at particular locations, activity production rates represented by the slopes of the line, and scheduling conflicts due to work location constraints. The continuous flow of

work along the alignment becomes the driving factor in scheduling linear projects of this type. Thus continuous resource usage is critical in establishing the project duration.

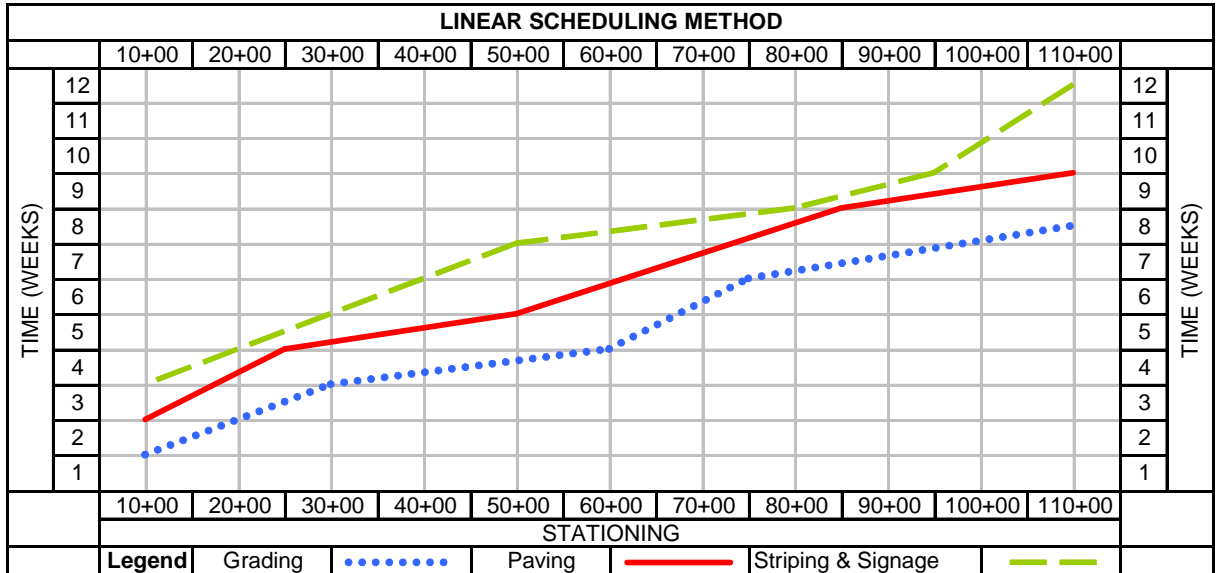


Figure 4 – Linear Scheduling of Alignment-based Repetitive Activities

Although linear scheduling has been in existence for quite some time, its use in the U.S. pipeline industry has been very limited compared to bar charts and CPM. The primary reason for the lack of widespread use of linear scheduling is the lack of commercially available software in the U.S. that addresses the pipeline industry’s needs. Aggressive marketing by CPM software developers has dominated the U.S. market and diminished the use of other scheduling techniques.

To better understand the concept of linear scheduling, one must understand the types of activities associated with these types of projects and how they are depicted on a linear schedule. Figure 5 illustrates the types of activities that can be used for linear scheduling; lines, bars, or blocks.

The most common activity type is a “*line*” which represents a continuous activity throughout the project. An example of such an activity is paving a road or laying pipe. The “*line*” is a plot of the movement of the crew performing the activity throughout the project with respect to time. A “*line*” could also be modified to take the shape of a *parallelogram*. The parallelogram has the attributes of a line activity, but adds an additional time buffer to account for situations such as concrete curing, which delays the start of a following activity to allow the concrete to cure, although the concrete crew may have moved on to a different place on the project. The primary advantage of representing continuous activities as a “*line*” in a linear schedule is that the slope of the line will determine the production rate required to complete the work on-time. This slope represents the rate that work in a space must be completed (distance/time), and it can be used to calculate the rate at which a quantity is placed, moved, or consumed (quantity/time). This type of information is very valuable to the project manager for the implementation of project controls as the work is completed and the schedule is updated.

Sometimes an activity does not consist of a continuous work path throughout a project, but instead is defined by work that takes place at the same location over a period of time. An example of such activity is the construction of a bridge or box culvert in a highway project. This type of activity is represented by a “*bar*”, which sets aside a time period, at a specific place, for the work to be completed before any other activities are allowed to occupy that space.

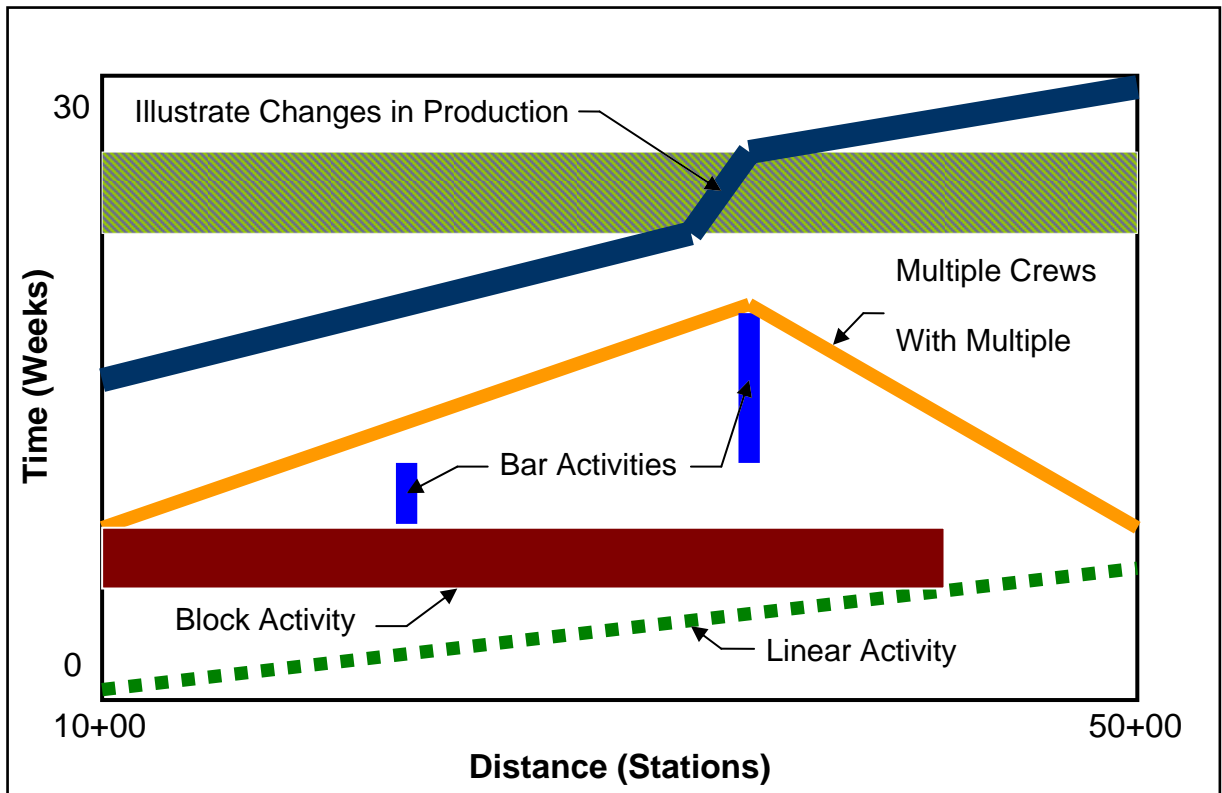


Figure 5 – Types of Activities in Linear Scheduling

The third type of activity used in linear scheduling is a “*block*”. A block represents an activity that takes place over a given space for a period of time. An example of such an activity is grading of a profile for a highway project. This type of activity requires both time and space, but the nature of the work does not allow for a continuous and smooth progression from one area to the next. As a result, the area requiring grading is blocked off from other activities on the schedule to allow the work to be completed. A block can also be used to illustrate project constraints such as weather or areas of the project that have restricted access during a certain time period. An example of restricted access would be placing a “block” along a section of roadway that the local government wants to remain open during periods of heavy travel. In this case, a “block” is placed at that location on the schedule for the period of time associated with

the government imposed restriction, in order to assist the project manager in planning the work around that constraint.

The power of the linear scheduling method does not lie in its ability to organize a project's individual activities, but instead it is gained from the multitude of graphical capabilities inherent to this method. For instance, a scheduler may choose to place a scaled plan or profile from the project's drawings alongside the distance scale in order to create a connection between an activity and a physical location on the proposed plan. In addition, each activity can be assigned a unique line style, type, thickness, or color to distinguish it from the rest of the activities. The project manager may choose to add a resource histogram or cumulative cost curve aligned with the time scale to help visualize the project's status during the planning and construction phase. All of the graphics can be tied together and defined through the use of a legend, in a similar manner to one that is found on any map. The use of graphics and the visual intuitiveness provided by the separate activity types enables project managers, schedulers, owners, and construction personnel to better visualize the plan of action and more easily communicate the plan to everyone involved with the project.

CHAPTER II

LITERATURE REVIEW

Linear scheduling has evolved into two types of repetitive projects; point-based projects and alignment-based projects. The literature review in this chapter gives a synopsis the work that has been developed for scheduling each of these types of projects.

Point-Based Repetitive Scheduling Techniques

Scheduling of point-based projects is an adaptation of the scheduling method called Line of Balance (LOB) which was developed by the U.S. Navy in the early 1950s [30] to monitor and evaluate the rate of completion of manufactured units as they pass through an assembly process.

In 1975, O'Brien [35] introduced a process of scheduling repetitive projects called Vertical Production Method (VPM). The process can be used to schedule construction of the different stories of high-rise buildings. Using this method, the author created a chart with the story of the building as the ordinate and time on the abscissa, which shows a simple view of crews moving from one floor to the next. O'Brien reports that the scheduling of the initial phases of high-rise construction, such as site work and

foundations, can be modeled with a CPM diagram. However, the CPM loses its power when attempting to schedule similar repetitive floors. The author suggests using a combination of CPM and VPM for scheduling the construction of high-rise buildings.

In 1982, Stradal and Cacha [44] introduced the time-space scheduling method (TSSM), which is a form of linear scheduling. Although the method focused on scheduling point-based projects, it did include a limited application to alignment-based projects. The authors provided examples of the application of TSSM for a pump foundation project, an apartment complex, a multistory building, and a roadway project. They concluded that the primary advantage of TSSM is the clarity and robust representation of the flow of work on the time-space diagram.

In 1986, Arditi and Albulak applied Line of Balance Scheduling to the construction of highway projects [1]. An example highway project was scheduled on an early start basis with no buffers between activities. The following is a brief summary of their major findings:

1. Linear scheduling is sensitive to productivity estimates for each activity.
2. Stage buffers are useful to accommodate variations in productivity rates.
3. The preparation of LOB a schedule is generally easier than the preparation of a network schedule and its related calculations, especially as repetition increases.
4. The LOB schedule should be kept as simple as possible. The level of detail shown on the schedule should show information that is easily discerned.

5. Using the LOB method provides valuable insight at the early stages of project planning, because the LOB scheduling is based on production rates that in turn depend upon available resources.
6. Foremen and subcontractors were more receptive to LOB diagrams than arrow diagrams, but not receptive enough to use them in lieu of bar charts. The LOB schedule can be used to produce weekly bar charts.
7. The visual presentation of LOB scheduling is helpful in project control.

Alignment-Based Linear Scheduling

As stated earlier, the term “*alignment scheduling*” is used throughout this report to denote linear scheduling methods applied to projects with a definable horizontal alignment. Table 1 illustrates some of the research efforts and chosen designated names that have been made to advance alignment scheduling in the academic community.

Table 1 – Previous Works in Alignment-Based Linear Scheduling

Nomenclature Utilized for Linear Scheduling	Researcher (s)	Year
Linear Scheduling Method	Johnston [30]	1981
Linear Scheduling Method	Chrzanowski & Johnston [7]	1986
Linear Scheduling Method	Vorster, Belivieu, & Bafna [46]	1992
Linear Scheduling Model	Harmelink [17]	1995
Linear Scheduling Model	Mattila [33]	1997
Linear Scheduling Model	Harmelink & Rowings [15]	1998
Linear Construction Planning Model	El-Sayegh [11]	1998
Linear Scheduling Model	Shu-Shun Liu [32]	1999
Linear Scheduling Method	Herbsman [20]	1999
Visual Linear Scheduling Model	Yamin [47]	2001
Linear Scheduling Method	Cosma [8]	2003
Linear Scheduling Model	Yen [48]	2005

In 1981, Johnston introduced the term “linear scheduling method” to the highway construction industry [30]. Figure 6 is an example of LSM applied to a highway construction job using line, block, and bar activities. The schedule utilizes line-type activities to represent clearing & grubbing, paving, and shoulders. It uses block activity types to represent the subbase and base. A complex activity type is used to represent the excavation work. The complex activity type represents excavation work that will be in progress at different levels of production, which may be caused by varying quantities of earthwork, blasting, and varying equipment or terrain. The final activity type shown in Figure 6 is the bar activity, which represents the culvert construction.

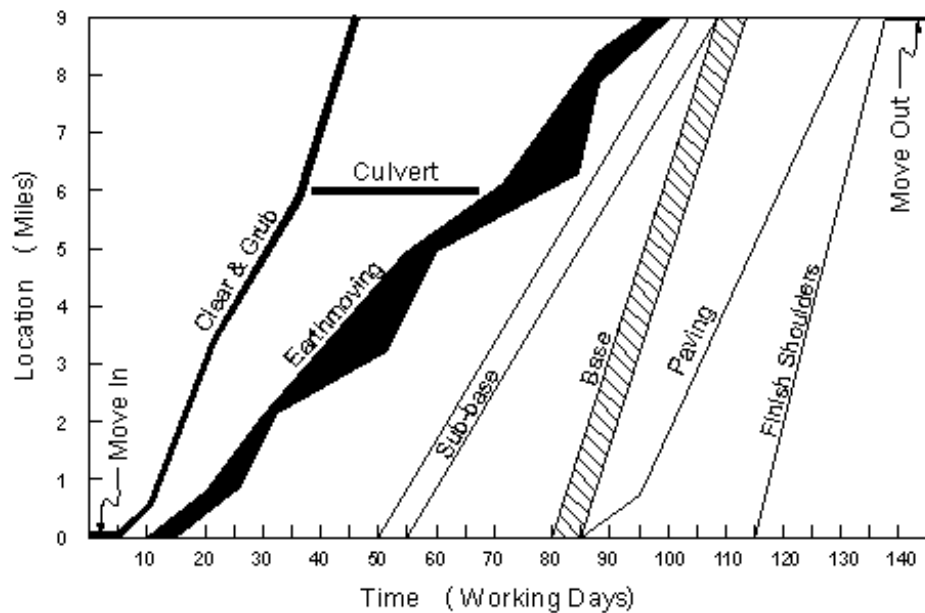


Figure 6 – Example of Linear Schedule for a Highway Project [30]

Johnston’s work included the utilization of production rates, activity interruptions, buffers, calendar considerations, and project resources to develop linear schedules for highway construction projects. In addition, he conducted a limited survey of highway

contractors, which concluded that none of the contractors were familiar with linear scheduling. The survey also indicated that a void existed between bar charts and CPM diagrams, and that LSM may be a tool to help fill that void. The following is a paraphrased summary of the main conclusions reached by Johnston [30]:

1. LSM provides more information concerning the planned method of construction than a bar chart.
2. In certain types of projects, LSM offers some advantages over the network scheduling approach (CPM). Network methods are a more powerful tool for most situations, especially projects with discrete activities. However, in repetitive portions of projects, LSM more quickly conveys the nature of the work and helps in identifying and solving problems. In a single project having both types of work, each type of scheduling can be applied to respective portions and coordinated.
3. LSM can be used for scheduling transportation-related projects, such as highway construction, resurfacing and maintenance, airport runway construction and resurfacing, tunnels, mass transit systems, pipelines, and railroads.
4. Although the method is not new, it has been given very little exposure among highway contractors.
5. Highway contractors who were surveyed indicated interest in the method and were of the opinion that it may have some potential.
6. LSM can assist in organizing construction work and reducing construction time; thus, it has measurable benefits in construction cost and safety that can offset the cost of schedule development.

7. Implementation of LSM will require educating and training the contractors on this scheduling technology. This would be followed by trial field use, feedback, improvements, and reuse until the method, if beneficial, is accepted.
8. Contract-letting agencies might consider either allowing LSM as an alternate to a required bar chart, or requiring both on some projects, to encourage trial use by contractors.
9. Perhaps the most significant advantage of LSM is the simplicity with which it can convey a detailed work schedule. When the schedule is easily understood by larger proportions of the field staff and workers, the schedule becomes a goal which can lead to improvements in productivity and reduced cost. Schedules developed and analyzed using more powerful network analysis methods, perhaps involving lead/lag techniques, can be charted in the form of LSM diagrams as a means of simply conveying the analysis results.

In 1986, Chrzanowski, Jr. and Johnston [7] added to Johnston's previous work by comparing and contrasting CPM and LSM utilizing an as-built highway schedule. The simplicity of LSM was noted as its largest asset. However there may be times when it would be advantageous to use LSM in conjunction with CPM. The authors noted that the user "receives fairly detailed information without being confronted with the numerical data and degree of abstraction found in network methods." They also addressed some of the limitations of linear scheduling. For a project with discrete activities, a network diagram may be needed to model the interrelationship and sequencing of activities. If a project has multiple alignments, such as two intersecting roadways, then it may be necessary to develop a separate schedule for each roadway, which would require multiple

schedules for a single project. Finally, CAD based software is needed because linear scheduling is a graphic, or visual based, scheduling technique. In conclusion, the authors noted that LSM was best used as a complement to CPM.

Nine years later, in his 1995 thesis, Harmelink developed a model of linear scheduling in conjunction with an AutoCAD-based program [17]. His work focused on two important aspects of linear scheduling: 1) proving computerization of linear scheduling is possible and 2) illustrating procedures to identify the controlling activity path in the schedule. In CPM, the critical path is defined as the longest path, time wise, through the sequence of activities. In LSM, an analogous path is called the *controlling activity path*.

Hamelink's model determined the controlling path using "an upward and a downward pass, analogous to the forward and backward pass used in CPM scheduling techniques." Using time on the vertical axis and distance on the horizontal axis, the upward and downward pass moves through the project in a time-scale fashion to determine activity relationships, hence the correlation to the forward and backward pass. The thesis shows illustrations of several cases used to calculate the controlling path during the upward and downward pass. It also provides examples to show how these cases work and the calculations necessary to derive the schedule for the different cases.

As shown in Figure 7, Harmelink utilized three key features to define the controlling activity path. These key features are the least time interval (LT), coincident duration, and the least distance interval (LD). The least time interval is "the shortest time interval between any two consecutive activities". The coincident duration is "an interval

in time during which the two activities connected by the least time interval are both in progress.” Lastly, the least distance interval is “the shortest distance between any two activities that lies within the coincident duration interval and intersects the least time interval.” The LT, coincident duration, and LD for the paving and striping activities are depicted in Figure 7. The coincident duration between weeks 7 and 9 (highlighted in yellow in Figure 7) shows the LT and LD interrelationship between the activities “paving” and “striping & signage”. Another coincident duration exists between weeks 4 and 5 due to the LT and LD interrelationship between activities “grading” and “paving”; however, this coincident duration is not highlighted to prevent excessive detail in Figure 7.

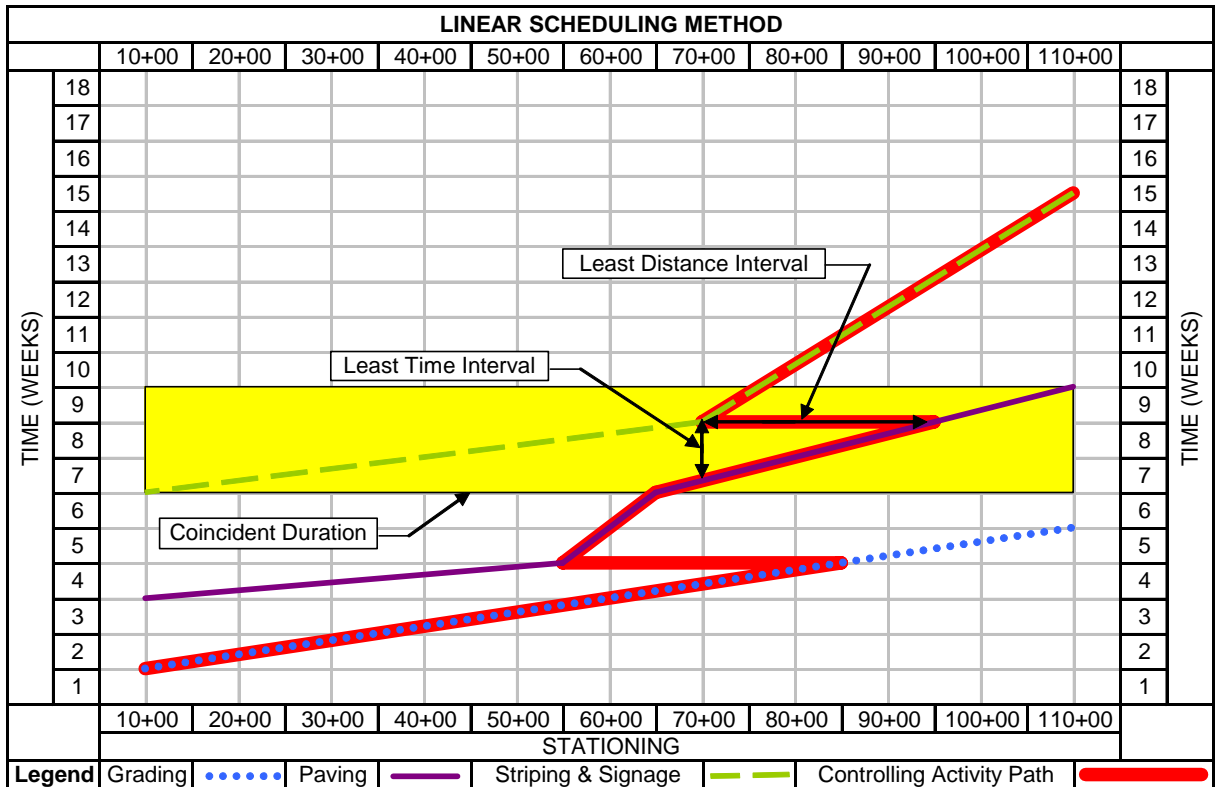


Figure 7 – Example of a Linear Schedule with the Controlling Activity Path Displayed

A summary of the activity types and associated terminology that were defined in the linear scheduling model of Harmelink are described in Table 2 and Figure 8 [42]. Table 2 shows a listing of activity types. Figure 8 is a graphical example that shows the three main types of activities: lines, blocks, and bars. Furthermore, Harmelink's model characterized activities as full-span or partial-span to denote the relationship between activities and the length of the project. Full-span activities run the entire length of the project; whereas partial-span activities run only a portion of the length of the project. Harmelink's model also defined activities as continuous or intermittent, as shown in Figure 8. Continuous activities take place along the entire alignment of the project and intermittent activities are performed periodically along the length of the job. Using these activity types and calculation methods, the author utilized AutoLisp, a programming language for AutoCAD, to generate linear schedules in AutoCAD and compare the output with CPM diagrams. Harmelink concluded that LSM has the following advantages over CPM:

1. The Linear Scheduling Model can realistically determine the controlling activity path.
2. The Linear Scheduling Model can accurately model the production rate characteristics of linear activities.
3. As-built production rate information can be easily utilized to track the progress of linear activities on the project, providing managers with realistic information for making decisions.

Table 2 – List of Linear Scheduling Activity Types [42]

Activity Type	Activity Description
Linear Continuous Full-Span	Activities that are linear in nature, require continuous uninterrupted construction activity and span from the physical project start to the physical project finish.
Linear Continuous Partial-Span	Activities that are linear in nature, require continuous construction activity and span from some physical mid point of the project to some other physical mid point of the project.
Linear Continuous Segmented	Activities that are linear in nature, that can be broken into continuous segments of construction activity based upon the available equipment spreads and span from the physical project start to the physical project finish.
Linear Intermittent Full-Span	Activities that are linear in nature, require uninterrupted construction activity that occurs at selected locations and span from the physical project start to the physical project finish.
Linear Intermittent Partial-Span	Activities that are linear in nature, require uninterrupted construction activity that occurs at selected locations and span from some physical mid point of the project to some other physical mid point of the project.
Linear Intermittent Segmented	Activities that are linear in nature, that can be broken into uninterrupted segments of construction activity that occurs at selected locations based upon the available equipment spreads and span from the physical project start to the physical project finish.
Linear Spacial Full-Span	Activities that are linear in nature, require continuous uninterrupted construction activity, require continued operations (time span) at all locations and span from the physical project start to the physical project finish.
Linear Spacial Partial-Span	Activities that are linear in nature, require continuous uninterrupted construction activity, require continued operations (time span) at all locations and span from some physical mid point of the project to some other physical mid point of the project.
Block Full-Span	Activities that require intermittent construction activity over the entire project.
Block Partial-Span	Activities that require intermittent construction activity over an area from some physical mid point of the project to some other physical mid point of the project.
Bar Discrete	Activities that require construction work at a discrete location on the project.
Bar Repetitive	Activities that require construction work repeated over time at a discrete location on the project.
Bar Intermittent	Activities that require various construction work at varying intervals at a discrete location on the project.

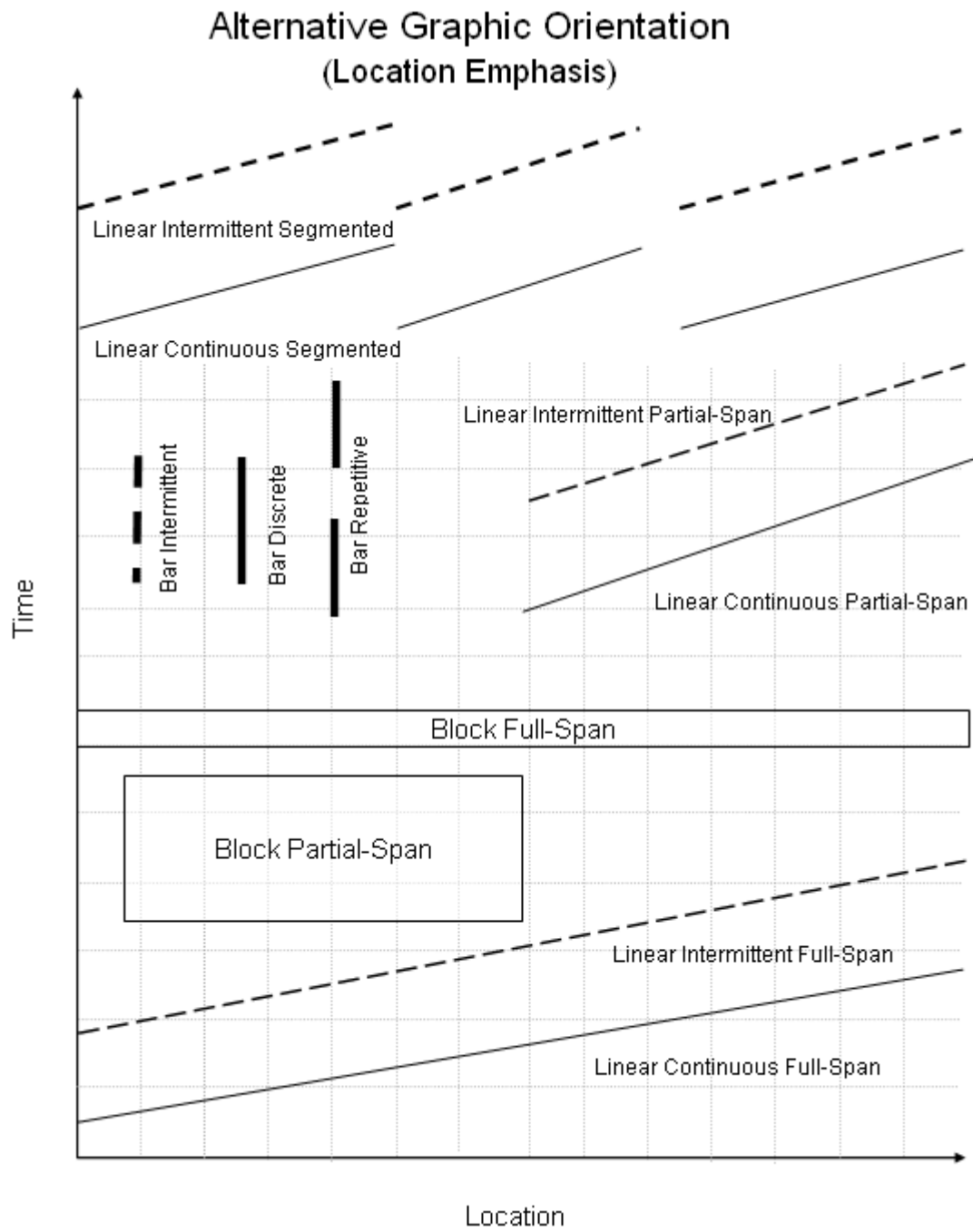


Figure 8 – Graphical Presentation of Activity Types in Linear Scheduling [42]

4. The Linear Scheduling Model provides a visual method of planning linear projects and greatly facilitates the communication of the project plan to other parties involved in the project.

Harmelink also noted that development of linear scheduling software would need to have features that already exist in current commercial CPM software, such as cost loading of the linear schedule, allocation of resources, and the ability to perform resource leveling.

In 1998, Harmelink and Rowings published a journal article that focused on the development of the controlling activity path [15]. The controlling activity path that was developed by Harmelink in 1995 represents a path similar to the critical path in CPM scheduling. The difference is that LSM allows segments of an activity to be controlling, whereas CPM only allows an entire activity to be critical. If only a portion of a CPM activity should be shown as critical, it is necessary to break the activity into two activities to better represent the actual critical path. This process of segmenting activities adds numerous activities quickly, which increases the complexity to the CPM diagram. The authors concluded that development of LSM provides a foundation on which to build a robust linear scheduling application with the level of functionality as rich as CPM provides for discrete logic scheduling.

Also in 1998, El-Sayegh developed deterministic and probabilistic models for calculating resource-based linear schedules [11]. The deterministic model can be used to produce a linear schedule based solely on user input. The probabilistic model may be used to produce a linear schedule based on Monte Carlo simulation, which accounts for variability and uncertainty of construction projects. The models were included in a

windows-based software package named “Linear Construction Planning Model” (LCPM). LCPM allows input of work-breakdown structures, resource constraints, crew dynamics, and labor and material costs. The software is capable of outputting linear schedules (both deterministic and probabilistic) sorted by work areas, crew movement charts, and the active and idle times of crewmembers. The models, developed with the prototype software, allow the calculation of numerical data similar to CPM, such as early start, late start, early finish, late finish, and total float. A disadvantage of the program is that it requires the user to manually account for time and location buffers. The following is a paraphrased list El-Sayegh’s recommendations for development of LCPM software:

1. LCPM focused on Macro-level planning that is needed for project managers.
There is a need to combine the macro-level planning with micro-level planning, which focuses on determining production rates for the different operations.
2. There is a need to enhance the graphical capabilities of the prototype software.
Some graphical entities that need to be represented in the linear schedule include cut and fill areas and blocks to represent inaccessible areas due to weather or site constraints.
3. The software should have cost information features; including budgeted costs and the ability to monitor project progress using earned value calculations.
4. There is a need to educate both civil engineering students and practitioners about the use and advantages of the LCPM. Finally, departments of transportation should require the use of linear scheduling techniques on their projects.

In 1999, Liu defined a method for evaluating resource constraints in linear schedules [32]. He used a heuristic approach to the scheduling of resources that allows

the user to input certain criteria for basing decisions on resource usage and allocation. This approach allows resource conflict resolution with a reasonable schedule duration. Liu's approach also included developing an algorithm to determine near optimal solutions based on minimum schedule duration. A Java application was produced to implement the algorithms into a usable package. Recommendations for further research included the extension of this application into a web-based version for either the internet or company intranets.

A study sponsored by the Florida DOT in 1999 revealed that very few state DOTs had worked with linear scheduling methods [20]. The research team conducted a survey of the state DOTs in the United States with 37 responding. The survey showed that 65% of those responding were not familiar with linear scheduling methods. Two states, Connecticut and Texas, reported using linear scheduling in their construction operations and claims analysis. The research team developed a linear scheduling application FLSP V1.0, which can produce linear schedules, resource histograms, and s-cost curves.

Following are the conclusions reached from the Florida DOT study:

1. LSM is a planning method that is very easy to prepare and use, particularly for construction projects characterized by the repetitiveness and linearity of the activities (roads, highways, tunnels, etc.).
2. Linear schedules are easy to understand at all the managerial levels; project superintendents and crew foreman actually use them to monitor and evaluate performance.
3. One of the main characteristics of LSM is the ability to visually communicate both the location and the progress of work. Linear Scheduling monitors the

progress of multiple continuous activities by illustrating in a graphical manner the time, location of work, and rates of production.

4. LSM is a reliable planning method that ensures that all resources are considered during planning to assist in the efficient design of the project.
5. The value of LSM relies in the fact that it can be used to prove or disprove claims and requests for time extensions, thus helping to manage both time and money, as well as to improve chances of recognizing causes and impacts of delays.

The Florida research team also noted one of the main reasons for not implementing the linear scheduling method is a lack of commercially available software.

In 2001, Yamin [47] developed an approach to analyze the cumulative effect of productivity rate variability (CEPRV) on linear activities in highway projects. The focus of the research was to advance the risk analysis capabilities of linear scheduling to allow managers to forecast the probability of project delay. This and other statistical analysis tools are prevalent with CPM, but are lacking in linear scheduling methods. Yamin also developed methods for determining *secondary controlling activity paths* (SCAPs). These SCAPs occur due to activities that are near critical and have high productivity rate variability (PRV.) The probability that such activities may become critical is high. The author suggests further research in evaluating PRV by statistically analyzing construction factors such as: type of work being done, soil conditions, weather, equipment type, experience of labor, and general layout. This would enable managers and schedulers to better forecast the impacts of the variability of the different components.

Also in 2001, Harmelink and Yamin [16] compared and contrasted CPM and LSM for scheduling linear projects. Their work stressed the importance of using the

appropriate tool for scheduling projects. For example an alignment-based linear schedule would be used for highway work, while a multi-story building would best be scheduled with a point-based schedule.

Table 3 lists different types of construction projects and the scheduling methods and characteristics most often associated with those projects. The authors provided two examples, a bridge project and a road rehabilitation project, that were both scheduled by CPM and LSM. Findings drawn from the two example projects concerning the attributes of CPM and LSM are summarized in Table 4. The authors concluded that much work needed to be done with LSM to provide the same abilities as CPM, particularly in the resource management and duration uncertainty for LSM.

Table 3 – Recommended Scheduling Tool for Different Types of Projects [16]

Type of Project	Scheduling Method	Main Characteristic
Linear and continuous projects (pipelines, railroads, tunnels, highways)	LSM	<ul style="list-style-type: none"> • Few activities • Executed along a linear path/space • Hard sequence logic • Work continuity crucial for effective performance
Multunit repetitive projects (housing complex, buildings)	LOB	<ul style="list-style-type: none"> • Final Product a group of similar units • Same activities during all projects • Balance between different activities achieved to reach objective production
High-rise buildings	LOB/VPM	<ul style="list-style-type: none"> • Repetitive activities • Hard logic for some activities, soft for others • Large amount of activities • Every floor considered a production unit
Refineries and other very complex projects	PERT/CPM	<ul style="list-style-type: none"> • Extremely large number of activities • Complex design • Activities discrete in nature • Crucial to keep project in critical path
Simple projects (of any kind)	Bar/Gantt	<ul style="list-style-type: none"> • Indicates only time dimension (when to start and end activities) • Relatively few activities

Table 4 – Comparison of Critical Path Method (CPM) and Linear Scheduling Method (LSM) along with Important Project Management Attributes [16]

Attribute/dimension	CPM	LSM
Aid in reduction of uncertainty/risk	Although CPM schedules use fixed duration for activities, it can be easily complemented by PERT with statistical capabilities. This feature helps planners to get a better idea of time and schedule risks.	There is no formal method developed to date that could allow LSM to determine uncertainties in time completion
Aid in improving production and economical operation	With the incorporation of resource leveling/allocation techniques, CPM schedules can improve the overall completion time and costs by affecting production (add or remove resources). Some limitations have been identified when scheduling continuous projects-difficult to maintain continuity in crew utilization.	Limited capabilities in improving production by changing resources. Easy to schedule continuity on linear projects, improving coordination and productivity.
Aid in achieving better understanding of objectives	In complex projects, CPM network can be very convoluted. This complexity makes them difficult to understand and communicate.	LSM is very easy to understand, and it can be used at every level of the construction project.
Accurate calculations	CPM allows the PM to calculate the time it would take to complete a project, and together with the PERT could provide statistical insights to this process. It is difficult to accurately determine and represent space restrictions (if any).	Location/time calculation is easily done. This is the greatest advantage of LSM over CPM when scheduling linear projects. This capability allows PM to accurately plan activities both in time and location
Critical path	It is the main feature of the CPM, which can be done very easily	The LSM algorithm calculated the controlling activity path (CAP) which is equivalent to the critical path, with the additional feature of location criticality.
Ease of use	Extensive computerization has made the CPM method easier to use. However, the user needs a considerable amount of training before actually being able to produce valuable information for controlling purposes.	Very intuitive and easy to understand. It can be used at all levels of the company (managers, superintendents and crew). Lack of computerization makes it difficult to use in large and complex projects.
Easy to update	The method could be difficult to update. Once several updates have been done, it becomes difficult to read. Updated schedules are usually out of date when they are finished.	Updating LSM is simple. Linear schedules can be used as as-built documents for claim purposes or for historical productivity databases.

Overview of Existing Commercial Software

This section provides an overview of available software packages for developing linear schedules of alignment-based projects. Successful implementation of linear scheduling methods will require a software package for ease of calculation and schedule updating. A search for software packages capable of producing alignment-based linear schedules revealed the following commercially available products: Chainlink (England) [28], LinearPlus (England) [26], Spider Project Professional (Russia) [27], TILOS (England/Germany) [22], and Time Chainage (England). The remainder of this section provides a description of each software package and an evaluation of the different packages based on the following criteria:

- 1) Data input and interface
- 2) Output capabilities
- 3) Adaptability to scheduling highway construction projects

Chainlink version 4.2

Chainlink is a linear scheduling software package produced in England by Steven Wood [28]. Chainlink displays distance on the horizontal axis and time on the vertical axis. The software lacks the ability to include activity relationships and the accompanying calculations, and therefore serves more as a linear display of a schedule created from another software package. Chainlink will import and export files to Primavera, MS Project, and generic comma delimited files. The software has the ability

to display various activity types such as linear and block activities, and also has the ability to include graphic files.

Data Input

The simplest method of inputting data into Chainlink is by importing the data from a scheduling program that has the ability to calculate the start and finish dates based on network logic. The user can also enter start and finish dates manually using a spreadsheet interface in the activity data tab shown in Figure 9. The user can choose the desired color, line-type, and the shape for each activity. Picture files may also be added to the diagram, such as the plan and profile or other pertinent information related to the linear schedule. The input screen shown in Figure 9 also shows other tabs for project data, key/legend, labels, milestones/notes, and graphs/clipart.

Activity ID	Duration (Day)	Calendar	Description	Sort Code 1	Sort Code 2	Start Reference	Finish Reference	Bar Direction	Bar Style	Bar Colour	Bar Text	Location Offset	Time Offset	Start Date 1	Finish Date 1	Total Float
1	3500	88	S Stream Bridge	3500	0000	1608	1612	As Reference	27	Yes		0	0	06/01/1999	10/01/1999	0
2	4030	5	S Access Road	4000	0000	1760	1720	As Reference	10	No		0	0	03/22/1999	03/26/1999	0
3	4165	1	S Wearing Course	4000	0000	1580	1740	As Reference	17	No		0	0	10/23/1999	10/22/1999	0
4	4145	2	S Roadbase	4000	0000	1580	1740	As Reference	12	No		0	0	10/20/1999	10/19/1999	0
5	3040	2	S Topsoil Strip	4000	0000	1580	1640	As Reference	14	No		0	0	03/01/1999	03/02/1999	0
6	3090	5	S Fill	4000	0000	1580	1640	As Reference	12	No		0	0	03/08/1999	03/12/1999	0
7	3030	5	S Access Road	4000	0000	1580	1640	As Reference	10	No		0	0	03/15/1999	03/19/1999	0
8	4132	10	S Kerbs	4000	0000	1580	1740	As Reference	17	No		0	0	10/04/1999	10/15/1999	0
9	4530	45	S East Pier	4500	0000	1690	1690	As Reference	27	Yes		0	0	04/19/1999	06/22/1999	0
10	4520	44	S West Pier	4500	0000	1670	1670	As Reference	27	Yes		0	0	05/10/1999	07/09/1999	0
11	4510	33	S West Abutment	4500	0000	1650	1650	As Reference	27	Yes		0	0	05/24/1999	07/08/1999	0
12	4540	32	S East Abutment	4500	0000	1710	1710	As Reference	27	Yes		0	0	05/04/1999	06/17/1999	0
13	4050	10	S Permanent Fencing	5000	0000	1740	2100	As Reference	12	No		0	0	02/15/1999	02/26/1999	0
14	4020	10	S Stone Walling	5000	0000	2100	1740	As Reference	17	No		0	0	07/05/1999	07/16/1999	0
15	4100	5	S Capping	5000	0000	1740	2100	As Reference	14	No		0	0	05/17/1999	05/21/1999	0
16	4120	5	S Sub-Base	5000	0000	1740	2100	As Reference	17	No		0	0	06/14/1999	06/25/1999	0
17	4200	10	S Arrestor Bed	5000	0000	2050	1880	As Reference	17	No		0	0	06/28/1999	07/09/1999	0
18	4170	5	S Signs, Lights, Road Mar	5000	0000	2100	1740	As Reference	17	No		0	0	08/23/1999	08/27/1999	0
19	4134	10	S Kerbs	5000	0000	1940	2200	As Reference	17	No		0	0	10/25/1999	11/05/1999	0
20	4130	15	S Kerbs	5000	0000	2100	1740	As Reference	17	No		0	0	07/12/1999	07/30/1999	0
21	4110	10	S Drainage	5000	0000	1740	2040	As Reference	17	No		0	0	06/07/1999	06/18/1999	0
22	4060	9	S Pre-Earthworks Drainag	5000	0000	1700	1840	As Reference	12	No		0	0	03/29/1999	04/08/1999	0
23	4090	14	S Fill	5000	0000	1740	2100	As Reference	12	No		0	0	04/26/1999	05/14/1999	0
24	4040	5	S Topsoil Strip	5000	0000	1700	2100	As Reference	14	No		0	0	03/29/1999	04/02/1999	0
25	4190	8	S Landscaping	5000	0000	2100	1740	As Reference	11	No		0	0	07/26/1999	08/04/1999	0

Figure 9 – Activity Data Input Tab in Chainlink Software

Output Capabilities

Chainlink can output linear schedules in a variety of displays. Sorting features allow the user to display certain activities for specific schedules. The user can also customize the layout of the page and select the dates and locations displayed per page. The ability of Chainlink to incorporate graphics and customize the appearance of the activities provides an output that is effective in communicating the schedule. The software lacks the ability to produce bar charts, CPM diagrams, and reports. Figure 10 shows the output of a completed schedule from Chainlink. As shown in this figure, the picture of the roadway and interchange is shown at the top of the output page. Line and bar activities are shown in the various colors to enhance the display of the linear schedule. The legend for the linear schedule is shown on the right hand side of this output page.

Adaptability to Scheduling Pipeline Construction Projects

Chainlink is a useful tool for the visual display of project schedule information in a linear format. The program incorporates many features useful to visualizing a pipeline project such as graphics and variable activity types. However, the inability to calculate the data associated with predecessor/successor relationships is a significant limitation of the software package as a viable solution for pipeline contractors in the United States.

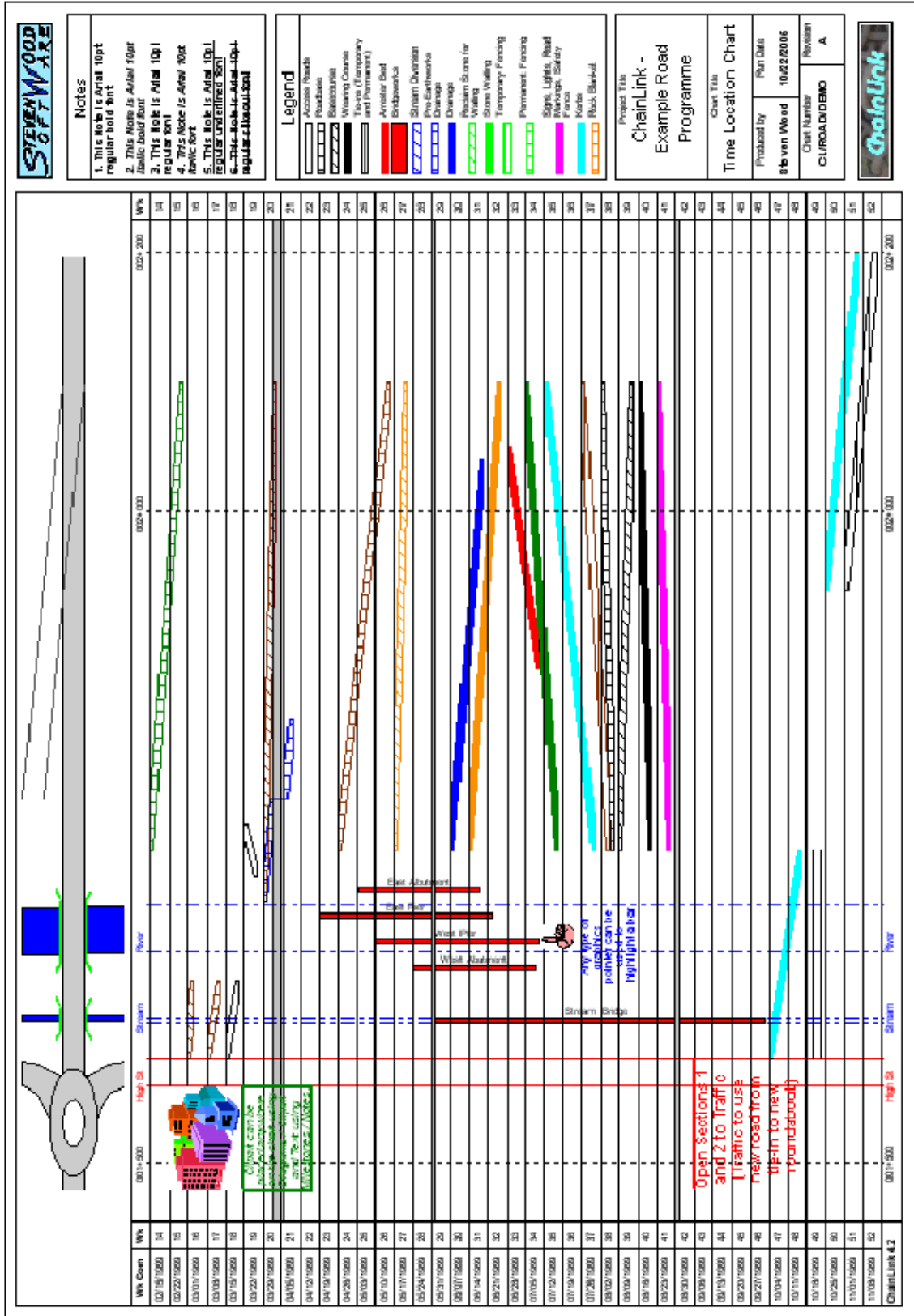


Figure 10 – Schedule for a Road Project from Chainlink Software

Linear Plus version 2.1

Linear Plus is scheduling software produced by PCF Ltd., an England based company [26]. The software package was produced to assist in scheduling construction of the Channel Tunnel or “Chunnel”. The software displays time on the horizontal axis and distance on the vertical axis. The product allows a variety of visual information to be incorporated in the linear diagram.

Data Input

Linear Plus allows the user to input activity data in both a spreadsheet and graphical fashion. Start locations and dates can be entered numerically or by clicking on the time-space grid of the project. The software allows the creation of linear, block, and complex activities. The linear activities are displayed as lines, while the blocks are represented as rectangles, and the complex activities are parallelograms. Once an activity is created the user can edit the activity graphically by dragging it to the desired location.

The software allows the user to setup templates, resource libraries, and import external project data. Once the templates and resources are setup, they can be used for future projects, which greatly reduces the time required to create a linear schedule.

Linear Plus allows the insertion of graphics and text onto the linear schedule. The package allows the user to create their own objects or import vector files, such as dxf or HP-GL files. The ability to import dxf files easily allows the user to place CAD information on the schedule, such as the plan view or the profile view as shown in Figure 11. This data can be scaled to the appropriate location on the diagram. The graphics can also contain links that open web pages or other documents pertinent to a feature or activity.

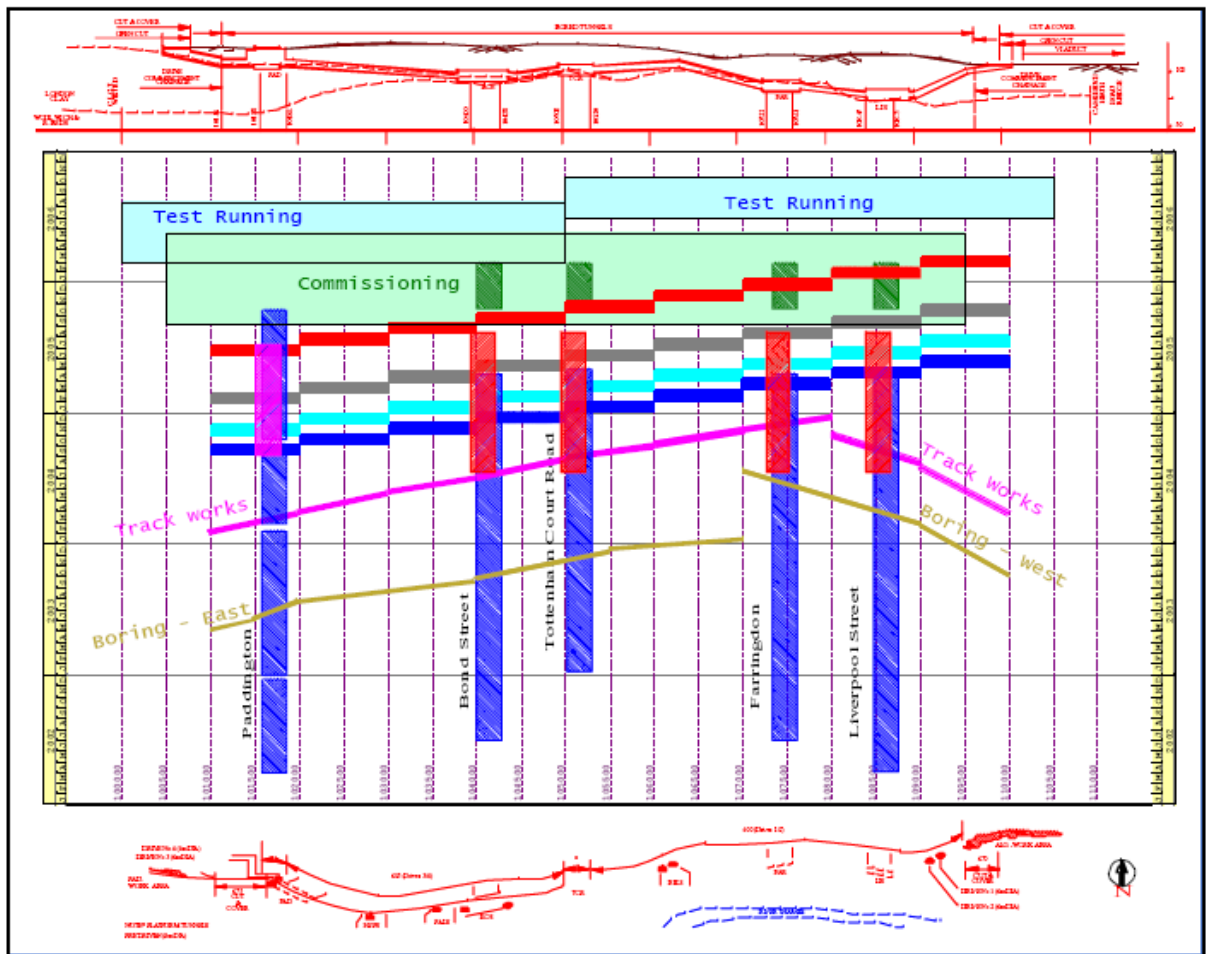


Figure 11 – Road Project Schedule from Linear Plus Software

Output Capabilities

Linear Plus outputs linear schedules with a variety of graphics and project information as shown in Figure 12. The program is flexible for displaying activities and it contains features such as linking and dxf input, which make the output appealing. The program also allows the user to output the schedule into a web-friendly format to easily display project schedules via the internet. Linear Plus can also include both cost and resource histograms on the linear schedule, but the package does not have the ability to output CPM diagrams and project reports. However, the user does have the option to export project information to various programs to accomplish these tasks.

Adaptability to Scheduling Pipeline Construction Projects

Linear Plus is a versatile package for creating and manipulating activities. The software has benefits for pipeline contractors wishing to use a linear schedule along with traditional scheduling methods. PCF Ltd. offers a product called QEI that performs project management functions, including features such as CPM diagrams, written reports, and earned value analysis. This product requires an add-on to produce linear schedules, which was not available for testing. QEI is a robust management software. QEI with the linear scheduling add-on would allow pipeline contractors the most flexibility and thus provide an appealing solution for scheduling pipeline projects.

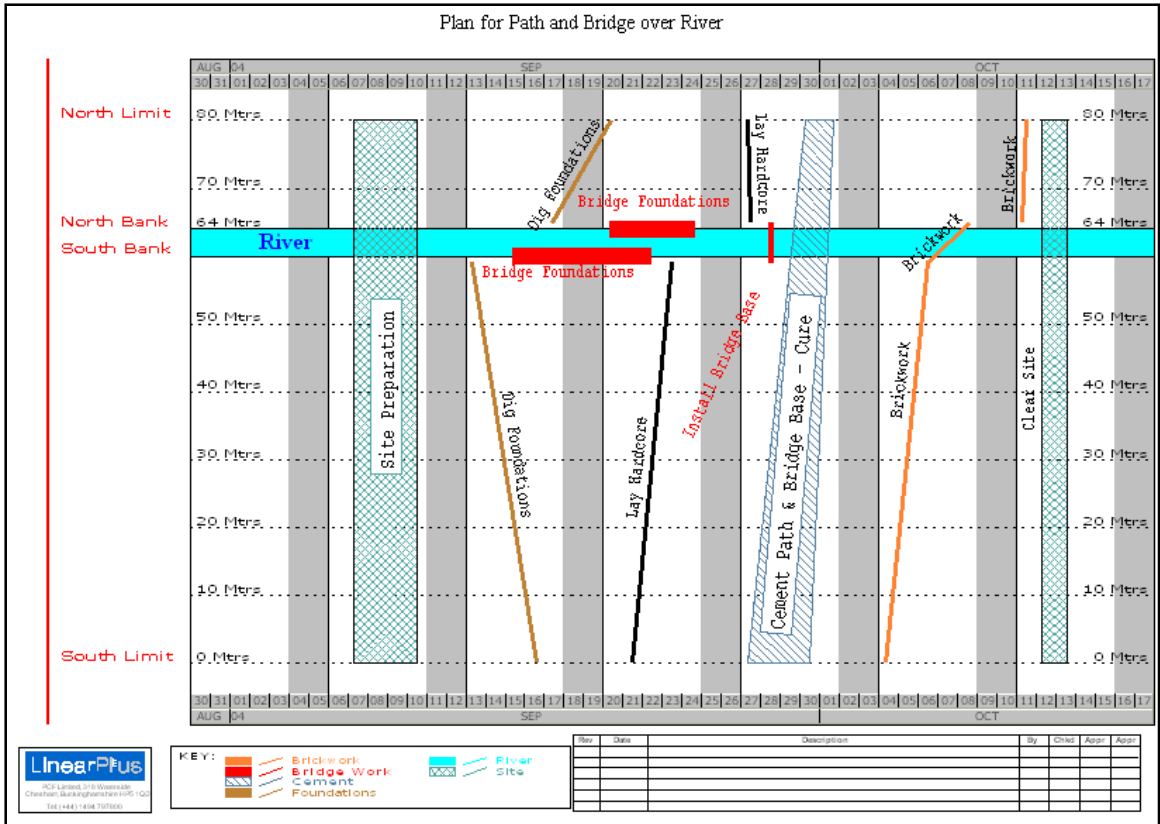


Figure 12 – Schedule for Path and Bridge over River Project from Linear Plus Software

Spider Project version 8.09 revision 11

Spider Project is a complete project management software package developed in Russia by Spider Management Technologies [27]. The software includes many views familiar to schedulers in the United States. Spider Project is capable of displaying schedules in the following formats: Gantt chart, Resource Gantt Chart, Activity Network or Precedence Diagram, and Linear Chart. The linear chart represents this program’s approach to incorporating a linear type of schedule within its package. The software allows both point-based and alignment-based linear scheduling. The alignment-based linear schedule displays distance on the horizontal axis and time on the vertical axis.

Data Input

Spider Project's graphical interface, consisting of buttons and drop down menus, is relatively intuitive for users accustomed to other scheduling software in the United States. Activities and their attributes are created and defined in a spreadsheet-like activity list. One of the attributes utilized in Spider Project is the distance location start and finish of the activity, referred to as "metrics start" and "metrics end". Upon completion of entering the activities, the user can then switch to the linear diagram mode. From the linear diagram view, the user accesses the options menu, where the axes are defined and the activities that one wishes to be displayed are selected. The options menu is shown in Figure 13. The user can then define the location, or metrics, desired to be displayed for the X-axis.

Output Capabilities

Spider Project is capable of outputting schedules in a variety of ways, including multiple on-screen views and printing options. The linear diagram is printed exactly as it appears on screen. The user is able to add simple text and scalable pictures to a diagram and change the line-type and color of the activities linear appearance. The software only allows the input of line-type activities, as shown in Figure 14, on the linear diagram; thus reducing the versatility of the display of the work.

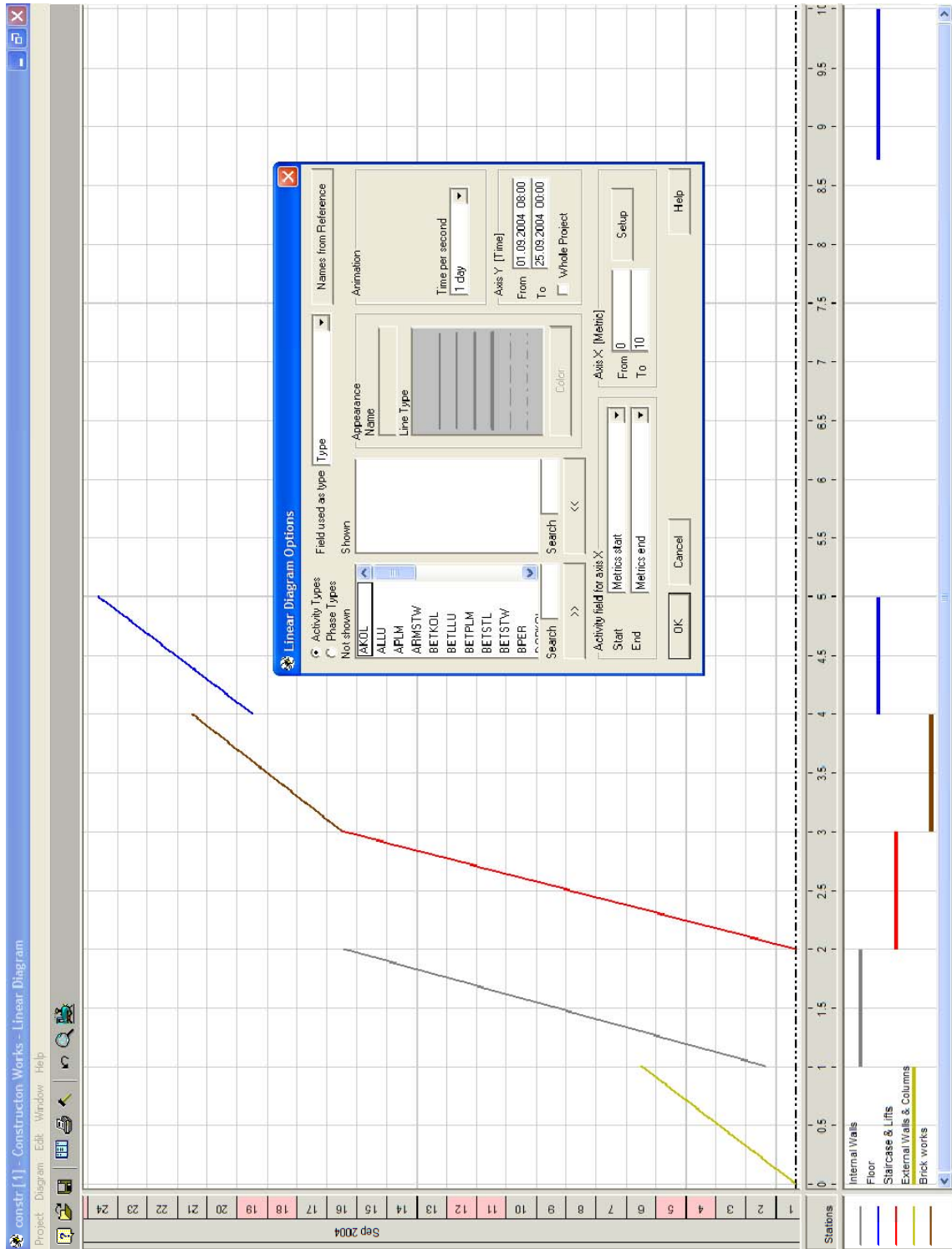


Figure 13 – Linear Diagram Options used in Spider Project

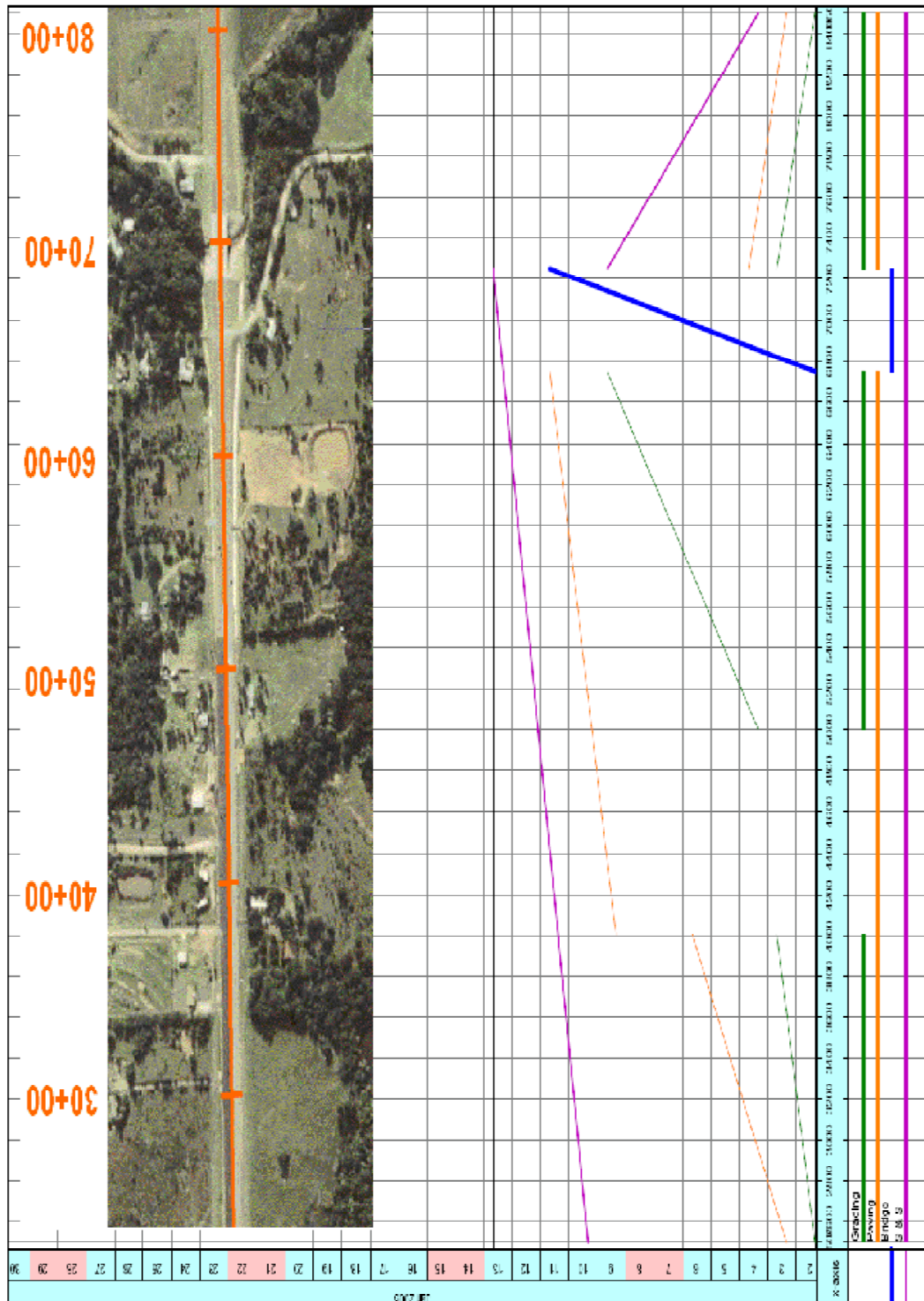


Figure 14 – Example of a Linear Diagram Produced in Spider Project

Adaptability to Scheduling Pipeline Construction Projects

Spider Project is an interesting project management software suite. The developers of this software combined several features for project scheduling into one package. Spider Project allows contractors to manage and schedule many aspects of pipeline projects; however the linear diagram lacks customization features and lacks the ability to draw activities in a CAD-type interface.

TILOS version 4.0.02

TILOS is a graphics based linear scheduling software package developed in Germany and distributed by Asta Development [22]. This program is based on linear scheduling concepts and is capable of producing schedules that are visually appealing and display pertinent project information. TILOS has the ability to add multiple graphics to a schedule, including a scaled view of the project's plan and profile. It can also display resource and cost histograms and curves. The software is capable of displaying a project in either a Gantt chart view or a linear schedule view. The program is flexible and can be customized to include multiple user-defined activity libraries and schedule views. The activity libraries allow the user to define the appearance, resource allocation, production rate, and cost associated with the activities.

Data Input

The process of creating a schedule in TILOS is made simpler through the use of project templates, which include activity libraries and preprogrammed schedule views

that are then customized to fit the attributes of a new project. A template is opened and project attributes such as calendars, start and end dates and distances are entered to define the new project. The user can then begin to add activities by actually drawing them on the schedule, similar to a CAD program, or by entering time and space constraints in a tabular format. After each activity is placed on the schedule, the user can choose to adjust its attributes by using the mouse, which opens an activity details menu at the bottom of the screen. This menu, shown in Figure 15, allows the user to adjust the activity's calculation method, details, location, progress, dependencies, resources, and costs.

After all of the activities are created and modified to meet the attributes of the project, the user is able to tailor the linear schedule to meet their needs by adding additional graphics. The types of graphics that can be added include: image or graphics files (bmp, wmf, emf), resource profile, or integrated cost curve. A particular advantage to this software is its ability to integrate the plan graphic and the schedule in a scaled manner, so the distance scale is indicative of the actual project at all times. The ability to add graphics is user-defined and customizable and is accomplished with the mouse.

The TILOS interface allows the user to input project information, activities, and graphics in a very simple and straightforward manner. However, the process differs from prominent scheduling software in the United States. The main difference is drawing the activities on a time-space grid instead of tabular input. As a result, there is a learning

curve involved as the user becomes accustomed to the idea of adding data with drawing tools as opposed to spreadsheet type views.

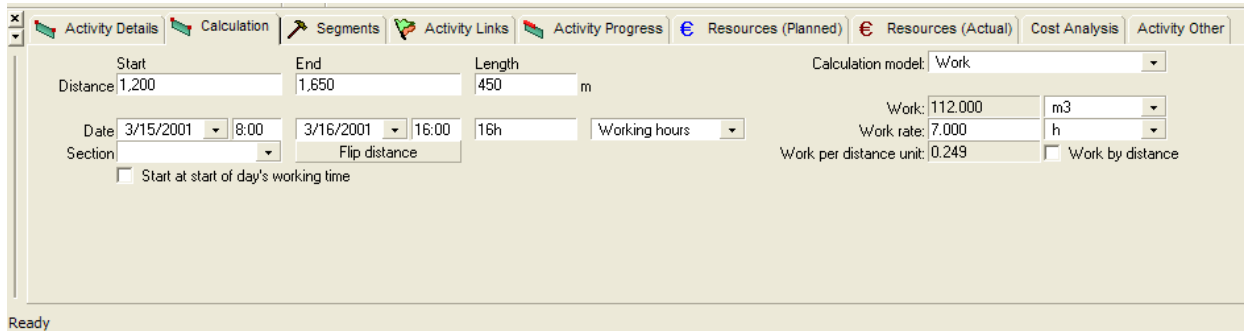


Figure 15 – Activity Details Menu used to Modify Activities in TILOS

Output Capabilities

TILOS is capable of outputting a completed schedule in a multitude of ways. Since this program was designed with emphasis on graphics, it is easy to produce visually appealing linear schedules. TILOS is designed to print the linear schedule exactly as it appears on the screen. As a result, a linear schedule created in TILOS can be designed to incorporate the linear schedule itself, graphics and a title block. The schedule can be viewed on the computer or printed in a variety of sizes or converted to a PDF file. An example of a completed linear schedule is shown in Figure 16. As mentioned earlier, schedules can be viewed as a bar chart, but TILOS does not allow the user to print the bar chart view. The program gives the user the ability to create any type of report that is required for the project and export that report to Microsoft Excel for printing. TILOS also allows the import and export of project information to several formats including: an ascii file, MS Project, MS Excel, and Asta PowerProject.

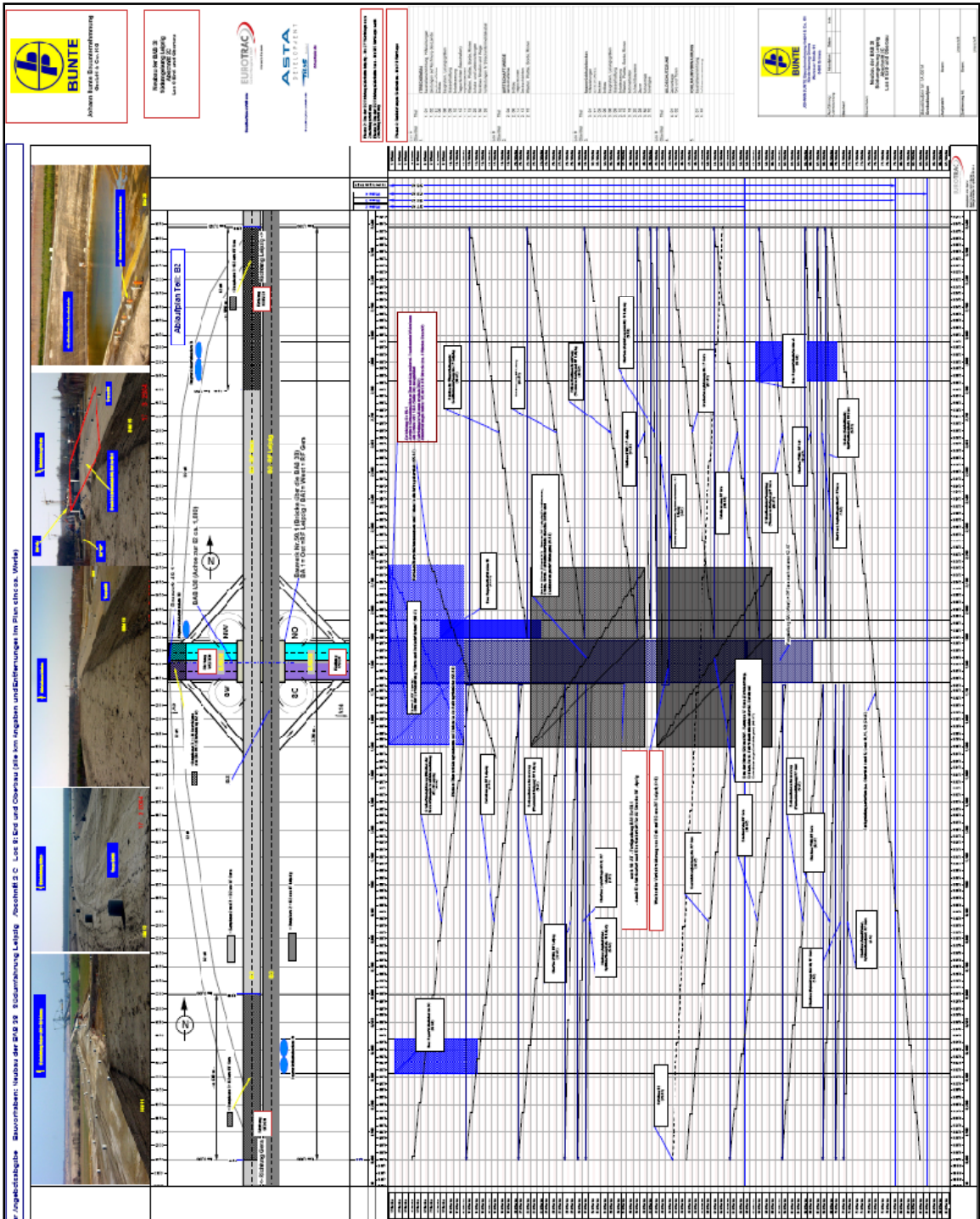


Figure 16 – An Example of a Highway Linear Schedule in TILOS

Adaptability to Scheduling Pipeline Construction Projects

TILOS is a powerful program for creating linear schedules. Its ability to combine the analytical calculations of project management and the visual attributes of the linear scheduling method make it a viable solution for scheduling of pipeline projects in the United States. The key for the successful implementation of TILOS in the United States would rely on the development of templates and activity libraries specific to the standards used in the U.S. (At the time of publication of this research, TILOS version 6.0 became available which incorporates templates and features highly customized to the U.S. pipeline industry.)

Time Chainage

Time Chainage is a software package developed by Peter Clarke in England specifically for linear scheduling [25]. The software package displays distance or “chainage” along the horizontal axis and time along the vertical axis. The software package allows constraints in a network analysis and production rates can be used as input to calculate the schedule.

Data Input

The process of entering data in Time Chainage is through the use of a spreadsheet type interface. The user enters the activity details including production rates, activity relationships, and the location where the activity takes place. The user may also choose

to group activities together using the task group details box. Grouping the activities allows the user to print schedules based on the chosen groups, which enables the user to output schedules specific to the work of the subcontractor. Actual production and activity progress may also be entered to track the project during construction.

Project details may also be added to the linear schedule. For example scalable graphics, such as a schematic of a plan or profile view of the project, may be added for clarity. Text may also be added, which allow the user to add notes on the schedule.

Output Capabilities

Time Chainage is specifically created for linear scheduling and is capable of outputting planned, actual, or planned and actual schedules. Figure 17 illustrates the output of a progress schedule for a Sewer Tunnel project. The user can adjust many of the output features such as scale, location printed, and appearance of activities. Time Chainage allows the user to utilize different activity shapes, such as line, block, or parallelogram. The software package also outputs reports displaying progress versus distance and percent complete. However, Time Chainage does not have the ability to create custom reports or print a bar chart or CPM diagram.

Adaptability to Scheduling Pipeline Construction Projects

Time Chainage provides a tool for manipulating and calculating planned and as-built linear schedules. The software package allows flexibility for enhancing the visual

display of the linear diagrams by using graphics and text. Time Chainage provides the user with a straightforward tool to plan projects using linear scheduling methods.

Time Chainage would be more advantageous for pipeline contractors in the United States if it allowed the display and printing of bar charts, CPM diagrams, and custom reports. The software package also does not allow the import or export of project data, which requires the user to re-enter data to obtain a bar chart view.

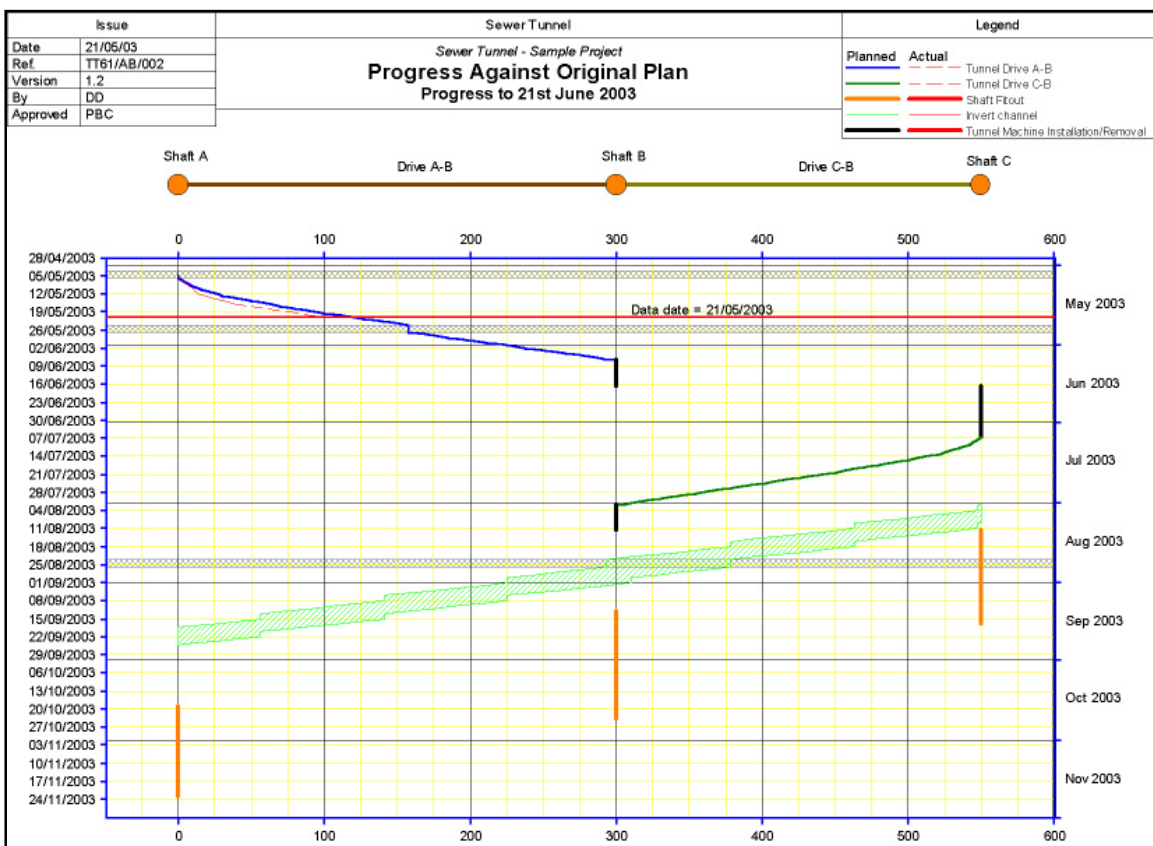


Figure 17 – Planned vs. Actual for Sewer Tunnel from Time Chainage

Summary and Comparison of Software

Software packages capable of performing linear scheduling although limited in use, are available for commercial use. Table 5 summarizes the evaluation and comparison of

the five software packages. The table summarizes the software into two categories: 1) Data Input and Interface and 2) Output Capabilities. These two headings are broken down into multiple subheadings, which represent some of the important attributes that contribute to the evaluation of each criterion. Each program is summarized in the table according to whether or not they contain each attribute.

Table 5 – Summary of Software Comparison

	Chainlink	Linear Plus	Spider Project	TILOS	Time Chainage
Data Input and Interface					
Software Created Exclusively for Linear Scheduling	Y	Y	N	Y	Y
Ability to Draw Activities	N	N	N	Y	N
Ability to Adjust Activities Graphically	N	Y	N	Y	N
Ability to enter Activities and Their Attributes in a Spreadsheet	Y	Y	Y	Y	Y
Ability to Update Projects and Create a Baseline Schedule	N	Y	Y	Y	Y
Ability to Import Project Data from Other Scheduling Programs	Y	Y	Y	Y	N
Ability to Setup Templates and Resource Libraries	N	Y	Y	Y	N
Ability to Calculate CPM Type Schedule Dates	N	Y	Y	Y	Y
Output Capabilities					
Written Reports	N	N	Y	N	N
Written Reports Via Exporting to Another Program	N	Y	Y	Y	N
Graphical Reports other than the Linear Diagram	N	Y	Y	Y	Y
Bar Chart View	N	Y	Y	Y	N
Logic Diagram View	N	N	Y	N	N
Resource or Cost Histogram	N	Y	Y	Y	N
Earned Value Analysis	N	Y	Y	Y	Y
Ability to Place Other Graphics on Schedules	Y	Y	Y	Y	Y
Ability to Customize Printed Output	Y	Y	Y	Y	Y

Each of the software packages offers a unique set of advantages and disadvantages. All the software packages reviewed could be used for scheduling pipeline projects with varying success. Of the software packages reviewed, Linear Plus and TILOS displayed the most potential for use by the pipeline industry in the United States. While Chainlink, Spider Project, Time Chainage offer excellent solutions for producing

linear schedules, they lack some basic features that are necessary to gain acceptance in the U.S. market.

While both Linear Plus and TILOS produce high quality products, TILOS offers some significant advantages with its ability to draw linear schedules in a CAD-type interface and flexibility with outputting resource and cost information as part of the linear schedule. Both products will require serious marketing efforts to introduce linear scheduling into the mainstream of pipeline construction scheduling.

Summary and Conclusions

Avoiding delays during the construction phase of pipeline projects can yield significant benefits to owners, pipeline contractors, and the public. Delays in completing pipeline construction projects not only result in higher costs to owners and contractors, but also add to the cost passed down to the end users. Although some of the variables causing delay are difficult to control, good planning and scheduling of pipeline construction projects can reduce the time and cost of construction.

Bar charts and CPM are the two primary methods used for scheduling pipeline construction projects. Bar charts have been used by the construction industry for nearly 100 years (since 1917) and CPM has been used for over 50 years (since 1957). Bar charts are simple to develop and easy to understand, but only provide a general overview of the work to be performed and have limited value for effectively managing a project. The CPM is more difficult to develop than a bar chart, but it can provide extensive information for effectively managing the work to complete a project. CPM assumes that construction activities can be divided into relatively small discrete activities that can then

be sequenced in the order of their performance. CPM focuses on the sequencing and interrelationship of activities.

Both bar charts and the CPM are excellent tools for scheduling projects consisting of discrete activities, but are not good tools for scheduling linear or repetitive activities. The additional information conveyed in a linear schedule provides superior planning and management information for projects of a repetitive or linear nature.

This chapter classified projects involving repetitive activities into two groups; *point-based projects* and *alignment-based projects*. Point-based projects include multi-unit housing complexes and high-rise building projects. Alignment-based projects include pipelines and highway construction projects. For alignment-based projects, activities are performed continuously along the length of the horizontal alignment of the project. The Linear Scheduling Method (LSM) is a very useful and informative tool for scheduling alignment-based projects. LSM typically shows time on the vertical axis and distance, or stationing, on the horizontal axis. Thus, the progression of each activity in relation to location and time is plotted on the LSM chart. Users can determine activities in progress at particular locations, activity production rates (derived from the slopes of the line), and scheduling conflicts due to work location constraints (such as relocation of utilities). The continuous flow of work along the alignment becomes the driving factor in scheduling linear projects. Thus, continuous resource usage is critical in establishing the project duration.

A review of literature shows many publications on the development and application of linear scheduling methods. Significant work that has been done related to

this research study includes papers by Johnston, Harmelink, and El-Sayegh. Johnston applied linear scheduling specifically to highway projects. Harmelink developed models for identifying the *controlling activity path*, which is analogous to the critical path in the CPM. El-Sayegh developed several models and used computer methods to output linear schedules and provide the numerical data that is typically provided by CPM. A common theme of the published papers reveals the following advantages of alignment-based linear scheduling.

- Linear scheduling is applicable to pipeline construction projects.
- Linear schedules can display a vast amount of information in a simple format.
- Linear schedules better model the continuous nature of pipeline activities than other scheduling methods.
- Linear schedules allow the user to visualize the construction plan, whereas other scheduling methods only display the dates associated with the construction.

Interviews of people in the pipeline industry provided valuable insight on the application of linear scheduling to pipeline projects. Both owners and contractors placed a large emphasis on the number of feet of pipeline placed per day or per week. The contractors noted that linear schedules allow a direct reading of the required production per day, which was extremely valuable in managing work in the field and reporting progress of work back to management. Linear schedules provide them with a tool to visually observe and compare planned production rates to actual production rates.

Following is a summary of the advantages of using linear scheduling as reported by the pipeline industry:

- The line slope of an activity on a linear schedule determines production rate, which is important in repetitive work projects.
- Gaps or obstacles in a project are clearly shown on the linear schedule, which aids in risk management.
- Linear schedules are better than CPM for analyzing claims.
- Linear schedules provide a two dimensional picture of the job.

Although linear scheduling has been in existence for quite some time, its use in the U.S. pipeline industry has been very limited compared to bar charts and CPM. The primary reason for the lack of widespread use of linear scheduling is the lack of commercially available software in the U.S. that addresses the pipeline industry's needs. A review of commercially available linear scheduling software has been provided to detail the existence of such software; however its use in the United States is quite limited.

Aggressive marketing by CPM software developers has dominated the U.S. market and diminished the use of other scheduling techniques, such as LSM.

CHAPTER III

LINEAR SCHEDULING MODEL WITH VARYING PRODUCTION RATES

Figure 18 provides an overview of the methodology for this research.

Determining the research objectives and the scope of those objectives is the first step. After the research direction was chosen, a thorough literature review was necessary to learn from previous research and narrow the research focus. Following the literature review, it was necessary to perform two tasks: collect pipeline construction data and develop a model for using that data to produce linear schedules. Construction data regarding production rate information is difficult and time consuming to find, while the weather data needed is found fairly easily on the internet. Upon receipt of the production rate information, data analysis was carried out. The end result of the analysis was a list of variables that affect the production rate of pipeline construction activities and regression equations used to apply these variables. The next task was to integrate the regression analysis with the linear scheduling method. Once accomplished, a test case was run to validate the model. Finally the research was summarized and recommendations for further research were described.

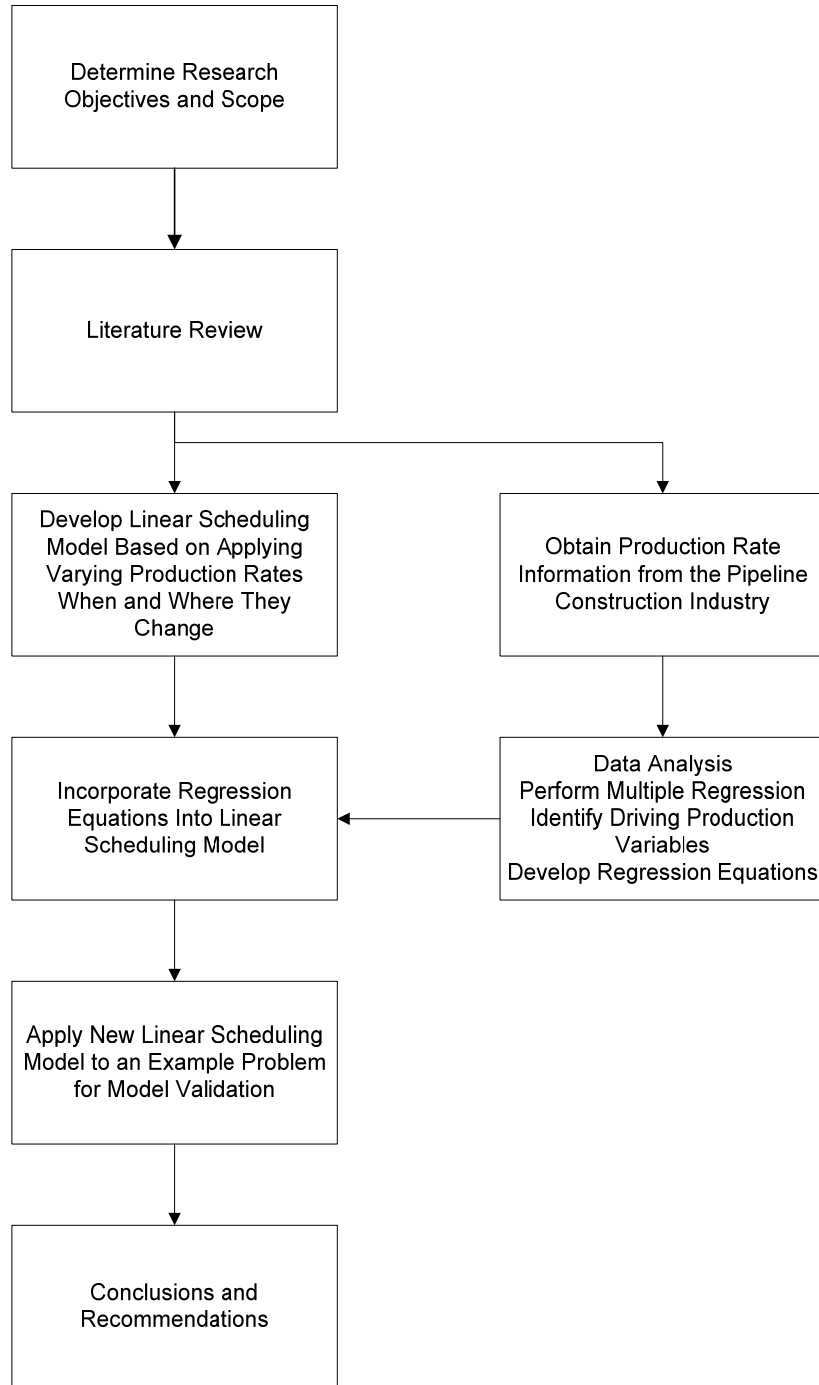


Figure 18 Overview of the Research Methodology

The value of linear scheduling is the large amount of information conveyed by a single schedule. One piece of information imparted is the production rate of each activity, which is simply the slope of the line in the schedule. Much research has been conducted to accurately predict the production rate that may occur for a given construction activity; however, little to none of the production rate research has been performed on pipeline projects. Further yet, no known research to date has been performed to illustrate and predict when and where changes in production rates occur.

The objective of this research is to lay a framework for predicting and illustrating the changing nature of production rates as the crews move along the length of pipeline construction projects. The Linear Scheduling Model with Variable Production Rates (LSM_{VPR}) is a new model developed in this research which enhances the visual capabilities of linear scheduling and enhances the planning of pipeline construction projects.

The Linear Scheduling Model with Varying Production Rates (LSM_{VPR}) has been developed in this research study as a framework for applying changes in production rates when and where they occur in time and space for a given linear construction project. Figure 19 depicts an overview of the information flow for creating a linear schedule utilizing LSM_{VPR} . Linear scheduling processes to date have all required the input of some variation of the general project data along with the activities and the buffers between those activities. While some research has been performed to account for varying production rates, most methods have approached it using simulation. These methods are valid and provide the user an idea of the production rates to expect overall; however, this research seeks to display the variances when and where they will occur. A visual

snapshot of production rate changes can help the project team to better develop strategies to construct pipelines.

LSM_{VPR} adds to the visual nature of linear scheduling by introducing the concept of Working Windows, which is defined in this paragraph. A traditional linear schedule depicts the entire time and location when and where the construction is proposed. The overall time-location for the entire project is referred in this research as the project's Time-Location Chart (TLC). For the purposes of this research, the Time-Location Chart is assumed to depict time on the ordinate and location on the abscissa. When dealing with factors that affect production rates, it is necessary to look at smaller pieces of the TLC. When the TLC is sliced into a grid of smaller cells on a user-defined interval, these cells depict the project's Working Windows. A Working Window (WW) is a time-space rectangle with a homogenous set of variables that affect the construction production rate. Working Windows are discussed in detail later in this chapter.

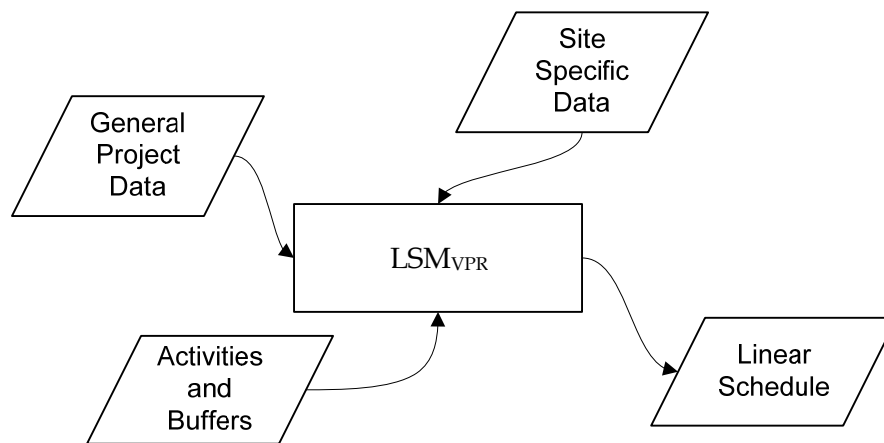


Figure 19 – Flow of Inputs for LSM_{VPR} to Output a Linear Schedule

In order to select the appropriate size of the working windows the scheduler needs to have an understanding of the *Production Variables*, or variables that can affect the production rates of construction. Although many variables may influence the actual production rates achieved in the field, they can be separated into four types:

- 1) General Variables – Broad constraints which affect the production, but are not related to a specific time or location.
- 2) Time Variables – Variables which change with respect to time only.
- 3) Location Variables – Variables that change with respect to location only.
- 4) Time–Location Variables – Variables that change with respect to both time and location.

Table 6 depicts the four types of production variables with examples of common variables in each category. The next four paragraphs elaborate on specific variables that affect production rates in each of the four categories.

Table 6 – Types of Production Variables with Examples

Type of Production Variable	Examples
General	Number of Workers, Safety Requirements, Construction Methods
Time	Work Week, Holiday Schedule, Learning
Location	Terrain, Urbanization, Site Conditions, Geotechnical Data, Work Space
Time-Location	Weather, Environmental Windows, Site Conditions

General production variables by definition do not change with respect to time or location. Such a condition is the number of workers on the project, which is typically a constraint set by the project team and/or the current market demand and/or the availability for that type of labor. Another type of general production variable is the method used for construction; which may be a company philosophy or a constraint of the equipment available.

Time production variables change only with respect to time. An example of a time production variable is the number of holidays per month. It should be expected that production will be lower during December as compared to August, solely on the basis of the holiday season in December. Another example of a time production variable is the effect of learning on the construction process. For example, the workers on the job tend to get into a more productive rhythm after the initial start of the job. This trait is known as “learning”. Many studies have documented this increase in productivity once the crews have been performing a repetitive task over an extended period.

Conditions that change with respect to horizontal location along the alignment are location type production variables. Examples of such changes include: terrain, site conditions, geotechnical conditions such as existence of rock, urbanization, or right-of-way width along the project. These variables allow the scheduler to change the production rates with respect to locations along the horizontal alignment. For example, one can visualize the variation in construction conditions when constructing pipeline in the mountains versus flat prairie land. It is also important to incorporate changes for a pipeline project that is maneuvering through a populated area versus an open farm land.

The last type of variable, time-location production variables, change with respect to time and location. Examples of these production variables include weather and environmental windows. For example, performing construction during the winter months is typically more difficult than during the summer months. However, weather is also dependent upon location because the winter in Wyoming is quite different than winter in Florida. A project may span a time and distance great enough to see these types of variation in weather patterns. Another example of a production variable that changes

with time and location is environmental windows. For example, an environmental window may negate all construction during the months of March through July for a certain location due to wildlife constraints. The team planning the construction will need to understand and visualize what these conditions may do to the flow of construction activities.

The LSM_{VPR} allows the changes and reasons for change in production rate to become transparent, therefore allowing the user to visualize changes in production rate through time and space. The method for visualizing the reasons for changes is represented via color changes in the background of the linear schedule. This will be discussed in more detail later in this chapter.

Data Input

The process of creating a linear schedule with the LSM_{VPR} consists of distinct steps once the project route has been selected. These steps are similar to creating a CPM diagram. The process begins with planning the work that will take place. Pipeline construction has a very succinct set of activities which occur along the length of the project. Optional activities may consist of horizontal directional drilling, boring, aerial crossings, and others. Pipeline construction also has non-linear activities which occur at various points along the alignment; such as facility type activities to construct tanks or meter stations to facilitate delivery of the product being transported. This research has focused on the primary activities which make up the linear portion of pipeline construction. This is followed by sequencing the activities in the order they must occur. Pipeline projects have little flexibility in the order that must be followed to complete the

required activities. For example welding the pipeline can only occur after the pipe has been strung along the right-of-way, backfilling the ditch can only be done after the pipeline has been lowered in the ditch; therefore, the sequencing is fairly simple and rigid. The location and number of spreads utilized to perform the work is flexible in the scheduling of pipeline work. For instance, a two-hundred mile pipeline project may consist of multiple spreads. The number and starting location of spreads depend on the conditions along the length of the project. Upon completion of the sequencing the user must provide detailed information concerning each activity including start station, end station, production rates, changes in production rate (vertices in the line activities), quantities of work, and number of crews to perform the work.

General Project Information

Project information depicting the general nature of the project is the first portion of data required for starting the process of scheduling a pipeline construction job with LSM_{VPR}. This information consists of project name, client, start station, end station, units used for analysis, standard intervals to be shown (both time and distance), and other general information depicting the makeup of the project. This information will provide a base from which to build the site specific information and ultimately create the linear schedule.

Site Specific Project Information

Site specific information, for the purposes of this research, is any condition occurring along the length of the project that can impact production rates during

construction. Although there are many items to consider, the team should focus on items of significance. Table 7 lists some of the more common site specific conditions to be considered when planning a pipeline construction project. This research focuses on the first five conditions listed in the table because they were readily accessible for the project data collected and the conditions vary along the length and timing of the project.

Table 7 – Site Variables

Production Variables	Description	Sources
1. Weather	Temperature, wind, precipitation	www.ncdc.noaa.gov/oa/ncdc.html
2. Environmental Windows	Periods of reduced or no construction	State, Federal, or local governing agency
3. Terrain	Topography of the alignment	Survey data, quad maps, Google Earth
4. Work Week	Number of hours per day and days per week	Project Team
5. Holiday Schedule	Which Holidays are observed	Project Team
6. Site Conditions	Prarie, desert, swamp, etc.	Site visit
7. Geotechnical Data	Boring logs, NRCS soils data	Detailed Geotechnical investigation
8. Urbanization	Density of population	Aerial photography
9. Work Space	Width of Right-of-Way and extra work spaces	Easement and land parcel descriptions
10. Learning	Effects of learning the task on the job	Empirical Data

Note: This research focuses on production factors 1 through 5

The team must document when and where these site conditions change along the length of the job. These changes will be used by LSM_{VPR} to predict the varying production rates achieved during construction. The user selects a standard interval based on the frequency of production variable changes along the horizontal axis.

Activities and Buffers

An activity is a task required to complete the project. This research focuses on continuous full-span activities as defined by Harmelink. The “continuous” denotes activities have continuous work from their start to end stations, and the “full-span” denotes the activities occur from the start of the project to the end of the project.

There are several continuous full-span activities that comprise a typical pipeline construction project. While differences in naming convention are common, Table 8 comprises the names used in this research. The activities listed are the activities for which production rate information is available and comprise the majority of the construction effort. The activities are listed in the order in which they are typically performed. Additional activities that take place on a pipeline construction project include: mobilization, survey layout and as-built, road boring or directional drilling, inspection, x-ray of welds, testing, and startup. These activities will be critical at various times in the construction process, but the ones outlined in Table 8 comprise the majority of the cost and time consumed on pipeline construction projects and thus forms the basis for this research.

Table 8 – Pipeline Construction Activities

Activity	Description
Grading	Removing debris and leveling the right-of-way for construction access.
Stringing	The process of laying the pipe along the right-of-way in preparation of bending and welding.
Bending	Bending pipe sections in the field to a desired angle to facilitate the pipe fitting the right-of-way.
Welding	Joining the individual pieces of pipe by welding the ends to one another.
Trenching	Digging, either with a wheel trencher or backhoe, a ditch in which to place the pipe.
Coating	Applying coating over the welded ends of the pipe to protect from corrosion.
Lower-In	Several side-booms pick up lengths of welded pipe segments and place the pipe in the ditch.
Back-Fill	Covering the pipe that was lowered in the ditch with dirt.
Cleanup	Cleaning up any debris left from construction and reseeding ground cover to prevent erosion.

Figure 20 shows a schematic of the pipeline construction sequence; note the additional activity detail and variance in nomenclature. Pictures of various activities from actual pipeline construction are provided in Appendix A. The construction photos are arranged in the general order in which pipeline construction is executed.

While all the activities must be completed to finish a project, certain activities may “drive” a linear project. For highway construction, the driving activity may be

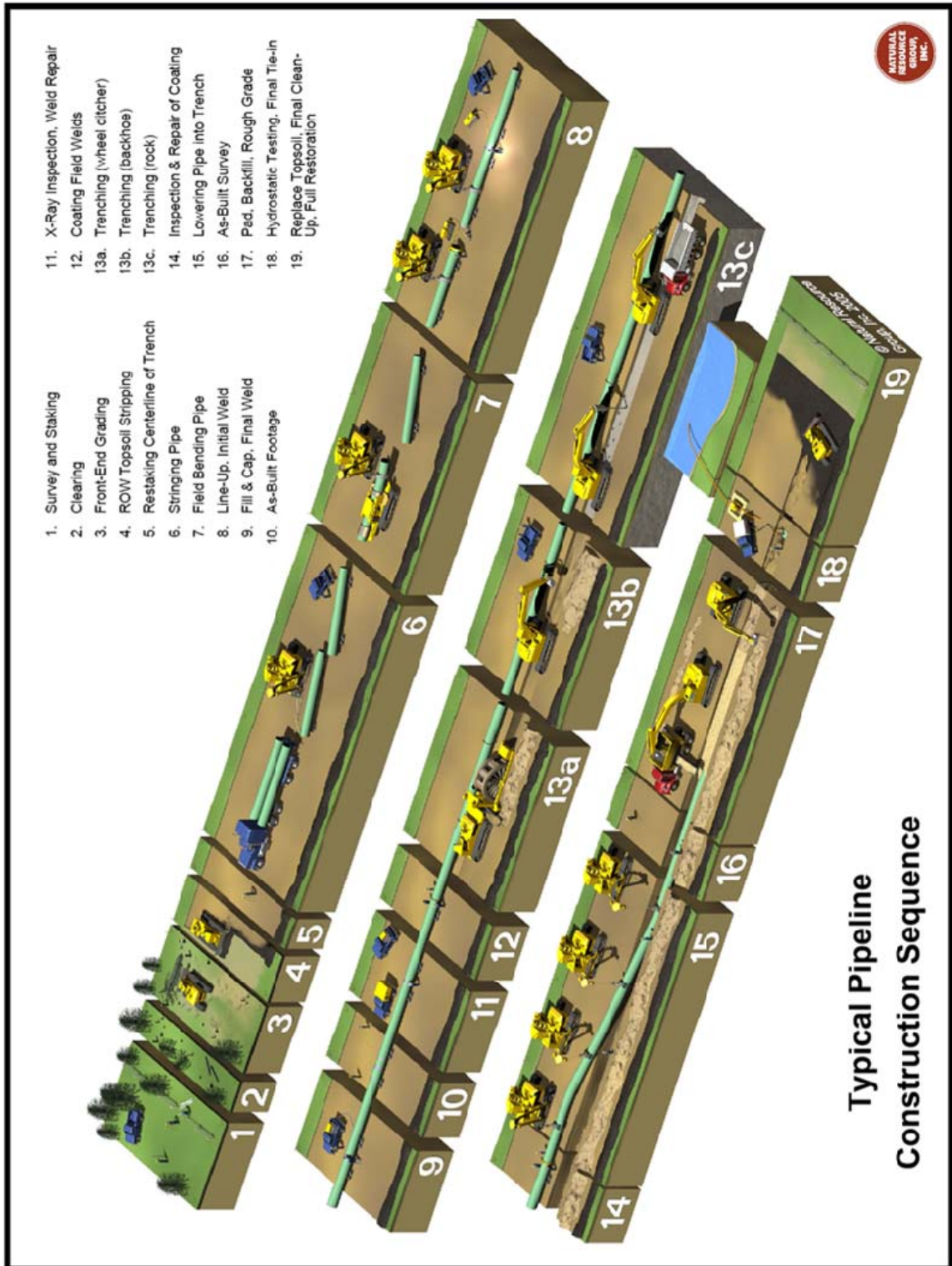


Figure 20 – Construction Activities and Typical Construction Sequence [24]

laying asphalt or pouring concrete pavement. For pipeline construction, welding is the activity that drives the construction process. All other activities are sequenced around welding to ensure nothing inhibits that activity from proceeding as smoothly as possible. This research will depict the driving nature of the welding activity when we review the correlation of the construction activities to the production variables of pipeline construction.

Activities require separation to provide a working area for one activity to complete before the next activity starts in that location. This separation is called a buffer. Linear scheduling buffers can be described in two ways, distance buffers and time buffers. A time buffer is synonymous with a start-to-start lead or lag in CPM scheduling. This lead or lag allows enough time for the preceding activity to get started before the following activity is started, reference Figure 21. A distance buffer is unique to linear scheduling, but is based on the same principle. A distance buffer stipulates a distance separation that must be maintained between two adjacent activities.

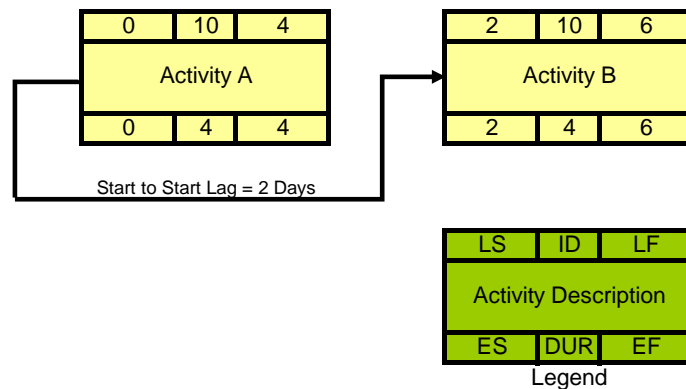


Figure 21 – Consecutive Activities with a Start to Start Lag of Two Days (CPM)

A distance buffer can be converted to a time buffer by using the production rate of the activities. For example, two consecutive activities with a production rate 1,000 feet per day that require a 2,000 distance buffer could be said to require a time buffer of two days, or 2,000 feet divided by 1,000 feet per day. Figure 21 illustrates a time buffer as depicted by CPM, while Figure 22 illustrates the same buffer as depicted in linear scheduling. While the two schedules convey the same concept, the linear schedule provides more information in its snapshot. One can see the distance buffer has been achieved as Activity B is never closer (horizontal distance) than 2 days or 2,000 feet to Activity A.

Figure 23 shows a bar chart, which is commonly used for a pipeline construction schedule. While the level of detail is typical of pipeline construction schedules, the schedule conveys very little information to the end user. The schedule is typically built using the start to start logic displayed in Figure 22, without any visual means to convey

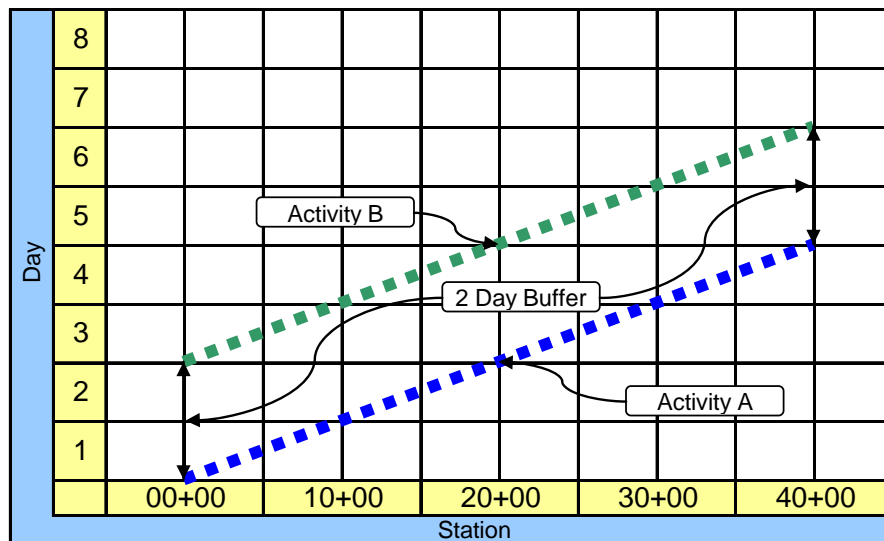


Figure 22 – Consecutive Activities with a Start to Start Lag of Two Days (LSM)

that information. The user cannot determine where the construction starts along the horizontal alignment or how the crew's production will vary along the alignment. These reasons and many more have led to many research efforts depicting the advantages of linear scheduling over bar charts and CPM for linear projects. This research builds upon the reasons linear scheduling is superior to other methods when scheduling linear projects.

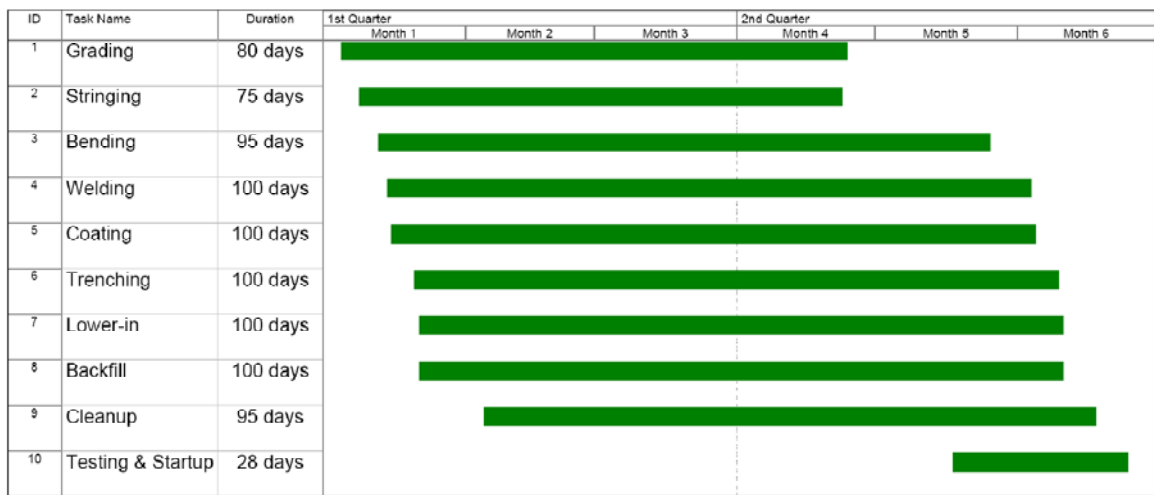


Figure 23 – Typical Pipeline Construction Schedule

Production Rates

Determining production rates is the key to planning and building any linear project. Since each activity following the start of construction is based upon the speed with which the preceding activity is completed, all activities provided in Table 8 can become critical. The speed with which a pipeline project can be completed is almost always driven by the welding rate achieved on the project. Therefore, welding rates are planned first and the other activities are typically staffed appropriately to allow continuous welding

production. There are of course exceptions to this rule, which may include special directional drilling requirements or stream crossings.

LSM_{VPR}, through the use of historical data, will help predict production rates given the site specific conditions defined for the project. Since these conditions directly affect the duration of the project, the more planning spent in determining these conditions, the more accurate the final schedule will be. Using empirically derived production rate equations limits the scope of calculating future projects to the limits of the data. For example the data used for this research consists of fourteen and sixteen inch pipe; therefore the equations would not be applicable to 42 inch pipe construction. Therefore collecting a wide variety of data from a wide variety of site conditions would improve the boundaries for which the equations are useful. This research provides the framework from which to build a more comprehensive production rate database.

Time and Location Intervals

Time and location intervals control the periods for which the production variables can change. The scheduler defines a standard interval with which to divide the distance across the bottom and side of the linear schedule. This standard interval will be marked and labeled across the chart. The scheduler then has the option of changing the input for any production variable at these intervals.

For example, if a project is 100,000 feet in length and a standard interval of 10,000 feet is selected, the scheduler could change any location based production variable

ten times or once every 10,000 feet. Figure 24 shows a project that starts at Station 00+00 and ends at 1000+00 with the corresponding slopes above the chart. The average slope indicates a value of 0.01 from station 00+00 to 400+00 and a value of 0.05 from 400+00 to 1000+00. Since slope is a location variable we now see the average slopes expected along the length of the project. While no time variable is defined for the figure, the same could be said about the ability to change the variables along the time axis.

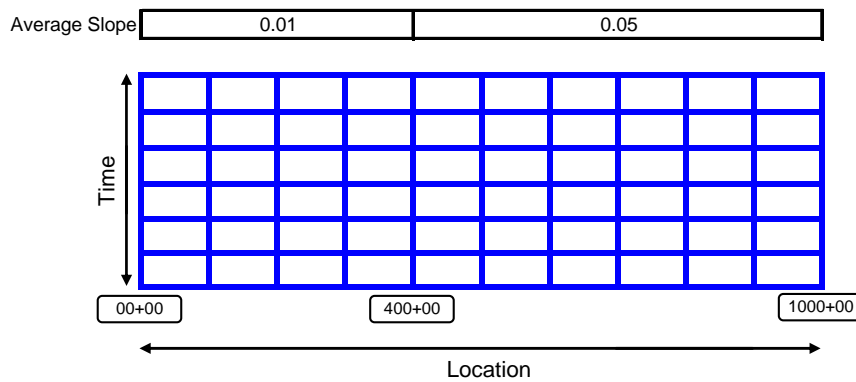


Figure 24 – Example with a Location Production Variable

Choosing an appropriate standard interval depends on several items; such as availability of data, physical changes across the project, and desired scale of the finished schedule. The interval needs to be small enough so the user can define detail at a useful level, but large enough so the user can input and output meaningful data. The required calculations quickly become numerous and tedious, but can be handled by the prototype software Velocity 1.0 discussed in Chapter V. The computer can easily make the calculations for a time interval based on days and a location interval of 1,000 feet for a 150 mile project. Utilizing a time interval of days also aids in the application of historical production data, which is typically recorded on a daily basis.

Figure 25 illustrates the breakdown of the project into a grid, which is the basis for all linear scheduling charts developed in this research. The grid is comprised of a cross hatch of the location list vs. the time list, which forms many rectangles across the chart. Each of these rectangles will have a set of values associated with production variables in order to determine the production rate achievable through that time-location area. These time-location rectangles are referred to as “working windows”.

Working Windows

Working windows display when and where these production variables may change along the pipeline project. Working windows are areas of time and location for which unique production variables can be assigned (e.g. a given working window has an average slope of 0.01). Since a linear scheduling chart depicts time on one axis and location on the other axis, drawing a grid on this chart breaks the chart into areas of time and location. Figure 25 is a general view of a grid of working windows which split up a project. The nomenclature for working windows is given as WW_{ij} ; where i represents the column and j represents the row. Given the i and j coordinates for the working window one can look up the appropriate production variables that should be applied to that working window.

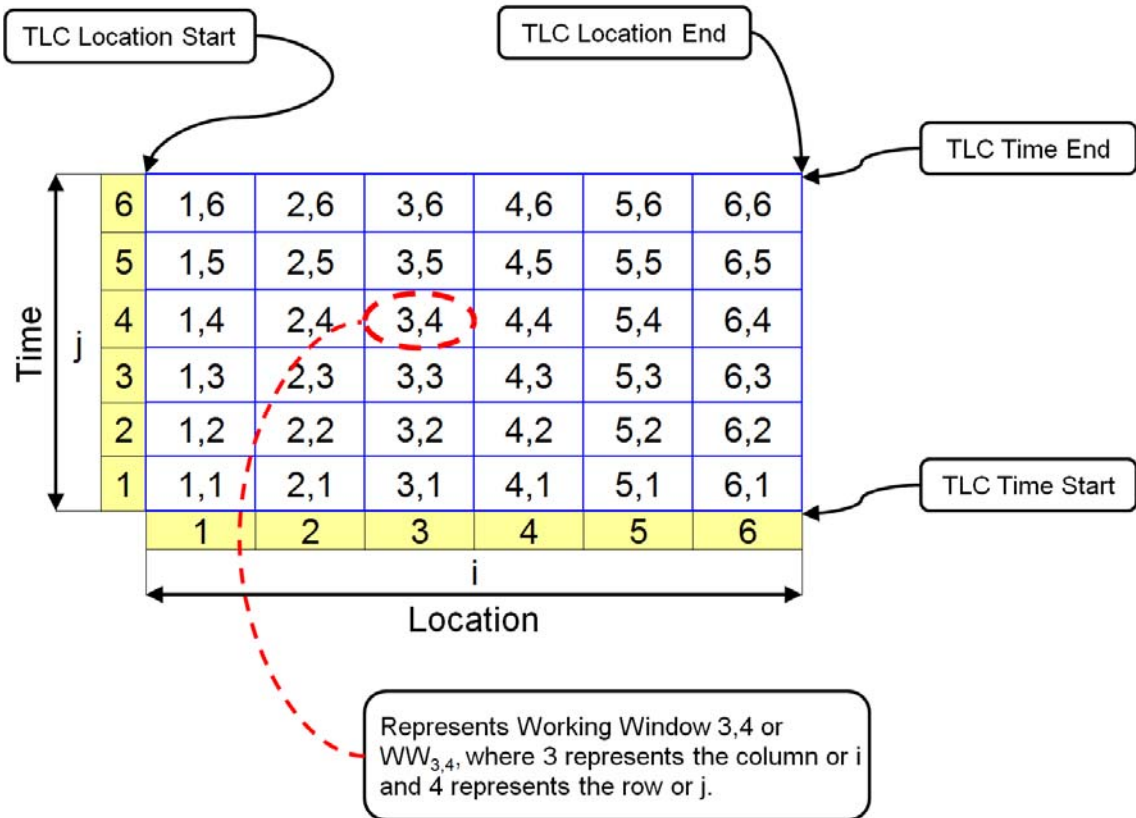


Figure 25 – Naming Conventions for Working Windows on Time Location Chart

We can take the same chart and add color to the background to provide the user with additional information about the production rates within the grid. Using the color in the background to indicate calculated performance relative to the desired production rate quickly allows the user to understand areas of difficulty.

The color added to the background is referred to as the Activity Performance Index or API. The API is a color scheme that indicates the status of production rates on the project. For example, red indicates very poor performance and green indicates favorable performance with regard to the desired production rate. The color indicates the relationship between a user-defined production rate (PR_{UD}) and the calculated production

rate, which is a most likely rate based on historical data (derived from regression equations and using LSM_{VPR}). Table 9 illustrates the default percentages for assigning color based on production performance.

Table 9 – Activity Performance Index and Corresponding Default Color Scheme

Upper	Lower	Color
100% or greater	90%	Green
90%	80%	Blue
80%	70%	Yellow
70%	60%	Orange
60%	50% or less	Red

To derive the percentages, the user determines a level of production desired for the given activity. At every working window a production rate is determined based on LSM_{VPR} . The percentage is then determined for each working window based on Equation 1. The color indicates the calculated production rate divided by the user-defined production rate as shown in Equation 1.

$$API_{ij} = PR_{ij} / PR_{UD} * 100 \quad (\text{Equation 1})$$

For example, if the scheduler desires a production rate of 10,000 linear feet per day for a given activity while the calculated production rate for the given working window is 8,500, the $API = 85\%$. This indicates the predicted production rate for that activity in that working window is 85% of the desired production level, thus the working window is shaded blue. This visual aid helps the scheduler easily determine the time-locations that may be problematic for construction. For instance, if the project requires welding to move at a rate of 10,000 linear feet per day, but the calculated production rate is less 5,000 feet per day, the user can easily see the red working windows indicating that historically this production rate has not been achieved under the given conditions. This

pattern of color also aids in determining optimal starting locations and dates for the spreads along the pipeline, providing a valuable front-end planning tool.

The color shaded in the working window is activity dependent by definition. This means the same working window could be different colors based on the calculated API for the different activities, so it is important to keep in mind which activity or activities drive the work. It is more important to portray the obstacles with the driving activity since the work is planned around the driver(s). For pipeline construction, welding is the most important activity, thus the schedule should be presented with the API based on the values for the welding activity. Again, Velocity 1.0 can be used to speed the user's ability to change the background based on other activities when appropriate.

Consider the example from Figure 24 for applying the API for a given activity. In the case of this example suppose the scheduler is planning on achieving 6,000 feet per day for a given activity. Let's further suppose the scheduler uses historical data to determine that an average slope of 0.01 produces a production rate of 5,600 feet per day, while an average slope of 0.05 produces a production rate of 4,000 feet per day. (While these production rates are fabricated for this example, Chapter IV details the derivation of production rate equations based on historical data.) These given production rates, when compared with the desired production rate, yield an API of 93% and 67% respectively. Referring to Table 9 shows the production rate associated with the 0.01 slope produces an API equivalent to the color green, while the slope of 0.05 is displayed as orange as shown in Figure 26. This color system easily conveys the increased difficulty of construction resulting from the steeper slope.

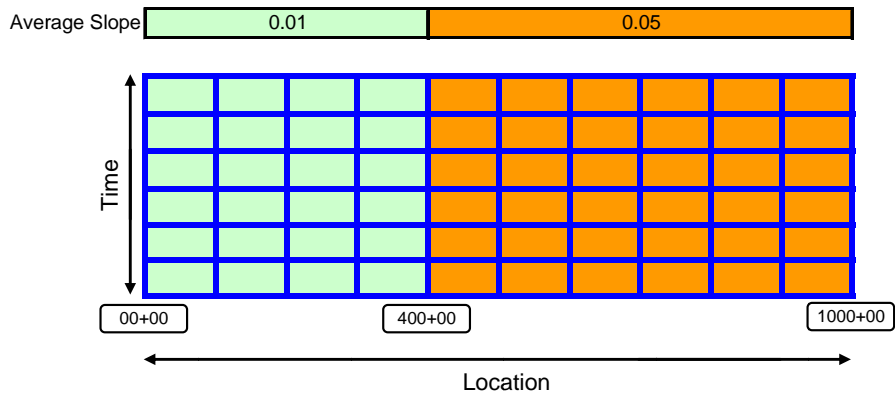


Figure 26 – Example Project with API Applied to the Display

The previous example changes the production variable at a standard interval mark (400+00); however, it may be desirable to illustrate a change that occurs at a smaller standard interval. For instance, suppose there is a slope of 0.01 from station 550+00 to 650+00 in the previous example. This requires a smaller standard interval be utilized to change production variables every 5,000 linear feet. Figure 27 illustrates the additional working windows calculated when the standard interval is changed to 5,000 linear feet.

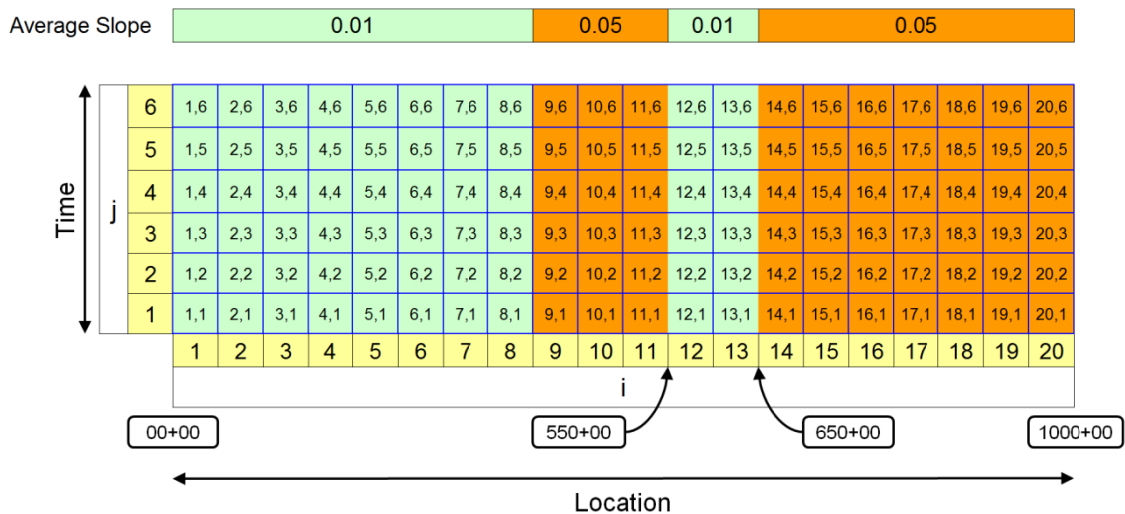


Figure 27 – Additional Changes in the Location Production Variable

The project team can now better visualize the implications of slope as it affects the project. The next step is to calculate the path of the activity as the activity is scheduled across the chart. Prior to making this calculation it is necessary to define some additional variables and further analyze how the schedule is calculated with the working window concept.

Figure 28 depicts a more detailed view of a typical working window. The working window naming conventions shown in Figure 28 applies to work moving from left to right or from lower stationing to higher stationing along the horizontal alignment. The location of the window begins with the Working Window Location Start (WWLS) and ends with the Working Window Location End (WWLE). Corresponding nomenclature depicts the time start and end with Working Window Time Start (WWTS) and Working Window Time End (WWTE) respectively. Again the use of the i and j variables allow a unique identifier for each working window and the corresponding variable carries through when naming the start and end of each window.

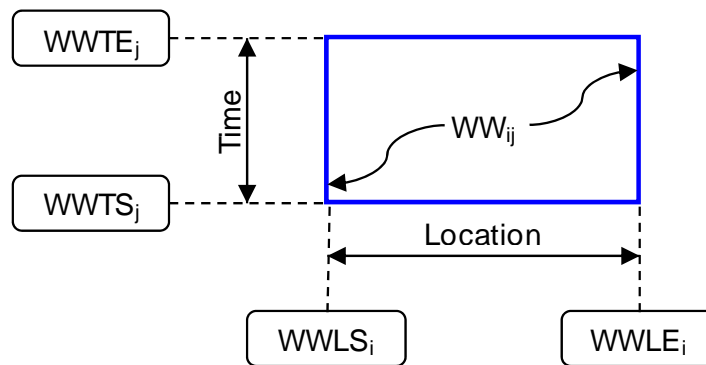


Figure 28 – Individual Working Window Nomenclature

Figure 29 adds an activity to the working window, along with nomenclature to specify the entry and exit coordinates of the activity. All activities will move in a straight line through the working window, because by definition the working window's production variables are constant and thus the production rate through the window is constant. The nomenclature for naming the coordinates of the activity vertices as it moves through the chart is to start at X_n, Y_n , and move to X_{n+1}, Y_{n+1} . Where X represents the distance or stationing coordinate and Y represents the time coordinate. The subscript "n" is the number of the vertex as the activity enters the working window and the subscript "n+1" denotes the coordinate of the vertex as the activity exits the working window. The vertices are numbered from left to right with the start of the activity beginning with the number zero or X_0, Y_0 . These vertices exist at every change in the working window even if the activity does not change slope through the working window.

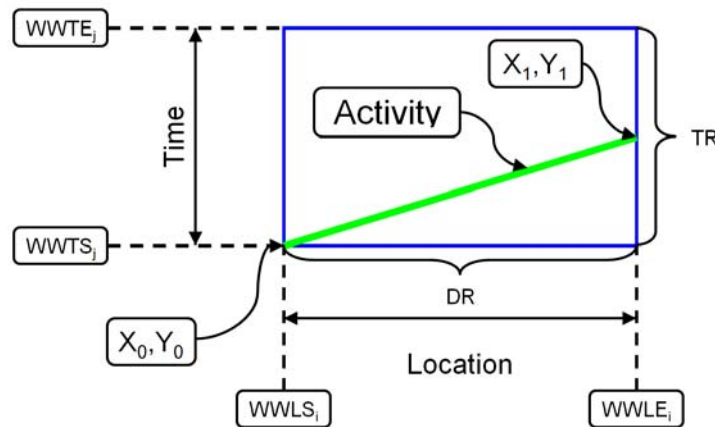


Figure 29 – Activity and Working Window Nomenclature

LSM_{VPR} Calculations

Figure 29 also includes additional terminology in the diagram to depict information necessary for making calculations later in this chapter. The Distance Remaining (DR) is the amount of distance that has not been completed in the current working window when the activity starts in that window. The Time Remaining (TR) is the amount of time that is remaining in the current working window when the activity starts in that window. Distance Remaining and Time Remaining can be calculated with the following equations:

$$DR_{ij} = WWLE_i - X_n \quad (\text{Equation 2})$$

$$TR_{ij} = WWTE_j - Y_n \quad (\text{Equation 3})$$

Given that Figure 29 is WW₁₁, the equations would take the following naming convention:

$$DR_{11} = WWLE_1 - X_0 \quad (\text{Equation 4})$$

$$TR_{11} = WWTE_1 - Y_0 \quad (\text{Equation 5})$$

Distance Remaining and Time Remaining are used to determine the movement of the activity through the linear scheduling chart; the movement from working window to working window. For example, there are three locations the activity can exit the working window once it enters, it can cross the top time axis, the right distance axis, or it can exit at the intersection of the two. The exit location is determined by a combination of the DR, TR, and production rate for that working window. A variable called Distance Traveled in Time Remaining (DTTR) is introduced for determining the exit location.

Equation 6 is the equation for DTTR, where PR_{ij} is the production rate for the given working window:

$$DTTR_{ij} = PR_{ij} * TR_{ij} \quad (\text{Equation 6})$$

The Distance Traveled in Time Remaining can then be compared with the Distance Remaining to determine the exit location. The following three outcomes can occur:

- 1) $DTTR_{ij} = DR_{ij} \rightarrow$ Activity exits at the intersection of the top time axis and right distance axis of the working window (Figure 30)
- 2) $DTTR_{ij} > DR_{ij} \rightarrow$ Activity exits at the right distance axis of the working window (Figure 31)
- 3) $DTTR_{ij} < DR_{ij} \rightarrow$ Activity exits at the top time axis of the working window (Figure 32)

The following three figures graphically illustrate the three cases provided above.

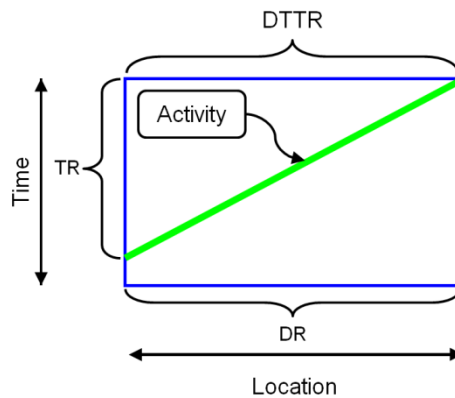


Figure 30 – Case 1 – DTTR is equal to DR

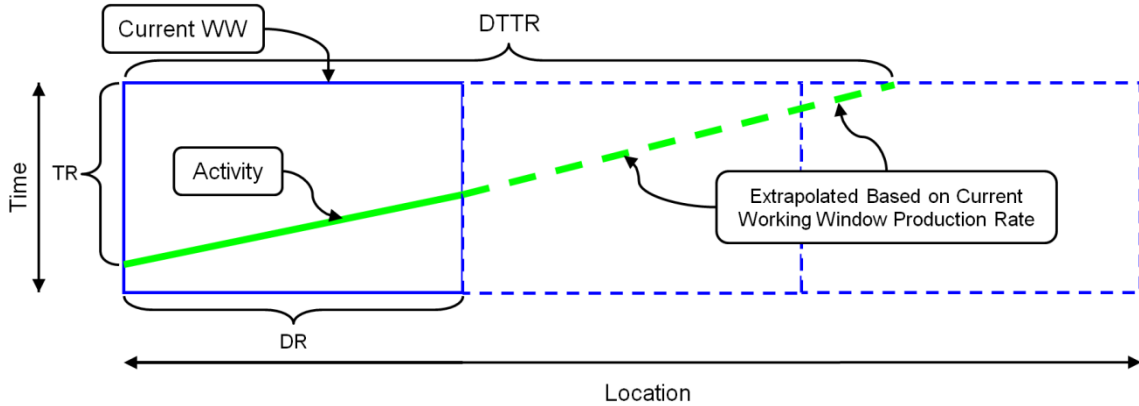


Figure 31 – Case 2 – DTTR is greater than DR

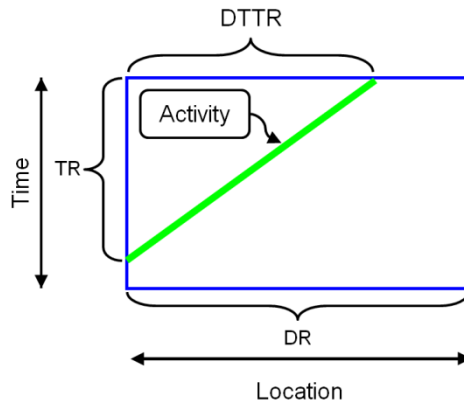


Figure 32 – Case 3 – DTTR is less than DR

By understanding how the activity exits the working window, the next production rate can be chosen to apply to the activity. Figure 33 illustrates the cases where the activity enters and exits the working window. (Again, all examples and calculations in LSM_{VPR} are based on working left to right across the chart, with location along the x-axis and time along the y-axis.) The first row of examples is indicative of the activity entering the working window along the Time Start Axis, while the second row illustrates activities which enter along the Distance Start Axis. The third row depicts activities which enter

the working window at the intersection of the Time Start and Distance Start Axes. The figures are further grouped by the exit location, with the exit location being the Distance End Axis, Intersection of the Distance End Axis and Time End Axis, Time End Axis, and Time End Axis for columns 1, 2, 3, and 4 respectively. Column 4 depicts a special

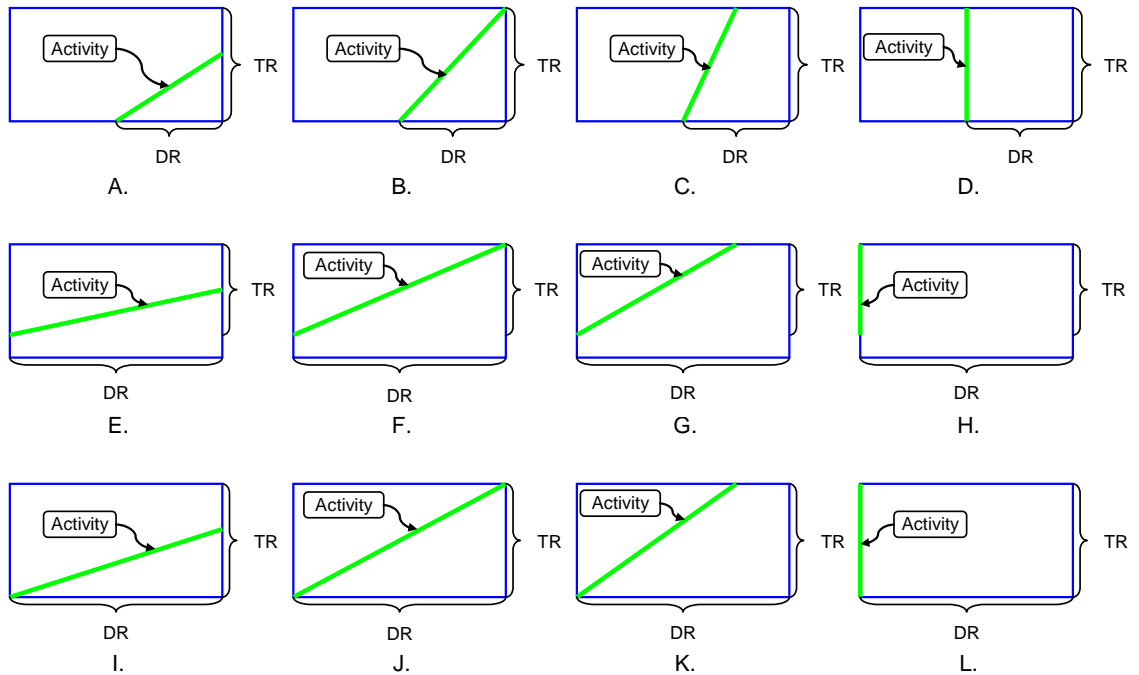


Figure 33 – Cases for the Entry and Exit of Working Windows by an Activity

condition of exiting through the Time End Axis in which case the production rate for the working window is equal to zero due to a non-working day.

Figure 34 shows an overview of the calculation procedure for LSM_{VPR} . The algorithm developed to calculate variable production rate linear schedules is based on a forward and backward pass methodology. In general the forward pass schedules the activity using the Minimum Lead (ML) specified from the activity input stage. The Minimum Lead is the minimum separation between activities based on time units. For example, Activity A may require a 10 day start ahead of Activity B to keep the crews

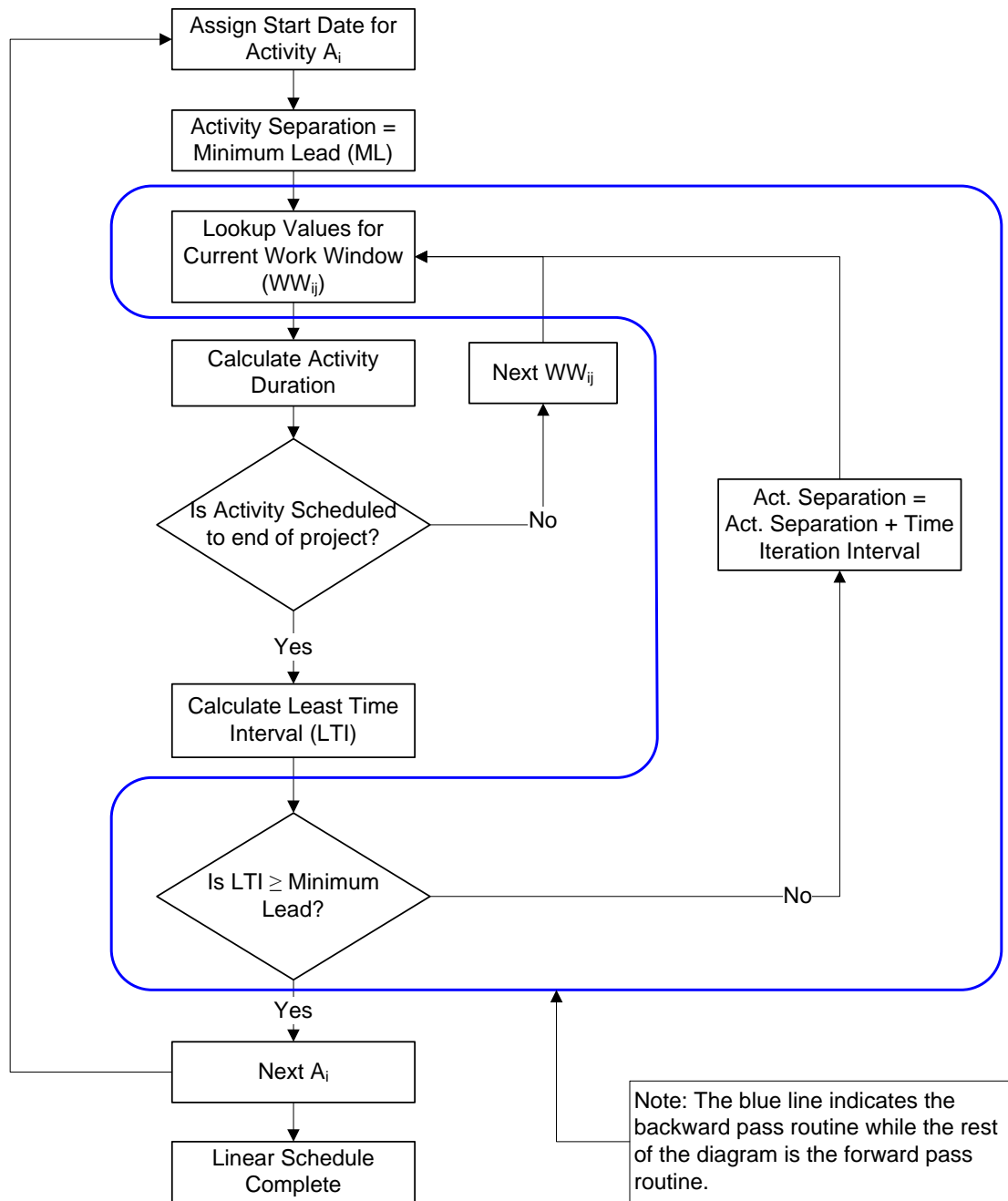


Figure 34 – Overview of the Calculation Procedure for LSM_{VPR}

from for the respective activities from interrupting one another's work. This 10 day buffer is the Minimum Lead and corresponds to a start to start relationship in CPM. For the initial calculation, the Activity Separation (AS) is set to the Minimum Lead. The Activity Separation is the difference between the start of the preceding activity and the activity being scheduled.

A backward pass is then performed to ensure that Minimum Lead is satisfied throughout the length of the activity. During the backward pass, the time difference between every vertex of both the activity being scheduled and the preceding activity is calculated. The Least Time Interval (LTI) is the minimum separation of time calculated between the two activities. The LTI is then compared to the Minimum Lead. If the LTI is greater than or equal to the Minimum Lead, the next activity can be scheduled. If the LTI is less than the Minimum Lead, the Activity Separation is increased by a value equal to the Time Iteration Interval (TII). The Time Iteration Interval is a user defined time interval. This process creates an iterative loop until the LTI is greater than or equal to the Minimum Lead. This looping nature is necessary, due to the possibility of incurring varying production rates with each iteration, to ensure the Minimum Lead is satisfied.

Figure 34 is a flow chart of the algorithm for the LSM_{VPR} process.

The steps to construct a linear schedule utilizing the Linear Scheduling Model with Variable Production Rates once the initial data has been entered are as follows:

- 1) Set the start date for the first activity to the project start date and subsequent activities to a start date equal to the start of the predecessor plus the Minimum Lead (ML) required
- 2) Set the Activity Separation equal to the Minimum Lead of the preceding activity, zero if no predecessor exists as in the case of the first activity in the schedule.
- 3) Lookup the Production Variables for the current Working Window (WW_{ij})
- 4) Calculate the Production Rate for the current Working Window
- 5) Calculate Distance Remaining (DR_{ij}), Time Remaining (TR_{ij}), and Distance Traveled in Remaining Time ($DTTR_{ij}$)
- 6) Use the following criteria to determine the exit location for the activity from the current Working Window
 1. $DTTR_{ij} = DR_{ij} \rightarrow$ Activity exits at the intersection of the top time axis and right distance axis of the working window
 2. $DTTR_{ij} > DR_{ij} \rightarrow$ Activity exits at the right distance axis of the working window
 3. $DTTR_{ij} < DR_{ij} \rightarrow$ Activity exits at the top time axis of the working window
- 7) Use the following criteria to calculate the exit coordinate for the activity
 1. $DTTR_{ij} = DR_{ij} \rightarrow (WWLE_i, WWTE_j)$ (Equation 7)
 2. $DTTR_{ij} > DR_{ij} \rightarrow (WWLE_i, ((DR_{ij}/PR_{ij})+Y_n))$ (Equation 8)
 3. $DTTR_{ij} < DR_{ij} \rightarrow ((X_n+DTTR_{ij}), WWTE_j)$ (Equation 9)

The naming convention for the exit coordinate follows (X, Y) where X represents location or distance on the project and Y represents time.

- 8) Determine if the activity has been calculated to the end of the project
- 9) If not, go to next Working Window and repeat steps 3 through 8 until the activity reaches the end of the project
- 10) Calculate the time difference vertically for every vertice in the current activity and the predecessor
- 11) Set the minimum distance value from step 10 to the Least Time Interval (LTI)
- 12) Compare the Least Time Interval with the Minimum Lead required, is the LTI greater than or equal to the ML required
- 13) If not, set the Activity Separation to the Activity Separation plus the Time Iteration Interval (TII), repeat steps 3 through 12 until the LTI is greater than or equal to the ML required
- 14) Next Activity, repeat steps 1 through 13 for all activities
- 15) Linear schedule complete

Location Variable Example

This section presents a simple example problem to illustrate the fundamentals of calculating an activity's linear schedule using the LSM_{VPR} model. The example illustrates calculations where the only production variable affecting the activity's production rate is a distance variable. A more complex example utilizing Velocity 1.0 is provided in Chapter V. Again, the examples and calculations are based on continuous full-span activity with the location in stations on the ordinate and time in days on the abscissa.

Assume the following conditions comprise a project activity whose linear schedule needs to be determined using LSM_{VPR} :

A single activity, Activity A, needs to be scheduled for a linear project spanning 400,000 feet. The start station for the project is 00+00 and the ending station is 4000+00.

The production rate of Activity is given by the following equation:

$PR_{ij} = -20,000 * X + 5,000$, in units of LF/day. (This equation is given for the example; Chapter IV will elaborate on deriving regression equations from historical data).

X represents the location variable that affects the production rate for Activity A. The location variable, X, has a value of 0.00 from station 00+00 to 2000+00, and a value of 0.15 from 2000+00 to 4000+00. The user desires a production rate of 3,000 feet per day, which will be used to calculate the API for each working window.

First the production rate for each working window needs to be calculated. The following calculations determine the production rate for an X-value of 0.00 and 0.15 respectively (Variables are given in this example which can be determined by regression equations as discussed in Chapter IV.):

$$PR_{ij} = -20,000 * X + 5,000$$

$$PR = -20,000 * 0.00 + 5,000 = 5,000 \text{ LF/Day} - \text{for Stations } 0+00 \text{ to } 2,000+00$$

$$PR = -20,000 * 0.15 + 5,000 = 2,000 \text{ LF/Day} - \text{for Stations } 2,000+00 \text{ to } 4,000+00$$

Referring back to Equation 1 (page 71) to calculate the Activity Performance Index (API) for each of the working windows yields the following for an X-value of 0.00 and 0.15 respectively:

$$API_{ij} = PR_{ij} / PR_{UD} * 100 \text{ (Equation 1)}$$

$$API = 5,000 / 3,000 * 100 = 167\% \text{ – for Stations 0+00 to 2,000+00}$$

$$API = 2,000 / 3,000 * 100 = 67\% \text{ – for Stations 2,000+00 to 4,000+00}$$

Referencing Table 9 (page 71) provides the color for each of the working windows. The working windows corresponding to X-value of 0.00 are green while the working windows with an X-value of 0.15 are orange.

Figure 35 depicts the API values calculated above and also displays the user-defined values for the standard time interval of 20 working days and the standard location interval of 200,000 feet. Stations are across the horizontal axis and working days are across the vertical axis. The large values for both the standard time and location intervals are intended to simplify the number of calculations required.

Figure 35 also has the working window naming convention illustrated on the linear chart. The subscript associated with the working window takes the format of distance column, time row. Since we have split the location portion of the project by only one division, there are only two column names for the project, while the time divisions have created eight rows on the chart.

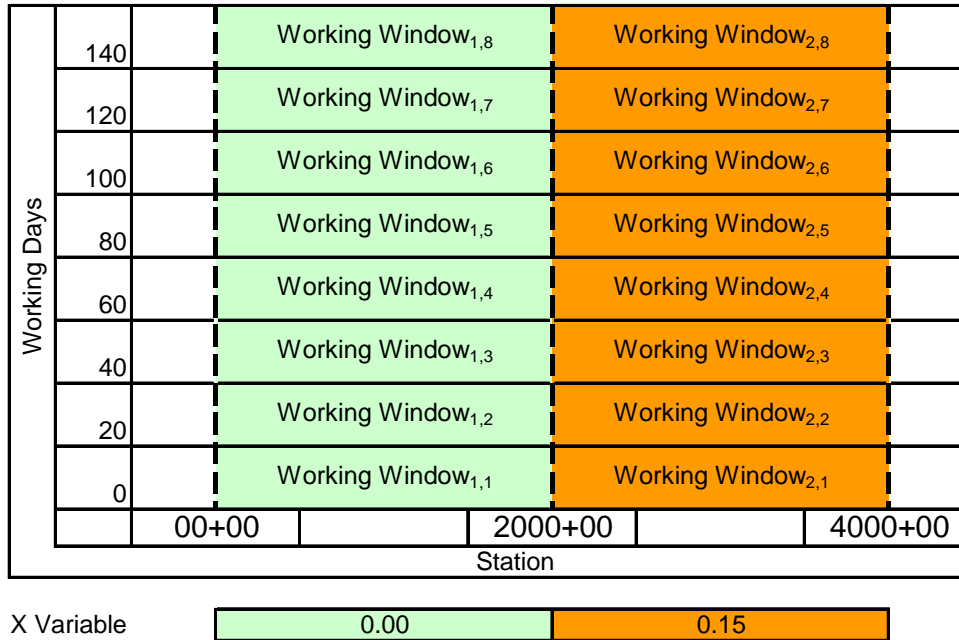


Figure 35 – Naming Convention for the Working Windows for Example One

All values are now set up and known to run the calculations for the linear schedule. The start time and location for the project is station 00+00 and working day 0. We then need to look up the variable values for the working window from which we are working, in this case WW_{1,1}. Since the only variable affecting the production rate is the location variable, all we need to know is the X-value for WW_{1,1} equals 0.00. We can then calculate the production rate from the equation given, or PR_{1,1} = -20,000 * 0.00 + 5,000, which equals 5,000 LF/day. We then proceed by calculating DR_{1,1}, TR_{1,1}, and DTTR_{1,1}, given by the following equations:

$$DR_{ij} = WWLE_i - X_n \quad (\text{Equation 2})$$

$$DR_{1,1} = 200,000 - 0 = 200,000 \text{ LF}$$

$$TR_{ij} = WWTE_j - Y_n \quad (\text{Equation 3})$$

$$TR_{1,1} = 20 - 0 = 20 \text{ Days}$$

$$DTTR_{ij} = PR_{ij} * TR_{ij} \quad (\text{Equation 6})$$

$$DTTR_{1,1} = 5,000 * 20 = 100,000 \text{ LF}$$

By comparing the $DTTR_{1,1}$ to the $DR_{1,1}$, we see that $DTTR_{1,1}$ is less than $DR_{1,1}$, thus the activity will exit $WW_{1,1}$ through the top of the working window. The coordinates of the exit location are given by $(DTTR_{1,1}, WWTE_1)$ or $(100000, 20)$. Figure 36 depicts the progress accomplished in the first working window.

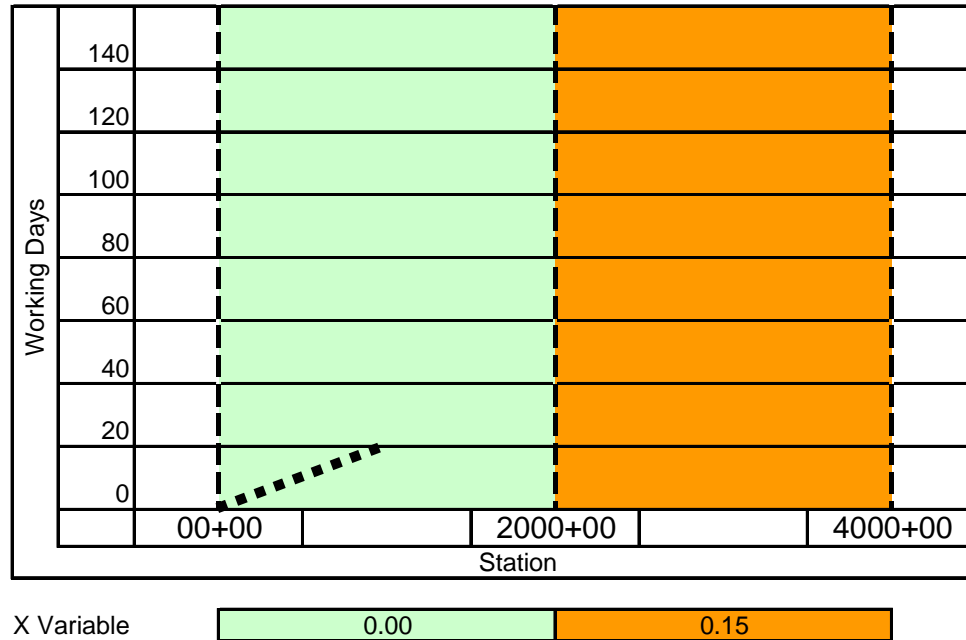


Figure 36 – First Activity Calculation for Example One

The activity then enters the next working window or $WW_{1,2}$. This window has the same production rate as the first window since the location variable remains the same and thus the production rate is the same as well. Solving the set of calculations for $WW_{1,2}$ yields the following:

$$DR_{ij} = WWLE_i - X_n$$

$$DR_{1,2} = 200,000 - 100,000 = 100,000 \text{ LF}$$

$$TR_{ij} = WWTE_j - Y_n$$

$$TR_{1,2} = 40 - 20 = 20 \text{ Days}$$

$$DTTR_{ij} = PR_{ij} * TR_{ij}$$

$$DTTR_{1,2} = 5,000 * 20 = 100,000 \text{ LF}$$

By comparing the $DTTR_{1,2}$ to the $DR_{1,2}$, we see that $DTTR_{1,1}$ is equal to $DR_{1,2}$, thus the activity will exit at the intersection of the $WWLE_1$ and the $WWTE_2$. The coordinates of the exit location are given by $(WWLE_1, WWTE_2)$ or $(200000, 40)$.

Figure 37 depicts the progress through the second working window. Also shown in this figure are the coordinate labels for the activity. As shown in the diagram, the subscripts are numbered based on consecutive numbering from left to right at changes in working windows.

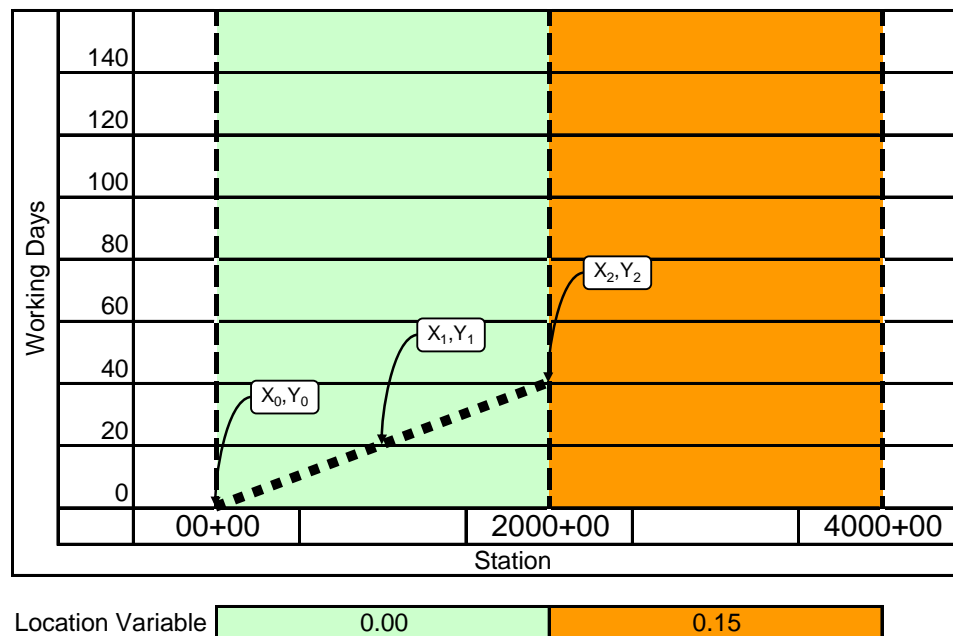


Figure 37 – Naming Convention for Activity Nodes

The next working window entered is $WW_{2,3}$, which has a different production rate than the previous working window due to the change in the location variable from 0.00 to

0.15. The production rate for $WW_{2,3}$ is given by $PR_{2,3} = -20,000 * 0.15 + 5,000$, or 2,000 LF/day. Next we calculate DR, TR, and DTTR as shown below:

$$DR_{2,3} = 400,000 - 200,000 = 200,000 \text{ LF}$$

$$TR_{2,3} = 60 - 40 = 20 \text{ Days}$$

$$DTTR_{2,3} = 2,000 * 20 = 40,000 \text{ LF}$$

By comparing the $DTTR_{2,3}$ to the $DR_{2,3}$, we see that $DTTR_{2,3}$ is less than $DR_{2,3}$, thus the activity will exit $WW_{2,3}$ through the top of the working window and thus the exit coordinate is given by $(DTTR_{2,3}, WWTE_3)$ or $(240000, 60)$.

Next, the calculations continue through working window $WW_{2,4}$

$$DR_{2,4} = 400,000 - 240,000 = 160,000 \text{ LF}$$

$$TR_{2,4} = 80 - 60 = 20 \text{ Days}$$

$$DTTR_{2,4} = 2,000 * 20 = 40,000 \text{ LF}$$

$$DTTR_{2,4} < DR_{2,4}$$

$$X_4, Y_4 = (DTTR_{2,4}, WWTE_4) = (280000, 80)$$

Next, the calculations continue through working window $WW_{2,5}$

$$DR_{2,5} = 400,000 - 280,000 = 120,000 \text{ LF}$$

$$TR_{2,5} = 100 - 80 = 20 \text{ Days}$$

$$DTTR_{2,5} = 2,000 * 20 = 40,000 \text{ LF}$$

$$DTTR_{2,5} < DR_{2,5}$$

$$X_5, Y_5 = (DTTR_{2,5}, WWTE_5) = (320000, 100)$$

Next, the calculations continue through working window $WW_{2,6}$

$$DR_{2,6} = 400,000 - 320,000 = 80,000 \text{ LF}$$

$$TR_{2,6} = 120 - 100 = 20 \text{ Days}$$

$$DTTR_{2,6} = 2,000 * 20 = 40,000 \text{ LF}$$

$$DTTR_{2,6} < DR_{2,6}$$

$$X_6, Y_6 = (DTTR_{2,6}, WWTE_6) = (360000, 120)$$

Next, the calculations continue through working window $WW_{2,7}$

$$DR_{2,7} = 400,000 - 360,000 = 40,000 \text{ LF}$$

$$TR_{2,7} = 140 - 120 = 20 \text{ Days}$$

$$DTTR_{2,7} = 2,000 * 20 = 40,000 \text{ LF}$$

$$DTTR_{2,7} = DR_{2,7}$$

$$X_7, Y_7 = (WWLE_2, WWTE_7) = (400000, 140)$$

The calculations for $WW_{2,7}$ complete progress for Activity A through the end of the project, and thus completes the linear schedule. Figure 38 is the completed linear schedule based on the above calculations. Since we are working an example that depicts only one activity the backward pass is unnecessary.

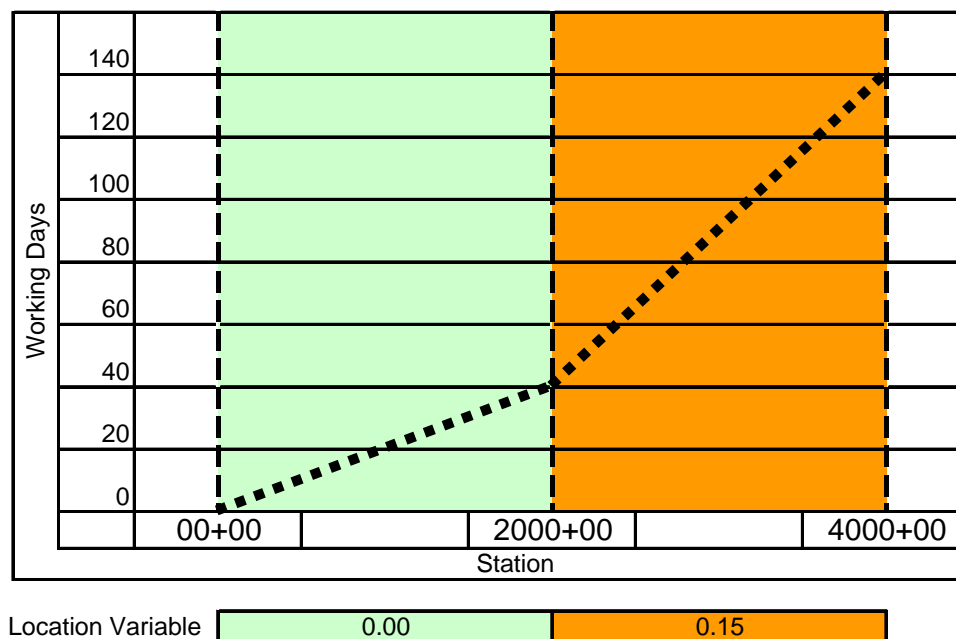


Figure 38 – Final Linear Schedule

The example problem is simple in nature to easily convey the calculation process. Construction projects are influenced by multiple variables with numerous changes in time and location variables. To calculate such complex schedules requires a scheduling tool capable of handling the computations. Chapters IV and V further discuss the model and tool respectively.

CHAPTER IV

DATA COLLECTION AND ANALYSIS

Historical production rate data and the regression analysis of this data serves as the core of LSM_{VPR} . The production rate information is analyzed to determine variables that affect production. Through the use of statistical software, regression equations can be derived to predict future production rates. Thus the availability of the appropriate historical production rate information is paramount to the success of modeling linear schedules using LSM_{VPR} . The remainder of this chapter describes the types of data collected and the method used for analyzing the data.

Data Collection

This research utilizes two types of data: field production data and historical weather data. The field production data is utilized to develop regression equations for the production rate of pipeline construction activities. The historical weather data is utilized at two points in the development of a linear schedule based on varying production rates. The first use for the weather data is during the development of the regression equations for the construction activities. The types of weather data that show correlations to the construction production rates become variables in the regression equations. The second

use for the weather data is for input to the regression equations to build a linear schedule based on varying production rates.

Pipeline Construction Data

The production rate information collected for this research was obtained from a 14 and 16 inch-750 mile liquefied natural gas pipeline project starting in Wyoming, spanning the Rocky Mountains and terminating in the center of Kansas. The project was broken up into five *spreads* or segments, each approximately 150 miles in length. The data obtained from the project is that which was required to monitor daily progress of construction activities associated with constructing a pipeline, namely start and end station for each activity each day. This data was collected on a daily basis by construction inspectors for each activity.

The form utilized to capture the production data is shown in Figure 39, while the coding system for collection the data is shown in Figure 40. The form captured the start and end of each activity as well as a general site and ground condition which aided in the validation of correlating the weather data. Production information was obtained for the following activities: grading, stringing, bending, welding, coating, lower-in, back-fill, and cleanup. Table 8 provides a description of each activity. The unit of productivity measure for all activities is linear feet per day along the horizontal alignment of the project. For example, welding is an activity that is performed to join two pieces of pipe together, the conversion to linear feet per day is accomplished through calculating the number of feet of pipe that were joined by the welding process each day. These activities are all continuous full-span activities as defined by Harmelink.

Date			Site Condition		Ground Condition				
*Only edit green cells, Do Not edit grey cells									
Activity	Code	Date	Start Station	End Station	Site Condition	Ground Condition	Hours/Day	Rock	LF

Figure 39 – Data Entry Form for Daily Construction Progress

Coding System			Site Condition	Ground Condition	Rock
Spread #	Activity	Crew	#	#	#
#	##	#			
Spread #	Activity	Crew	Site Condition	Ground Condition	Ground Condition
1 Spread 1	01 Fence	1 Crew 1	1 Warm & Calm	1 Dry	Rock Not a Factor
2 Spread 2	02 Clear	2 Crew 2	2 Warm & Breezy	2 Moist	1 Cobbles 6-12"
3 Spread 3	03 Grade	3 Crew 3	3 Warm & Windy	3 Wet	2 Rock 12" to 24"
4 Spread 4	04 String	4 Crew 4	4 Cool & Calm	4 Frozen	3 Easily Rippable
5 Spread 5	05 Bend	5 Crew 5	5 Cool & Breezy	5 Snow up to 12"	4 Difficult Rippable
	06 Trench		6 Cool & Windy	6 Snow greater than 12"	5 Requires Blasting
	07 Weld, Pipe Gang		7 Cold & Calm	7 Ice	
	08 Weld, Firing Line		8 Cold & Breezy	8 Ice & Snow	
	09 Coating		9 Cold & Windy		
	10 Lower-In		10 Raining		
	11 Back-Fill		11 Sleet		
	12 Tie-In		12 Snowing		
	13 Clean-Up		13 Blizzard		
	14 Test		14 Other		
	15 Road Crossing				
	16 Stream Crossing				
	17 HDD				
	18 Survey Staking				
	19 Conc Coated Pipe				
	20 Valve				
	21 Tee w/ LOR				
	22 Launcher/Receiver				
	23 Unused				
	24 Unused				
	25 Unused				

Warm = greater than 70 degrees
Cool = 40 to 70 degrees
Cold = less than 40 degrees

Figure 40 – Coding System for Daily Construction Progress Form

The production rate data collected was obtained from activities being performed by similar equipment and similar crew makeup. The number of welders and the total number of workers were also captured on a daily basis. Construction was performed with six day work weeks consisting of ten hour days.

Field production monitoring was obtained by hand written progress forms filled out by the construction inspectors. That information was transferred to the MS Excel© data form in Figure 39. The spreadsheets were then submitted via email for entry into a master database. The form allowed for the input of start and end stations for each activity. The form also allowed for the inspectors to indicate a general site and ground condition to aid in the validation of the weather data collected below.

Weather Data

Weather data was collected along the length of the project from stations within the National Climatic Data Center (NCDC) network. NCDC data is available via a GIS interface through their website, <http://www.ncdc.noaa.gov/oa/dataaccessstools.html>. Stations were utilized that had data available during the time period of construction when the production observations were made (October 2007 to April 2008). The stations had data for the following categories: mean temperature, minimum temperature, maximum temperature, average wind speed, maximum wind speed, and precipitation. The weather stations record data on an hourly basis and convert the data into daily summary values. The weather service depicts the data used as “surface data, global summary of the day.”

The weather station nearest the construction activity was then tied to the days on the construction inspection form. This allows a large amount of weather data to be

associated with each data point of production. The construction inspection notes were also reviewed to ensure that the weather conditions recorded at the weather station were similar to those encountered at the construction site on that day. A total of seven weather stations had data of the quality and timeframe described above, which averages to a weather station approximately every 100 miles along the construction alignment. This distance is further broken down by the weather stations being located at most, approximately 50 miles from any area of construction. (In all cases the daily weather data from the stations was compared to that recorded at the job site, if the two did not match, the data point was not used in the analysis described below.)

Data Analysis

Much research has been conducted regarding the analysis of production rates with respect to construction activities. General procedures have been outlined by Kuo [31] and Chong [6] and these procedures have been utilized for the analysis conducted in this research. Of particular importance in the analysis are the effects of multiple production variables on construction production rates. Multiple regression analysis was used to check for variables affecting production rates. The regression analysis yielded equations used by Velocity 1.0 to predict future production rates.

Multiple Regression Analysis

Multiple regression analysis is used to determine the effects of several independent variables on one or more dependent variables. This research has reviewed

all of the activities listed in Table 8 against mean temperature, minimum temperature, maximum temperature, average wind speed, maximum wind speed, precipitation, pipe length, number of welders, number of workers, elevation, and slope of terrain.

Production variables of work week and holiday schedule will be applied later in this research when predicting production rates. The multiple regression analysis was carried out using the following steps:

1. Ensure enough data points exist for the analysis (See Table 10) [13]
2. Perform check to ensure the dependent and independent variables are approximately normally distributed.
3. Utilize box plots and analyze standardized residuals to remove outliers.
4. Fit a regression model.
5. Check for collinearity among the variables selected for the model.
6. Check the validity of the model utilizing R^2 .

Table 10 – Sample Sizes and Number of Predictors [13]

Number of Predictors	Sample Sizes based on Power Analysis		
	Small	Medium	Large
	$R^2=0.02$	$R^2=0.13$	$R^2=0.26$
1	390	53	24
2	481	66	30
3	547	76	35
4	599	84	39
5	645	91	42
6	686	97	46
7	726	102	48
8	757	108	51
9	788	113	54
10	844	117	56
15	952	138	67
20	1066	156	77
30	1247	187	94
40	1407	213	110

The first three steps are performed to ensure a valid regression analysis, while the final three steps determine the regression equation fit to the activity and check the results. Correlations were then tested among the activities for the production variables listed above. Regression analysis was performed with the statistical software package SPSS[®].

The production variables examined were found only to correlate with the welding activity. The lack of correlation with other activities may be due to several reasons, but are most likely due to one of the following: different production variables need to be selected, different methods need to be employed to measure progress, or welding was the only driving activity in this pipeline construction project. Since welding is typically the driving activity for pipeline construction, all other activities are scheduled to ensure welding continues without interruption. This could cause the other activities production rates to appear sporadic and disrupt natural correlations which may exist with the given activities had they no tie to welding.

Pipeline welding was found to correlate with the following production variables: maximum temperature, maximum wind speed, precipitation, average pipe joint length, and slope of terrain (where all weather data is of the daily summary type described above). Interestingly the welding production rate did not correlate with the number of welders. This could have occurred for a number of reasons for which more analysis is required. This may have occurred due to the fact that the project was built when welders were at an all time high demand and the project was performed in extremely harsh

conditions, thus lowering the effectiveness of the welders being hired. It should be noted that the data used for welding used welders ranging from 10 to 26 per construction spread. Along with these production variables, we can add the variable of working day, which indicates whether the day is planned for work. A working day has a value of one while a non-working day (holiday, weekend, etc.) has a value of zero.

The following three tables show the summary output from the regression analysis performed with SPSS. Again, the results listed in the table are based upon four of the five spreads of the pipeline construction. This allows the fifth spread to be utilized as a test on the regression model derived. (A more comprehensive listing of the statistical output used to derive Equation 10 is provided in Appendix B.)

Table 11 – Model Summary for the Welding Activity

Model Summary^b

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.659 ^a	.435	.423	1.8788454E3	1.517

a. Predictors: (Constant), AvgLengthJoint, Precip, MaxWind, AvgSlope, MaxTemp

b. Dependent Variable: LF

Table 12 – ANOVA Results for the Welding Activity

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	6.655E8	5	1.331E8	37.704	.000 ^a
	Residual	8.649E8	245	3530059.886		
	Total	1.530E9	250			

a. Predictors: (Constant), AvgLengthJoint, Precip, MaxWind, AvgSlope, MaxTemp

b. Dependent Variable: LF

Table 13 – Regression Coefficients Calculated for the Welding Activity

		Coefficients ^a						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	3672.330	1061.795		3.459	.001		
	AvgSlope	-57951.923	11851.959	-.252	-4.890	.000	.869	1.150
	MaxTemp	31.840	10.111	.174	3.149	.002	.754	1.327
	MaxWind	-73.346	16.402	-.224	-4.472	.000	.918	1.089
	Precip	-34591.410	11790.726	-.143	-2.934	.004	.974	1.026
	AvgLengthJoint	75.323	14.553	.305	5.176	.000	.664	1.505

a. Dependent Variable: LF

The following equation depicts the fitted model for welding with an R² of 0.435 and a p-value of 0.000.

$$PR = WD * (31.840*MT - 73.346*MW - 34,591*P - 57,951*TS + 75.323*PJL + 3,672.3) \quad (\text{Equation 10})$$

PR = Production Rate of Welding (Linear Feet of Pipe Per Day)

WD = Working Day (Yes = 1, No = 0)

MT = Average Daily Maximum Temperature (Degrees Fahrenheit)

MW = Average Daily Maximum Wind Speed (Miles Per Hour)

P = Average Daily Precipitation (Inches)

TS = Average Slope of the Terrain (Decimal from 0.0 to 1.0)

PJL = Average Pipe Joint Length (Linear Feet)

Predicting Production Rates

The results of the multiple regression analysis performed on the pipeline construction data revealed correlations for the welding activity with several production variables.

Table 14 provides the results of the regression analysis and lists the limits where the welding production rate equation is applicable.

Table 14 – Welding Production Variables with Limits of Use

Production Variable	Unit	Low	High
Production Rate	Linear Feet	2,788	8,019
Maximum Temperature	Degrees Fahrenheit	3.9	79.0
Maximum Wind Speed	Miles Per Hour	5.9	43.6
Precipitation	Inches	0.00	0.08
Terrain Slope	Decimal	0.0001	0.0746
Pipe Joint Length	Linear Feet	58.0	78.0

* All weather characteristics are based on daily summary values

Equation 11 adds the working window nomenclature to Equation 10 and utilizes daily summary weather data as input. For the purposes of construction planning and scheduling, it may be desirable to determine the average production rate that may be achieved for a given month in lieu of varying the production rate daily. Velocity 1.0, discussed in Chapter V, addresses this issue.

$$\mathbf{PR_{ij} = WD * (31.016*MT_{ij} + 88.983*MW_{ij} + 39,219*P_{ij} + 66,214*TS_i + 57.442*PJL_i + 5,421.5)} \quad \text{(Equation 11)}$$

PR_{ij} = Production Rate of Welding (Linear Feet of Pipe Per Day)

WD_{ij} = Working Day (Yes = 1, No = 0)

MT_{ij} = Average Daily Maximum Temperature (Degrees Fahrenheit)

MW_{ij} = Average Daily Maximum Wind Speed (Miles per Hour)

P_{ij} = Average Daily Precipitation (Inches)

TS_i = Average Slope of the Terrain (Decimal from 0.0 to 1.0)

PJL_i = Average Pipe Joint Length (Linear Feet)

Predicting future production rates is accomplished by inputting the appropriate production variable values for each item in Equation 11. The data used for the weather variables is calculated by averaging all available daily summary values for the given day in the location being scheduled. For example, most of the weather stations analyzed for this research had a minimum 30 to 40 years of weather data available in the daily summary values format. This translates to a minimum of 30 to 40 data points for each day to determine the average weather patterns. Those average daily values are incorporated into the production rate equation for the appropriate working windows. Equation 11 depicts the i,j nomenclature assigned to the production rate equation, and thus translates into the production rate that could be expected within the i,j working window. Note that the Slope of the Terrain and the Pipe Joint Length only contain subscripts of i , which indicates this variable is only dependent upon the location along the horizontal alignment. (Working Day maintains the subscripts of i,j to account for varying work days from location to location, possibly due to union or non-union work or other variances due to location.)

Equation 11 serves as the basis for calculating the welding production rate for the model validation in Chapter V.

CHAPTER V

VELOCITY 1.0

Velocity 1.0 is an MS Excel based program developed to process the calculations required for implementing the algorithm utilized for LSM_{VPR} . The interface was chosen for ease and familiarity to the user and the computational and graphical abilities of the interface. The program consists of tabs within an Excel workbook that walk the user through the data entry process. Sub-routines not accomplished within the workbook are performed in Visual Basic for Applications (VBA) through the use of macros listed in Appendix C.

Introduction

The algorithm developed to solve linear schedules with changing production rates utilizes an iterative solution. The intent of the program is to speed the calculation process and provide a linear schedule that conveys as much information as possible. Linear scheduling by its nature provides a diagram that allows the user to easily understand the work flow and construction plan. By combining a traditional linear schedule with the use of working window shading and activities that change production based on time and location, the user can now also understand reasons for lower or higher production in different areas along the length of the alignment.

User Interface

Velocity 1.0 is an MS Excel based program which allows the average user to comfortably maneuver in the interface. Tabs differentiate the input of the information and are organized in an intuitive manner.

Input and Output

The input for the program is accomplished through a series of tabs with input progressing from left to right. The user is prompted for general project information, activities and relationships, average production rates of the activities (where regression equations are not available), and a series of tabs which incorporate various production variables. Green and grey cell color is used throughout the program to indicate user-input and calculated fields respectively.

The user must also input weather data for the stations nearest the construction that conform to the daily summary value described previously. The user then assigns which weather stations are used for the given stations in the project.

The output from Velocity 1.0 is a linear schedule which depicts production rate variance in the background. Due to the highly involved graphical nature of the output, it is recommended to plot D size (24" X 36") schedules at a minimum. It is also recommended to use high resolution video cards and monitors (1920 X 1080 or higher) to maximize the visual display of the information.

Figure 41 is the general project information required on the first tab in Velocity. This tab determines the overall route input and working times, calculation parameters, and the output display.

Velocity 1.0					
Project Data		Chart Display		Calculation	
Start Station	32654+31	Start Station	32500+00	WW Interval Stationing	1,000
End Station	39480+00	End Station	40750+00	WW Interval Time	Day
Start Date	11/6/07 0:00	Start Date for Display	10/1/07		
Days Per Work Week	6	End Date for Display	9/30/08		
Project Name		Grid Display		Background Display	
750 Mile LNG Pipeline - Spread 5		Major Axis Horizontal	25,000	Activity No. to Display	2
		Major Axis Vertical	Month	Desired Production	11,800
				WW Interval Stationing	1,000

Figure 41 – General Project Information Input Screen

The input information determines the general characteristics of the project, such as: start station, end station, length, start date, and number of working days per week.

This tab allows the user to easily change the desired start dates and analyze the differences in changing the number of working days in a week.

The screen also controls the calculation parameters. The “Calculation” heading contains two fields that deal with the interval for stationing and time. These fields indicate the size of the working windows that are used for calculating production rates. As shown, Velocity will calculate a production rate with working windows 1,000 feet in width by one day in height. As discussed in Chapter III, the scheduler may choose to work with production rates averaged over the month and a distance of 10,000 feet. Changing the parameters to 10,000 feet and Month would then change the working windows to that size.

The output of the linear schedule is also controlled from this tab, including: the start and end parameters of the chart, the interval for both the horizontal and vertical grid, and the activity performance index is displayed on the chart background. The scheduler selects the activity number (derived from the activity tab discussed later) to display in the

background. The user then inputs the desired production rate for that activity to have the API calculated, thus giving the visual display of time-location areas that may impede progress.

The next tab the user encounters is the “Activity” tab shown in Figure 42. Here the user will enter the activities that take place on the project and input additional information about the specific activities. The user must choose to utilize an average value for the activities production rate, i.e. a value the user inputs; or a calculated value by inputting the regression coefficients derived in Chapter IV. As shown in Figure 42, five production variables can be accounted for in Velocity, the user can enter zeroes for variables that do not apply to a given activity. Each activity also requires the necessary “Lead” be entered. This allows the scheduler to input the gap in days that is required between activities to prevent crews from interfering with one another.

Next the scheduler needs to select the holidays, or other non-work days, on the “Holiday” tab. The interface is a simple drop-down box where the user can select days of the year to demark as non-working days.

Next the user needs to input the raw data that will be used to calculate any activities that have been selected to be scheduled based on regression coefficients. This includes inputting the terrain data in the format of two columns consisting of Station and Elevation. The terrain information can be copied and pasted into the “Raw Terrain Data” tab. The raw weather data is input in much the same way. The user can copy and paste in the values in the same format that the NCDC distributes the daily summary weather values. The user will download all available data from the weather station along the alignment of the project and paste the data into the “Raw Weather Data” tab.

	Use Average or Calculated	Activity	Average Production Rate	Regression Model Data					Constant	Start Station	End Station	Req'd Lead
				Average Daily Max Temperature	Average Daily Max Sustained Wind	Average Daily Precipitation	Average Terrain Slope	Average Pipe Joint Length				
				Prod. Var. 1	Prod. Var. 2	Prod. Var. 3	Prod. Var. 4	Prod. Var. 5				
1	Average	Grading/Stringing	16,000							32654+31	39480+00	4
2	Calculated	Welding		31.840	-73.346	-34,591	-57,952	75.323	3,672.3	32654+31	39480+00	5
3	Average	Trenching	15,000							32654+31	39480+00	2
4	Average	Lower-In/Back-Fill	12,000							32654+31	39480+00	4
5	Average	Clean Up	15,000							32654+31	39480+00	
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												

Figure 42 – Activity Input Screen

Next the user selects the stations that apply to each of the weather stations that have information input into from the previous step. The grey cells automatically populate from the weather data input and the user then enters the start and end station for which to apply each of the weather stations values.

Weather Station	ID	Start Station	End Station
EVANSTON/BURNS FLD	725775	0+00	1050+00
RAWLINS MUNICIPAL AP	725745	1050+00	6800+00
ROCK SPRINGS ARPT	725744	6800+00	12900+00
LARAMIE GENERAL BREES FIELD	725645	12900+00	15840+00
CHEYENNE MUNICIPAL ARPT	725640	15840+00	20700+00
AKRON WASHINGTON CO AP	724698	20700+00	25600+00
GOODLAND RENNER FIELD	724650	25600+00	31500+00
HAYS MUNI (AWOS)	724518	31500+00	40120+00

Figure 43 – Weather Stations Input Tab

The user is now ready to schedule the project based on the input from the previous steps. The scheduling functions are located on the “Linear Schedule” tab.

Model Validation

The model developed in Chapter IV provides a basis to predict future construction projects. The model was developed using the construction production rate data from four of the five spreads of construction. This allows a validation to be performed using the remaining construction spread. The spread used for model validation is referred to as “Spread 5”. While the spread is approximately 160 miles in length, only the center 130 miles could be used due to *skips* at the beginning and end of the spread. The portion used for validation starts approximately seven miles north of Collyer, Kansas (Mile Post 611, Station 32654+31) and continues to approximately four miles east of Mitchell, Kansas (Mile Post 740, Station 39480+00). This spread was chosen as the order of construction was continuous from west to east without *skips* or *move-arounds*.

The model validation was performed using Velocity 1.0 following the procedures outlined in the previous section of this chapter. The regression coefficients applied to welding were those derived from construction spreads one through four. The production rates assumed for the other activities were averages from the construction data. Once the project data was input, Velocity 1.0 was run to provide a linear schedule. The welding activity was chosen as the background utilized in calculating API since it is the driving activity. The desired production used for welding to calculate API is 11,800 linear feet per day as this is the average that was provided in the initial contractor schedule.

Figure 44 is a view of the legend contained on the Velocity 1.0 linear schedule output. The API is defined by the decimals entered for the high and low values and the activities are assigned colors and line-styles accordingly.

API COLOR			LEGEND				750 Mile LNG Pipeline - Spread 5
COLOR	HIGH	LOW	COLOR	TYPE	WEIGHT	ACTIVITY	
	0.5	0.0		SOLID	THICK	Grading/Stringing	Linear Schedule
	0.7	0.5		SOLID	THICK	Welding	
	0.8	0.7		SOLID	THICK	Trenching	
	0.9	0.8		SOLID	THICK	Lower-In/Back-Fill	
	1.0	0.9		SOLID	THICK	Clean Up	
						Date:	3/23/09

Figure 44 – Velocity 1.0 API Scale and Legend

Figure 45 is the output of Velocity 1.0 in a graphical linear scheduling format. The color pattern in the background depicts the relationship between the contractor’s planned production rate for welding of 11,800 linear feet per day and the expected production rate utilizing LSM_{VPR} via the Activity Performance Index. The large band of red across the page is the winter holiday from December 22nd through January 1st. Areas of the chart depicted by something other than green indicate a time-location area that is not expected to produce the desired production rate. The scheduler can easily visualize differences in locations and time. The user can manipulate the start date to incur more favorable conditions. In this regard, LSM_{VPR} provides a tool to play “What If” scenarios with historically backed production methods.

Figure 46 is the output of Velocity 1.0 with the working window parameters changed to 10,000 feet horizontally by one month vertically. This allows the user to see an averaged view without the interference of the day to day variances.

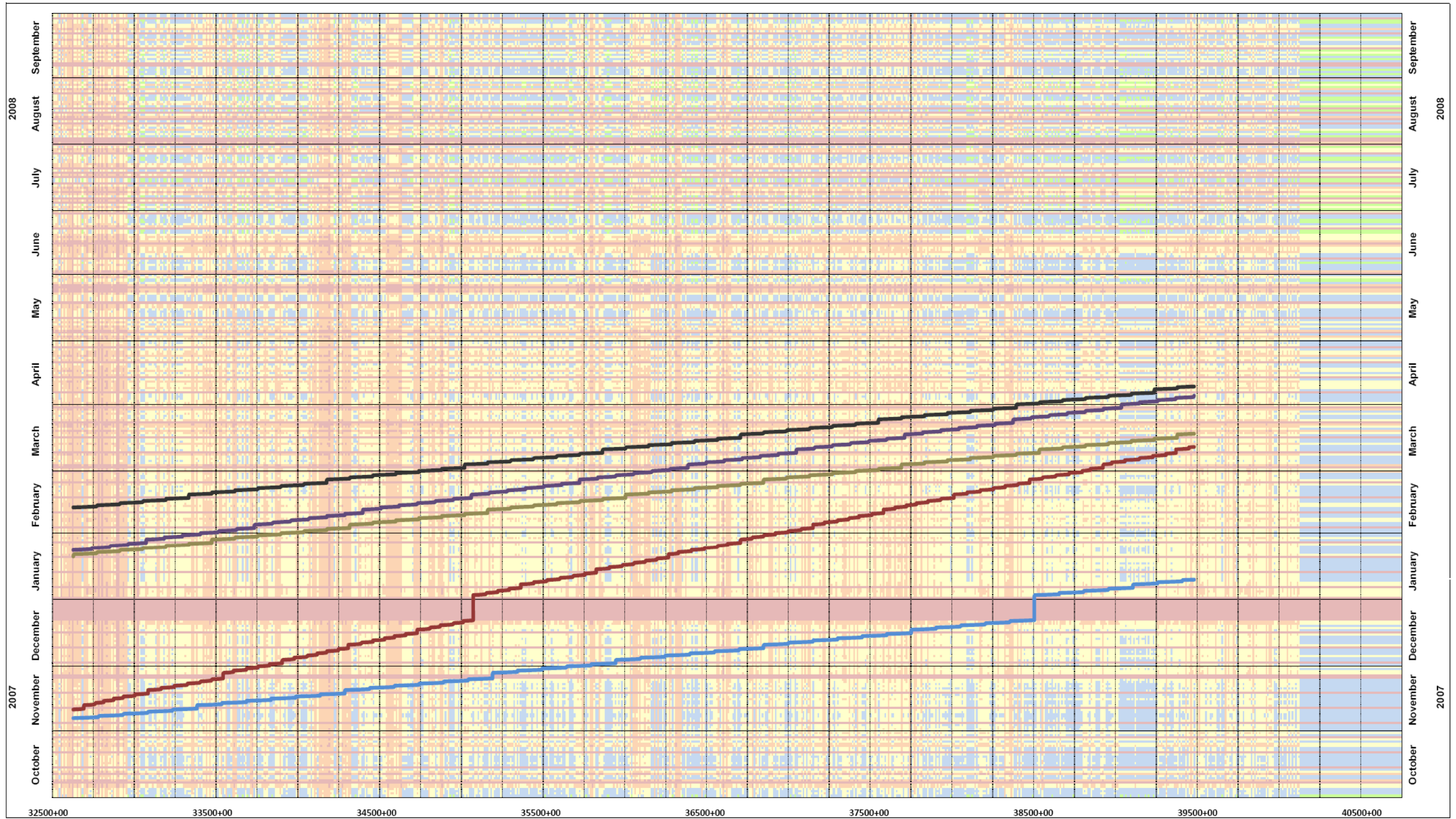


Figure 45 – Velocity 1.0 Linear Schedule (WW = 1,000 ft by One Day)

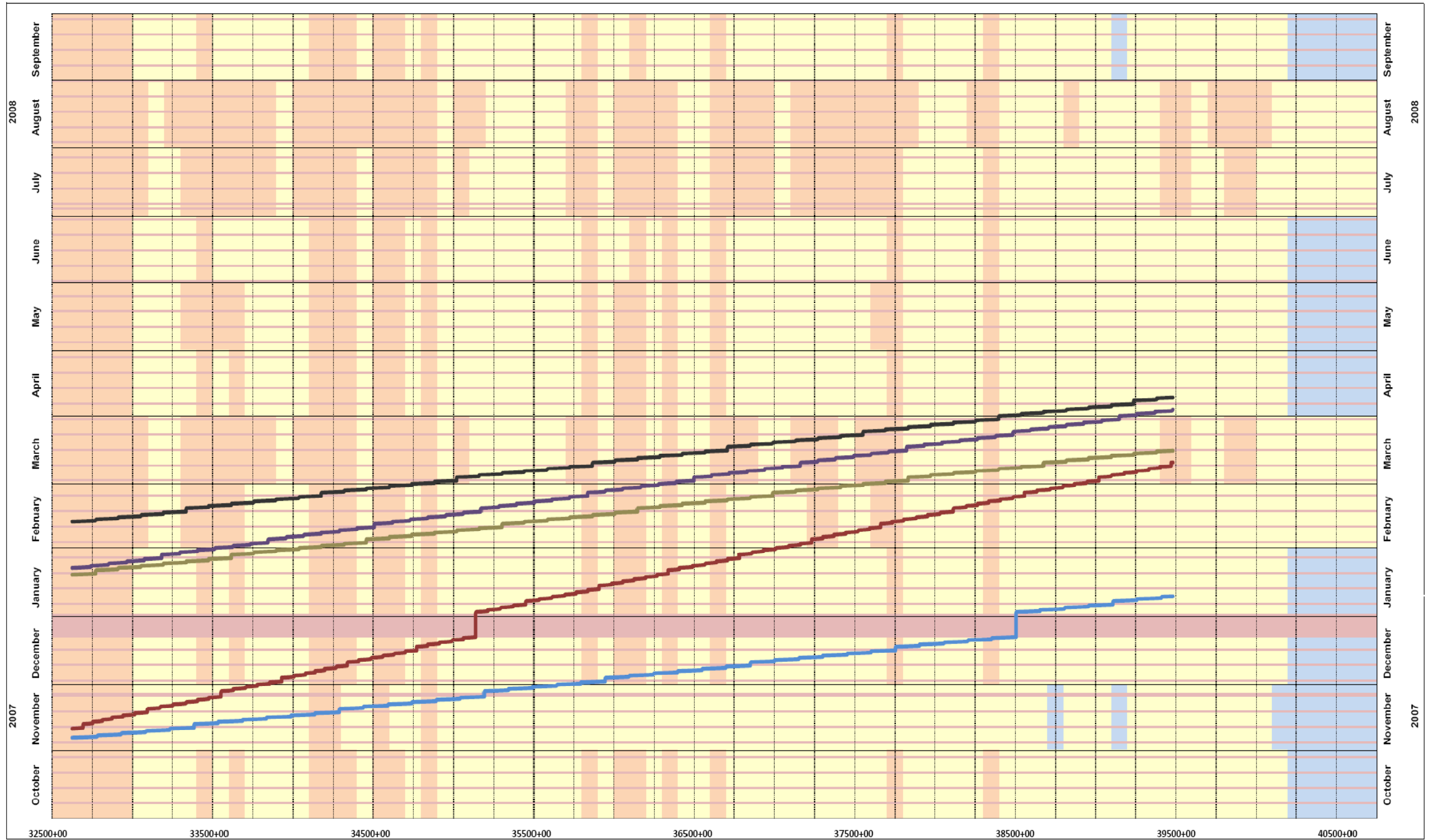


Figure 46 - Velocity 1.0 Linear Schedule (WW = 10,000 ft by One Month)

Figure 47 is a magnified view of the same linear schedule previously depicted. This view better illustrates the changing nature of the production rates of the welding activity. The working window size is one month by 10,000 feet, which produces the mosaic appearance of the background. As stated earlier, the user can switch the working window to monthly along with a larger horizontal scale to reduce the frequency of the production rate changes.

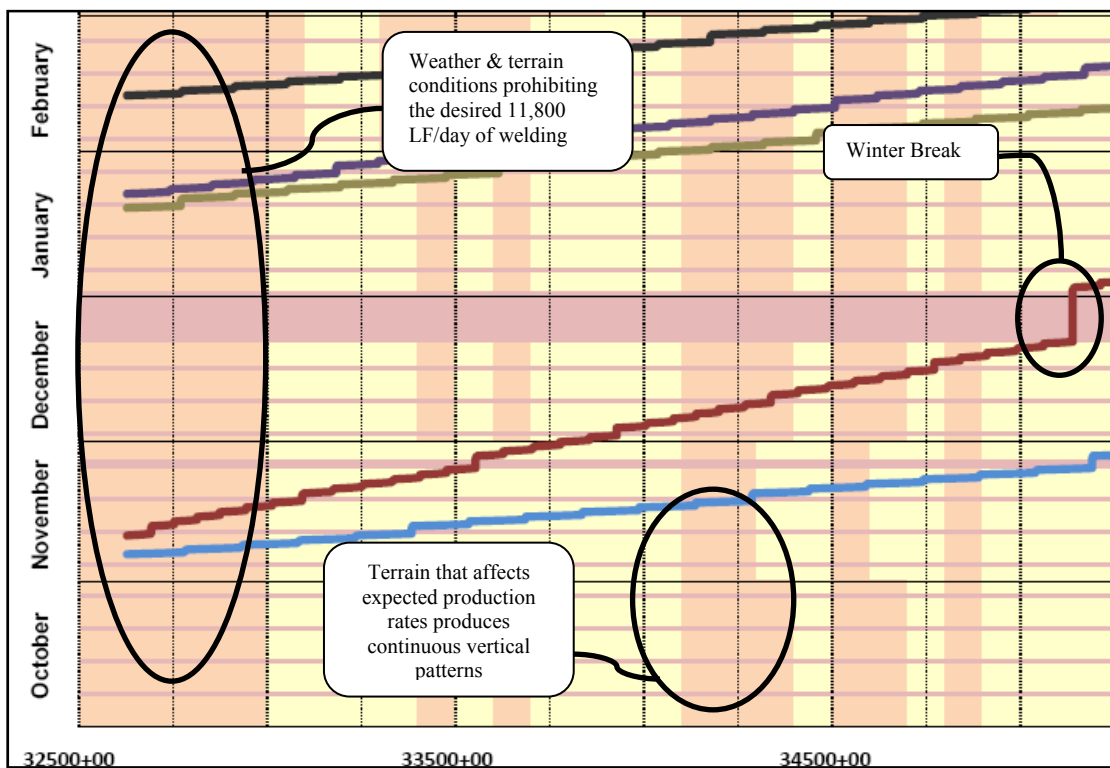


Figure 47 – Magnified View of the Linear Schedule depicted in Figure 45

Analyzing Figure 47 in more detail allows the user to understand the vast amount of information being conveyed by the schedule. The schedule displays a red row every seven days depicting the Sundays not worked due to a six day work week selection. The user can also understand how the production variables are affecting the production rate of the welding activity. The vertical bands of yellow and orange on the right side of station

34250+00 indicates a slowing of welding production due to an increased slope in this area. The user can also see that the red, orange, and yellow prevalent for the first 50,000 feet of the chart indicates generally worse weather and terrain conditions for this time and location of the project. As previously suggested, large plots will yield more legible and thus useful output.

The API associated with welding quickly shows the user that the 11,800 linear feet per day welding rate is unrealistic. The user could continue to adjust the desired production rate down until the API calculation yields a more favorable green background. This is part of the “What If” capabilities created using Velocity 1.0.

Figure 48 depicts the tabular output and bar chart output available from Velocity 1.0 that allows the user access to the start and end dates of each activity. This allows flexibility in transferring data to other non-linear scheduling software where necessary and providing dates for milestones or summary type reports. The bar chart view also provides familiarity to the user to help transition from bar chart type schedules to linear schedules.

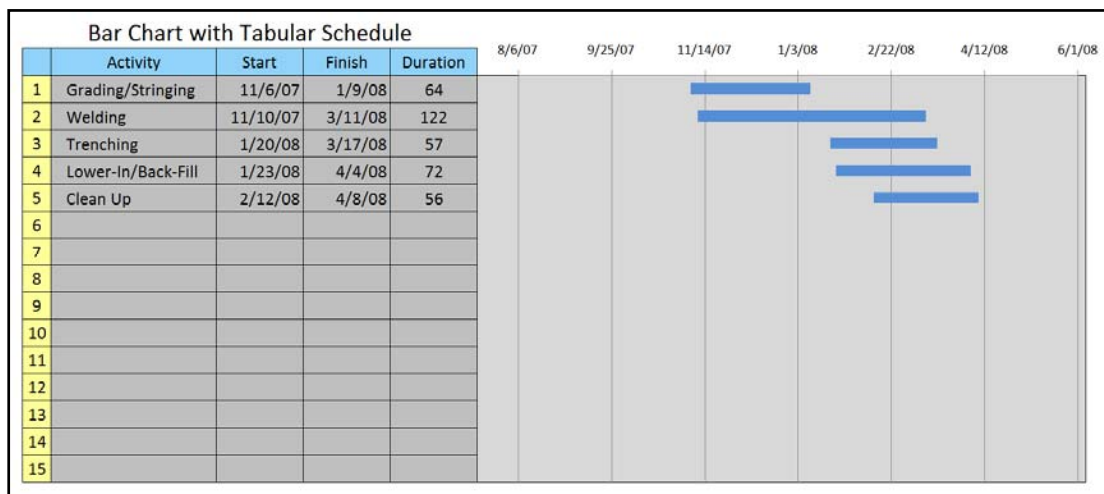


Figure 48 – Bar Chart Output from Velocity 1.0

Welding the pipeline joints together is the driving activity for pipeline construction, and is of the most interest for analysis. Figure 49 depicts the planned, actual, and LSM_{VPR} progress lines for the welding activity on construction spread five. The planned value is derived from the contractor's bar chart schedule and thus depicts a straight line production rate from start to finish. The actual progress line is charted from the historical data on the project, while the LSM_{VPR} progress line is taken from Velocity 1.0.

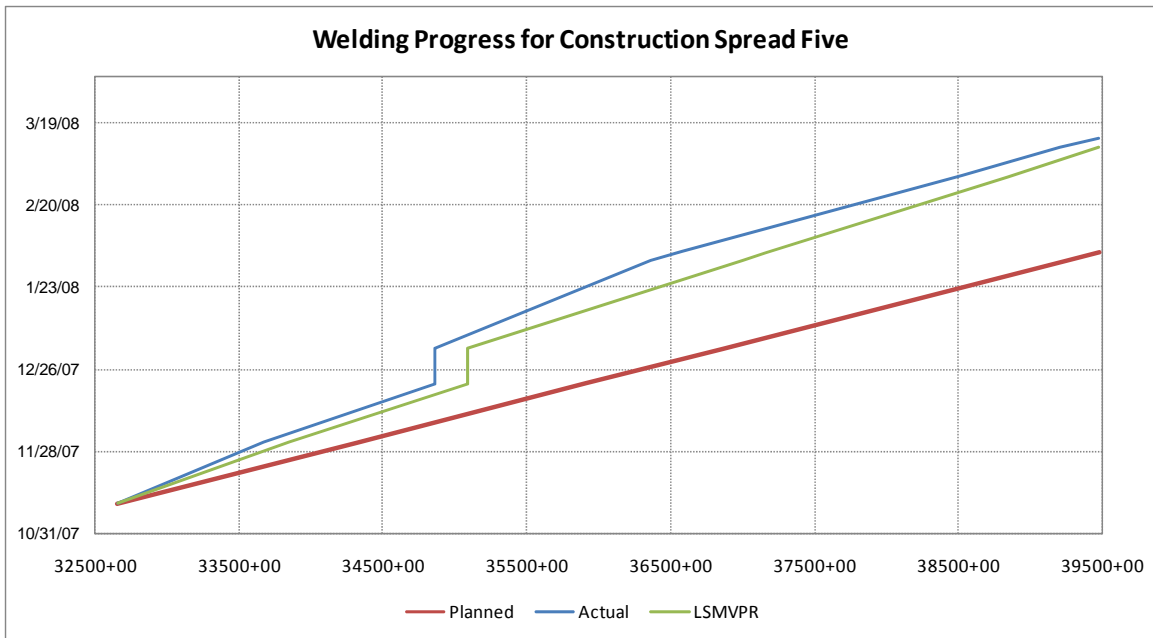


Figure 49 – Comparison of Welding Progress for Construction Spread Five

The progress calculated or forecast using Velocity 1.0 closely approximates the actual progress achieved on the project. The forecast for welding is within a week of the actual progress with most of the forecast within a few days of the actual welding progress. Table 15 contains the start and end dates associated with the graph in Figure

49. Again, the duration calculated for welding using LSM_{VPR} algorithm within Velocity 1.0 very nearly matches that which was actually achieved.

Table 15 – Tabular Output of the Welding Comparison for Spread Five

Location	Station	Planned	Actual	LSM _{VPR}
Start	32654+31	11/10/07	11/10/07	11/10/07
End	39480+00	2/4/08	3/14/08	3/11/08
Difference	682,569 LF	86 days	125 days	122 days

*Days are shown as calendar days

The planned dates are taken from the contractor’s original schedule to perform the construction of spread five. The schedule provided by the contractor provided no contingency for weather delays and simply stipulated that the schedule would be extended in proportion to the weather delays. (At the time of this project, most pipeline construction contracts were being performed on a time and materials basis.) While this is an easy method for the contractor to negotiate time extensions, this does not provide a tool with which to manage the project. It is this unknown or seemingly unpredictable weather delay that leaves much ambiguity in pipeline construction schedules. Velocity 1.0 provides a tool to combat this unknown. Specifically if the algorithm for predicting production rates is continually updated and expanded to include additional historical data, the ability to forecast appropriate schedules continues to grow.

Summary

Velocity 1.0 is prototype software for applying the Linear Scheduling Model with Varying Production Rates to pipeline construction projects. Velocity 1.0 allows the scheduler to visualize changes in production when and where they will occur. The user

input is minimal and intuitive, while the output conveys a large amount of information on one chart. Velocity 1.0 has the ability to utilize readily available data, such as weather and terrain information for predicting linear schedules. The user can include additional production variables and incorporate updated regression formulas as historical data is collected. The breadth and depth of Velocity 1.0 continues to grow and improve with additional historical information.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The pipeline construction industry is vital to the installation of underground infrastructures throughout the world. The industry spends large sums to update and create pipeline infrastructure around the world. The current scheduling technologies used to plan pipeline construction projects are ill-suited for linear jobs. This research has accomplished two major objectives by development of the new LSM_{VPR} and the prototype software Velocity 1.0. The first of these objectives was to outline a framework to apply changes in production rates when and where they occur along the horizontal alignment of the project. The second objective was to illustrate, through the use of background color or API, the difficulty or ease of construction through the time-location chart.

Summary

A model for scheduling pipeline projects based on production rates that change with time and location, (and a combination of time and location) has been developed. This model allows the scheduler to predict and visualize changes in productions rates when and where they will occur along a given route. This provides the project team with

the ability to better understand how changes in the project plan and schedule will impact production rates for the project. The framework of LSM_{VPR} was developed through five phases including: data collection, development of a welding regression equation, development of the algorithm, creation of a prototype software, and finally model validation.

The data collected included two distinct types of information. The first is that of historical production rate information from the construction industry. The construction data was collected from four spreads of a 750 mile LNG pipeline project. The fifth spread on the same project was utilized for model validation. The second type of data utilized is the weather data collected from the National Climatic Data Center, which in most cases spanned a minimum of thirty years of data.

Upon completion of the data collection, the data was analyzed and checked for correlations to various production variables. It was found that the only activity to correlate was the welding activity. This is most likely due to the fact that welding was the driving activity of the pipeline construction project that was monitored and all other activities were scheduled around keeping continuous workflow of the welding process. Welding was found to correlate with the following production variables: average daily maximum temperature, average daily maximum wind speed, average daily precipitation, average slope of the terrain, and the average pipe joint length.

Next an algorithm was created that accounts for changes in production rates based on time and location. The algorithm incorporates regression equations into the process of calculating production rates and ultimately the linear schedule. While this research

focused on pipeline construction projects, the framework created around the algorithm can accommodate other types of linear projects, such as highway projects.

The calculations required by the algorithm are numerous and thus necessitated the development of prototype software to calculate the linear schedule. The software developed, Velocity 1.0, is a MS Excel based program that calculates a linear schedule based on user input of historical data, production rate regression coefficients, and project specific information. The output of the software is a linear schedule with a background based on the Activity Performance Index, which allows the user to better understand the production variables that affect the overall schedule.

Velocity 1.0 was then used for validation of the Linear Scheduling Model with Variable Production Rates. The construction data used to create the regression equation for the welding activity was based on four of the five spreads on a 750 mile pipeline project. The model was then applied to 130 miles of the remaining spread of construction to compare planned versus actual versus calculated (LSM_{VPR}). The results showed that that the method was very accurate at predicting the outcome of the construction spread and that the model is a valid progression of linear scheduling.

The framework derived and tested through this research provides a variation of linear scheduling that incorporates historical data and allows the user to derive schedules that indicate changes in production when and where they occur. LSM_{VPR} can be expanded to other types of linear projects and its abilities broadened with additional historical production rate information.

Conclusions

This research showed that the changes in production rates due to time and location can be modeled for use in predicting future construction projects. The model created for this purpose is LSM_{VPR} (Linear Scheduling Model with Variable Production Rates). Using LSM_{VPR} allows the scheduler to develop schedule durations based on minimal project information. The model also allows the scheduler to analyze the impact of various routes or start dates for construction and the corresponding impact on the schedule. The graphical format also allows the construction team to visualize the obstacles in the project when and where they occur due to a new feature called the Activity Performance Index (API). This index is used to color the linear scheduling chart by time and location with the variation in color indicating the variance in predicted production rate from the desired production rate.

Research Recommendations

This research has laid a foundation for developing linear schedules that take into account varying production rates when and where they occur. Further research could expand upon three major areas: data collected for additional site specific or project specific considerations, expanding the capability of Velocity 1.0 to include additional features, and expanding the data collected to include other types of linear projects.

This research focused on a narrow band of production variables which affect pipeline construction production rates. Additional data should be collected in the following categories: varying pipe sizes, right-of-way widths, urbanization, effects of

learning, site conditions, and geotechnical data. This information would help to broaden the useful range of the production rate equations and allow for a higher accuracy in predicting the production rates achieved in the field.

Expanding the abilities of Velocity 1.0 would also aid in the analysis of complex linear construction projects. Additional features that would improve the capabilities of Velocity 1.0 include the following:

- 1) Allow the ability to use multiple crews starting in multiple locations
- 2) The ability to model activities moving across the project in both directions
- 3) Incorporate non-linear activities into the scheduling model
- 4) Include additional activity types
- 5) Incorporate Bayesian updating methods to allow updating the production rate model while construction is in progress

Finally, the model could be applied to other types of linear projects. The framework developed can be applied to most any linear project. Expanding the range of linear projects would require collecting data corresponding to the activities in those projects.

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APPENDICES

APPENDIX A – CONSTRUCTION ACTIVITIES



Figure 50 – Pipe Stacked Prior to Stringing



Figure 51 – Pipe Being Transported Along the Project’s Right-of-way



Figure 52 – Stringing Pipe Along the Length of the Project



Figure 53 – Pipe Strung Along the Length of the Project



Figure 54 – Pipe Being Lined up for Welding



Figure 55 – Welding Crew Welding a Pipe Joint



Figure 56 – Coating Field Welds with Fusion Bonded Epoxy Coating

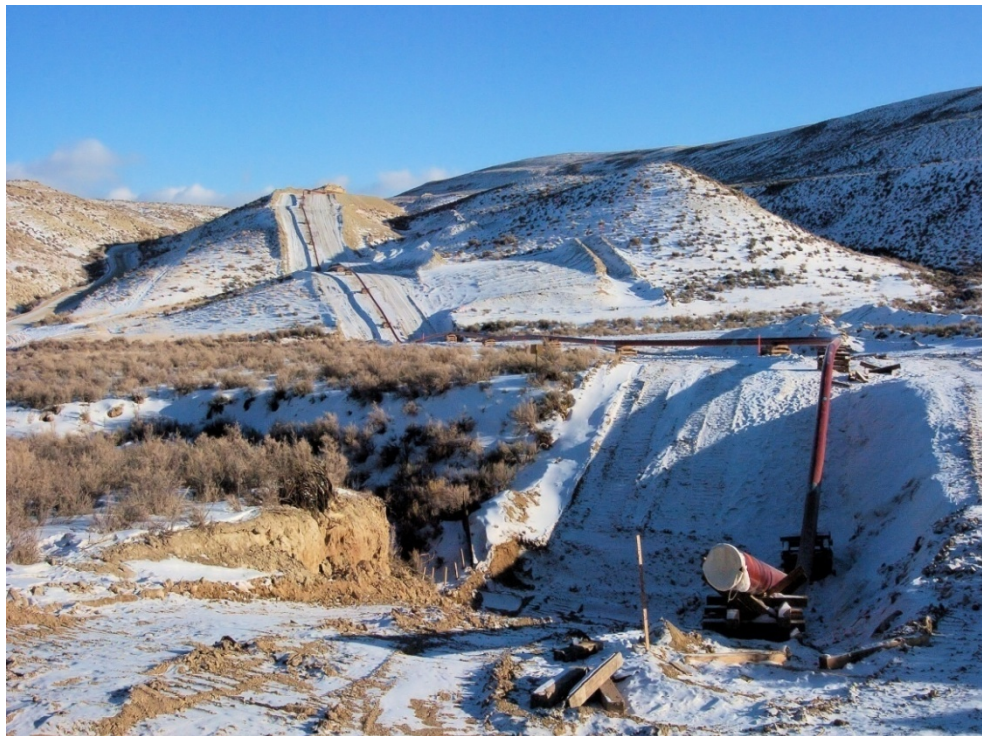


Figure 57 – Pipeline Welded and Supported on Wooden Skids



Figure 58 – Trenching with a Wheel Trencher



Figure 59 – Trenching with a Backhoe



Figure 60 – Trenching a Stream Crossing with a Backhoe



Figure 61 – Trenching a Stream Crossing with Cranes and Drag Lines



Figure 62 – Lowering-In the Pipeline



Figure 63 – Lowering-In a Stream Crossing with Portions of Concrete Coated Pipe



Figure 64 – Pipe Lowered into the Ditch



Figure 65 – Pipeline Being Backfilled

APPENDIX B – SPSS OUTPUT

Descriptive Statistics

	Mean	Std. Deviation	N
LF	7600.667331	2.4741411E3	251
AvgSlope	.010607	.0107530	251
MaxTemp	37.184064	13.5380938	251
MaxWind	22.589663	7.5599066	251
Precip	.002629	.0102107	251
AvgLengthJoint	67.801	10.0180	251

Variables Entered/Removed^b

Mode	Variables Entered	Variables Removed	Method
1	AvgLengthJoint, Precip, MaxWind, AvgSlope, MaxTemp ^a	.	Enter

a. All requested variables entered.

b. Dependent Variable: LF

Model Summary^b

Mode	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.659 ^a	.435	.423	1.8788454E3	1.517

a. Predictors: (Constant), AvgLengthJoint, Precip, MaxWind, AvgSlope, MaxTemp

b. Dependent Variable: LF

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	6.655E8	5	1.331E8	37.704	.000 ^a
	Residual	8.649E8	245	3530059.886		
	Total	1.530E9	250			

a. Predictors: (Constant), AvgLengthJoint, Precip, MaxWind, AvgSlope, MaxTemp

b. Dependent Variable: LF

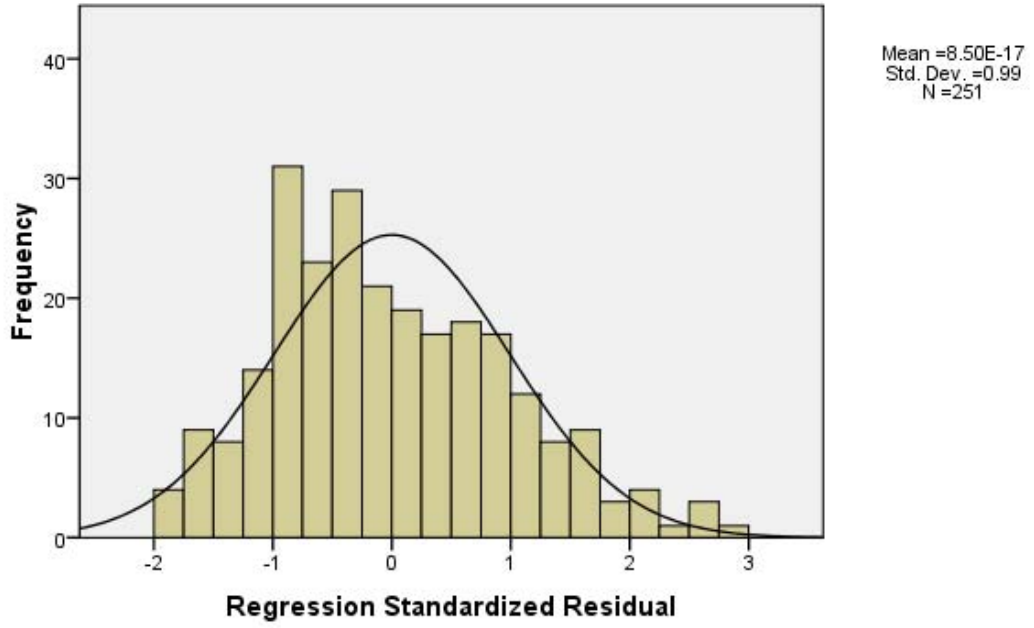
Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	3672.330	1061.795		3.459	.001		
	AvgSlope	-57951.923	11851.959	-.252	-4.890	.000	.869	1.150
	MaxTemp	31.840	10.111	.174	3.149	.002	.754	1.327
	MaxWind	-73.346	16.402	-.224	-4.472	.000	.918	1.089
	Precip	-34591.410	11790.726	-.143	-2.934	.004	.974	1.026
	AvgLengthJoint	75.323	14.553	.305	5.176	.000	.664	1.505

a. Dependent Variable: LF

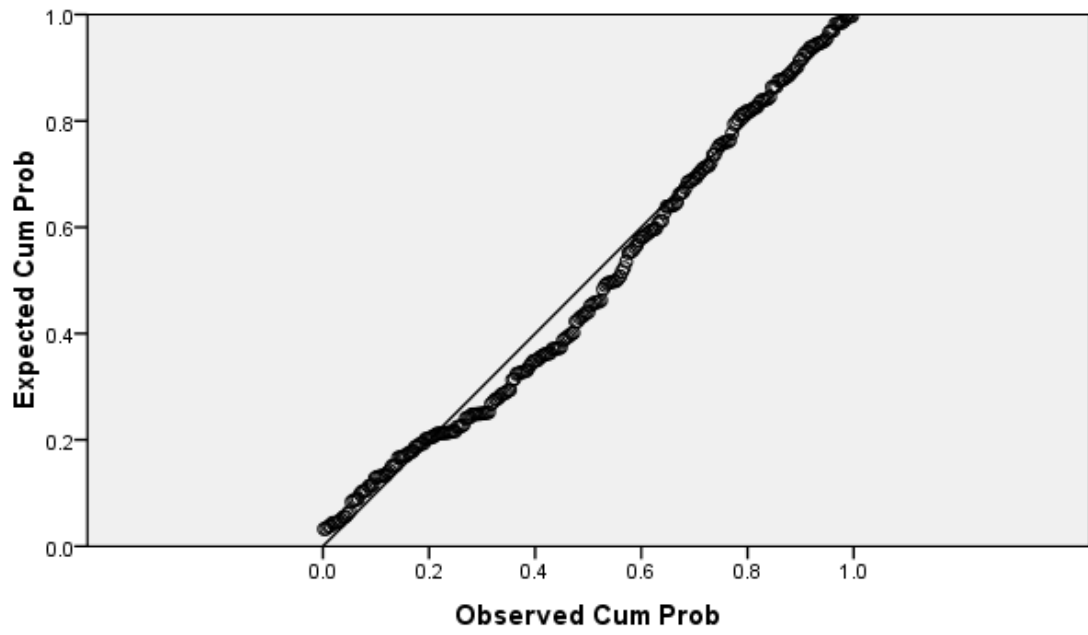
Histogram

Dependent Variable: LF



Normal P-P Plot of Regression Standardized Residual

Dependent Variable: LF



Casewise Diagnostics^a

Case Num	Std. Residual	LF	Predicted Value	Residual
1	1.213	5400.0000	7678.798847	2.2787988E3
2	-.094	7600.0000	7776.562652	-176.5626516
3	-.678	6600.0000	7873.755413	-1.2737554E3
4	.284	7658.0000	7125.075760	532.9242401
5	.417	7200.0000	6415.818440	784.1815600
6	.991	9400.0000	7538.825471	1.8611745E3
7	.634	8400.0000	7209.041726	1.1909553E3
8	.664	8400.0000	7152.489832	1.2475102E3
9	-.327	7000.0000	7614.580403	-614.5804035
10	.485	8200.0000	7287.950054	912.0499455
11	-.150	5200.0000	5481.682790	-281.6827898
12	.367	8000.0000	7311.335905	688.6640950
13	1.098	7724.0000	5660.402811	2.0635972E3
14	1.361	8676.0000	6119.576519	2.5564235E3
15	.853	8800.0000	7197.520942	1.6024791E3
16	-.195	5700.0000	6066.633331	-366.6333308
17	1.539	9342.0000	6450.870065	2.8911299E3
18	-.004	6188.0000	6195.564157	-7.5641572
19	-.561	3800.0000	4854.302391	-1.0543024E3
20	.006	6400.0000	6389.057180	10.9428204
21	1.097	8800.0000	6739.006815	2.0609932E3
22	-.969	3800.0000	5620.661094	-1.8206611E3
23	-.004	2979.0000	2986.643453	-7.6434528
24	-.674	2796.5000	4063.687470	-1.2671875E3
25	1.291	9200.0000	6773.722335	2.4262777E3
26	.246	7600.0000	7137.233530	462.7664695
27	.551	7820.0000	6784.594409	1.0354056E3
28	1.229	8852.0000	6542.399932	2.3096001E3
29	-1.086	4800.0000	6840.018876	-2.0400189E3
30	.890	7800.0000	6127.992762	1.6720072E3
31	-.888	4200.0000	5868.908619	-1.6689086E3
32	-1.114	5200.0000	7293.194019	-2.0931940E3
33	.242	8000.0000	7545.291285	454.7087155
34	-.953	5400.0000	7189.989920	-1.7899899E3
35	-.828	6248.0000	7803.044578	-1.5550446E3
36	-.591	5800.0000	6910.567254	-1.1105673E3
37	1.173	9552.0000	7348.190374	2.2038096E3
38	-.454	4800.0000	5653.468961	-853.4689614
39	.569	8400.0000	7330.657320	1.0693427E3
40	-1.123	4800.0000	6910.846107	-2.1108461E3

a. Dependent Variable: LF

Casewise Diagnostics^a

Case Num	Std. Residual	LF	Predicted Value	Residual
41	1.155	8600.0000	6429.143696	2.1708563E3
42	.481	4600.0000	3697.143119	902.8568811
43	-.672	3600.0000	4862.052659	-1.2620527E3
44	.691	6200.0000	4901.685592	1.2983144E3
45	.216	6200.0000	5795.100214	404.8997864
46	-1.251	4800.0000	7149.981036	-2.3499810E3
47	-.799	4200.0000	5702.063689	-1.5020637E3
48	-.419	1350.0000	2136.593509	-786.5935094
49	-.488	5200.0000	6117.362966	-917.3629656
50	-.447	5400.0000	6240.776811	-840.7768114
51	-.166	4400.0000	4711.263702	-311.2637022
52	-.797	5836.0000	7334.078690	-1.4980787E3
53	-.024	7364.0000	7408.763643	-44.7636429
54	-.354	3900.0000	4564.742280	-664.7422802
55	-.867	5600.0000	7228.046032	-1.6280460E3
56	-1.028	5300.0000	7232.352276	-1.9323523E3
57	-1.290	4800.0000	7224.461516	-2.4244615E3
58	-.177	5100.0000	5432.404406	-332.4044061
59	-.960	5600.0000	7403.093043	-1.8030930E3
60	.534	5600.0000	4596.582789	1.0034172E3
61	-.819	3800.0000	5338.275897	-1.5382759E3
62	.156	7400.0000	7106.680269	293.3197309
63	-1.198	4900.0000	7150.922505	-2.2509225E3
64	-.255	6400.0000	6878.520551	-478.5205508
65	.451	7800.0000	6952.786133	847.2138666
66	-.804	5300.0000	6810.046156	-1.5100462E3
67	-.120	7300.0000	7524.819003	-224.8190034
68	-.151	6900.0000	7184.002330	-284.0023300
69	.141	7140.0000	6875.431133	264.5688673
70	-.250	6100.0000	6569.290072	-469.2900719
71	-.757	5900.0000	7322.206252	-1.4222063E3
72	.525	7800.0000	6813.708333	986.2916672
73	.909	8700.0000	6991.649548	1.7083505E3
74	-.288	5000.0000	5540.483543	-540.4835433
75	-.757	5000.0000	6421.902785	-1.4219028E3
76	-.441	3900.0000	4728.618904	-828.6189042
77	-.264	6500.0000	6995.580027	-495.5800270
78	-.580	6000.0000	7088.902268	-1.0889023E3
79	-.927	1800.0000	3541.322410	-1.7413224E3
80	1.001	5700.0000	3818.418699	1.8815813E3

a. Dependent Variable: LF

Casewise Diagnostics^a

Case Num	Std. Residual	LF	Predicted Value	Residual
81	-.372	5000.0000	5696.409500	-696.4094997
82	-.326	5400.0000	6012.872722	-612.8727220
83	.889	7600.0000	5929.544357	1.6704556E3
84	1.100	7900.0000	5833.647269	2.0863527E3
85	.019	9000.0000	8963.924204	36.0757965
86	-.330	6400.0000	7019.515527	-619.5155274
87	.717	6900.0000	5552.904204	1.3470957E3
88	1.549	9100.0000	6190.481179	2.9095188E3
89	-.103	5700.0000	5893.987738	-193.9877385
90	.350	6000.0000	6656.714696	656.7146961
91	-.594	4200.0000	5316.262412	-1.1162624E3
92	.504	6600.0000	5652.815948	947.1840519
93	.482	6100.0000	7005.454628	905.4546280
94	2.251	10400.0000	6170.263309	4.2297367E3
95	.709	6400.0000	5068.762488	1.3312375E3
96	.909	7900.0000	6191.674446	1.7080256E3
97	1.202	8400.0000	6141.192561	2.2588074E3
98	1.160	8400.0000	6221.092070	2.1789079E3
99	2.601	12200.0000	7256.015882	4.9409841E3
100	-.679	5200.0000	6475.433610	-1.2754336E3
101	-.785	6000.0000	7475.157066	-1.4751571E3
102	-.279	9216.0000	9769.308888	-623.3088879
103	.927	10071.0000	8328.910008	1.7420900E3
104	-.680	6900.0000	8177.553223	-1.2775532E3
105	.378	8974.0000	8263.397462	710.6025379
106	-.439	7626.0000	8450.474422	-824.4744223
107	-.706	6100.0000	7425.894077	-1.3258941E3
108	.424	9100.0000	8302.595629	797.4043707
109	-.358	7400.0000	8073.021760	-673.0217596
110	-.169	8800.0000	9118.439983	-318.4399833
111	-.388	8282.0000	9010.423486	-728.4234862
112	-1.344	6200.0000	8725.561695	-2.5255617E3
113	-1.644	5508.0000	8597.402607	-3.0894026E3
114	-.365	7200.0000	7886.441955	-686.4419554
115	-1.771	4616.0000	7943.359749	-3.3273597E3
116	-1.846	5473.0000	8940.611722	-3.4676117E3
117	-.797	6078.0000	7574.706070	-1.4967061E3
118	-.008	8633.0000	8648.796070	-15.7960699
119	-.788	7274.0000	8755.422267	-1.4814223E3
120	-1.138	6983.0000	9121.175229	-2.1381752E3

a. Dependent Variable: LF

Casewise Diagnostics^a

Case Num	Std. Residual	LF	Predicted Value	Residual
121	.502	9661.0000	8718.682897	942.3171029
122	.129	9656.0000	9413.305004	242.6949962
123	.356	9353.0000	8684.886793	668.1132067
124	-.674	7747.0000	9013.082160	-1.2660822E3
125	-.823	5604.0000	7150.760668	-1.5467607E3
126	.240	9096.0000	8645.844463	450.1555375
127	.588	9752.0000	8648.051602	1.1039484E3
128	.089	9412.0000	9244.809060	167.1909396
129	-1.700	5142.0000	8335.128717	-3.1931287E3
130	.326	9194.0000	8581.008529	612.9914713
131	.688	9300.0000	8008.172780	1.2918272E3
132	.759	10328.0000	8901.761331	1.4262387E3
133	2.648	13472.0000	8497.747030	4.9742530E3
134	1.160	11308.0000	9129.191439	2.1788086E3
135	-.114	8812.0000	9025.407752	-213.4077525
136	-.951	5960.0000	7747.584637	-1.7875846E3
137	-.792	7520.0000	9008.112695	-1.4881127E3
138	.189	9340.0000	8985.233879	354.7661208
139	.989	11520.0000	9662.371018	1.8576290E3
140	-.328	8620.0000	9237.170026	-617.1700265
141	.936	10220.0000	8461.480227	1.7585198E3
142	.222	8300.0000	7883.467158	416.5328420
143	.993	11020.0000	9154.552833	1.8654472E3
144	.206	9180.0000	8792.936823	387.0631772
145	-.891	6800.0000	8473.791836	-1.6737918E3
146	-1.023	7700.0000	9622.502590	-1.9225026E3
147	-1.511	5500.0000	8338.003611	-2.8380036E3
148	-1.357	6000.0000	8549.180769	-2.5491808E3
149	-.752	5300.0000	6712.172789	-1.4121728E3
150	-1.112	4000.0000	6089.791480	-2.0897915E3
151	-1.124	5200.0000	7312.395340	-2.1123953E3
152	-.386	5286.0000	6011.185923	-725.1859229
153	.707	4815.0000	3486.356353	1.3286436E3
154	-.797	8722.0000	1.022012E4	-1.4981231E3
155	-1.683	6600.0000	9761.297731	-3.1612977E3
156	-.698	8632.0000	9943.488399	-1.3114884E3
157	-1.033	8447.0000	1.038874E4	-1.9417407E3
158	-1.589	5472.0000	8457.671298	-2.9856713E3
159	-1.204	7400.0000	9662.697855	-2.2626979E3
160	.489	10200.0000	9281.291730	918.7082704

a. Dependent Variable: LF

Casewise Diagnostics^a

Case Num	Std. Residual	LF	Predicted Value	Residual
161	.285	10400.0000	9864.889771	535.1102293
162	-.872	6800.0000	8438.711038	-1.6387110E3
163	-1.550	5520.0000	8431.317265	-2.9113173E3
164	-.920	8190.0000	9918.028686	-1.7280287E3
165	-1.836	6450.0000	9900.041970	-3.4500420E3
166	.231	9260.0000	8825.271482	434.7285175
167	-.933	7580.0000	9332.550550	-1.7525505E3
168	-1.261	6400.0000	8769.983505	-2.3699835E3
169	-.193	8600.0000	8962.057856	-362.0578558
170	-.964	6500.0000	8310.381106	-1.8103811E3
171	.203	9300.0000	8918.518254	381.4817464
172	.136	8083.0000	7826.948305	256.0516950
173	-1.383	6029.0000	8627.450322	-2.5984503E3
174	-1.781	6600.0000	9946.022724	-3.3460227E3
175	-.867	7442.0000	9070.453009	-1.6284530E3
176	-.272	8600.0000	9110.191411	-510.1914114
177	2.122	11000.0000	7012.558876	3.9874411E3
178	-.352	7800.0000	8462.237629	-662.2376289
179	-.456	7800.0000	8657.380817	-857.3808171
180	-.321	8665.0000	9268.194889	-603.1948891
181	.060	9420.0000	9307.665298	112.3347020
182	1.193	9420.0000	7178.303013	2.2416970E3
183	1.614	11315.0000	8282.609822	3.0323902E3
184	1.252	11200.0000	8847.564105	2.3524359E3
185	.567	9800.0000	8734.013769	1.0659862E3
186	-1.707	5385.0000	8592.034179	-3.2070342E3
187	-.677	6580.0000	7852.718043	-1.2727180E3
188	2.642	13130.0000	8166.386299	4.9636137E3
189	1.557	11340.0000	8414.004072	2.9259959E3
190	1.377	11880.0000	9292.911867	2.5870881E3
191	-1.702	5080.0000	8278.625523	-3.1986255E3
192	-.105	9800.0000	9997.099360	-197.0993598
193	.630	10076.0000	8891.405797	1.1845942E3
194	-.566	8005.0000	9068.572387	-1.0635724E3
195	.559	10504.0000	9454.377218	1.0496228E3
196	.269	9920.0000	9413.716687	506.2833127
197	.939	10900.0000	9135.031923	1.7649681E3
198	.429	9900.0000	9094.095445	805.9045548
199	.969	11800.0000	9979.820647	1.8201794E3
200	1.279	11400.0000	8996.218054	2.4037819E3

a. Dependent Variable: LF

Casewise Diagnostics^a

Case Num	Std. Residual	LF	Predicted Value	Residual
201	-.390	7480.0000	8212.193135	-732.1931352
202	1.017	11220.0000	9309.049171	1.9109508E3
203	1.434	12300.0000	9605.861569	2.6941384E3
204	.703	10700.0000	9379.718084	1.3202819E3
205	-1.069	5600.0000	7608.164201	-2.0081642E3
206	-1.111	7000.0000	9087.627578	-2.0876276E3
207	.820	11300.0000	9760.172065	1.5398279E3
208	1.874	13100.0000	9578.261248	3.5217388E3
209	-.541	9600.0000	1.061707E4	-1.0170708E3
210	.876	10200.0000	8554.631096	1.6453689E3
211	.042	10200.0000	1.012128E4	78.7172463
212	2.824	14800.0000	9493.422212	5.3065778E3
213	-1.363	7400.0000	9959.970720	-2.5599707E3
214	-.041	6627.0000	6704.841657	-77.8416573
215	-.546	4973.0000	5998.209258	-1.0252093E3
216	-.621	4567.0000	5734.196643	-1.1671966E3
217	.831	5600.0000	4038.360184	1.5616398E3
218	1.469	7500.0000	4740.073989	2.7599260E3
219	1.599	8000.0000	4994.994008	3.0050060E3
220	.912	7800.0000	6086.127270	1.7138727E3
221	.362	5600.0000	4920.463075	679.5369255
222	.355	7800.0000	7132.477541	667.5224593
223	-.833	4400.0000	5965.766449	-1.5657664E3
224	1.830	10400.0000	6962.046377	3.4379536E3
225	-.836	5900.0000	7470.485031	-1.5704850E3
226	2.166	11600.0000	7530.600663	4.0693993E3
227	-.010	7100.0000	7118.604556	-18.6045562
228	-.698	4850.0000	6160.982451	-1.3109825E3
229	-1.265	5175.0000	7551.534702	-2.3765347E3
230	-.556	5233.0000	6277.635864	-1.0446359E3
231	-.743	5452.0000	6847.849154	-1.3958492E3
232	-.668	4800.0000	6055.130908	-1.2551309E3
233	-.447	5500.0000	6338.986282	-838.9862822
234	-.785	5670.0000	7143.967239	-1.4739672E3
235	-.609	5530.0000	6673.293382	-1.1432934E3
236	-.794	4200.0000	5691.544451	-1.4915445E3
237	-.404	9600.0000	1.035880E4	-758.7988972
238	1.656	11800.0000	8688.048247	3.1119518E3
239	1.594	12600.0000	9604.576796	2.9954232E3
240	-1.603	4500.0000	7512.103850	-3.0121039E3

a. Dependent Variable: LF

Casewise Diagnostics^a

Case Num	Std. Residual	LF	Predicted Value	Residual
241	2.144	13700.0000	9670.974643	4.0290254E3
242	-.101	9600.0000	9790.445151	-190.4451509
243	.358	10000.0000	9326.829907	673.1700929
244	1.707	13200.0000	9992.975937	3.2070241E3
245	1.872	14000.0000	1.048286E4	3.5171396E3
246	1.480	12890.0000	1.010853E4	2.7814683E3
247	1.634	13010.0000	9940.532455	3.0694675E3
248	.167	9900.0000	9586.103619	313.8963815
249	-.014	9440.0000	9466.311146	-26.3111459
250	2.111	13560.0000	9594.526025	3.9654740E3
251	-.681	8536.0000	9815.633962	-1.2796340E3

a. Dependent Variable: LF

APPENDIX C – VELOCITY 1.0 CODE

Scheduling Routine

Sub Schedule()

```
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
'XXX Schedule Calculates the Vertices of all activities allowing for iteration to handle   XXX
'XXX the lead required for proper activity separation and continuous work flow.          XXX
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

Application.ScreenUpdating = False

'Assign initial values for the project and the first activity

```
WorkHours = Sheets("Setup").Cells(11, 3).Value / 24
StartDate = Sheets("Setup").Range("C9").Value + 7 / 24
StartStation = Sheets("Setup").Range("C7").Value
EndStation = Sheets("Setup").Range("C8").Value
FirstWW = Sheets("Setup").Range("p9").Value
ActivityCount = 0
Activity = Sheets("Activity").Cells(ActivityCount + 4, 3).Value
ActivityID = Sheets("Activity").Cells(ActivityCount + 4, 1).Value
ActivitiesTotal = Sheets("Activity").Cells(4, 24).Value
InitialLead = Sheets("Activity").Cells(ActivityCount + 3, 1).Value
```

'Assign values used for calculating the Working Window for production rate calculation

```
icount = 0
i = Sheets("Setup").Cells(9, 14).Value
jcount = 0
j = Sheets("Setup").Cells(9, 15).Value
```

'Assign Working Window Attributes to start the first activity

```
WWLE = Sheets("PV Grid").Cells(472, i + 1)
WWTE = Sheets("PV Grid").Cells(j, 8) + WorkHours
```

'Assign the initial activity starting position

```
ALS = StartStation
ATS = StartDate
```

'Assign counters used to write the vertices of the activities to the Vertices Spreadsheet

```
x = 2
y = 1
```

'Clear prior calculations

```
Sheets("Vertices").Range("A1:z1500").ClearContents
```

```
'Write the activity name, id, starting location, and start time of the first activity
```

```
Sheets("Vertices").Cells(x - 1, y).Value = ActivityID  
Sheets("Vertices").Cells(x - 1, y + 1).Value = Activity  
Sheets("Vertices").Cells(x, y).Value = ALS  
Sheets("Vertices").Cells(x, y + 1).Value = ATS
```

```
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  
'XXX Calculate the coordinates of all vertices for the first activity by looping through XXX  
'XXX given activities production rate sheet and applying the appropriate calculation. XXX  
'XXX The calculation type chosen is specified on the "Procuction Rates" worksheet as XXX  
'XXX either calculated or average. Calculated uses the empiracal data while average uses XXX  
'XXX the average rate input to the "Activity" worksheet. XXX  
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

```
Do
```

```
'Assign appropriate values to start the activities calculation
```

```
CurrentProduction = Worksheets(ActivityID).Cells(j, i).Value  
WWLE = Sheets("PV Grid").Cells(472, i + 1)  
WWTE = Sheets("PV Grid").Cells(j, 8) + WorkHours  
DR = WWLE - ALS  
TR = WWTE - ATS  
DTTR = CurrentProduction * TR
```

```
'This case occurs when the activity exits the Working Window at the intersection of the  
'WWLE and WWTE (the upper right corner of the Working Window).
```

```
If DTTR = DR Then
```

```
    i = i + 1  
    j = j - 1  
    ALE = WWLE  
    ATE = WWTE  
    ALS = ALE  
    ATS = Sheets("PV Grid").Cells(j, 8)
```

```
'This case occurs when the activity exits the Working Window through the WWLE or the  
'right side of the Working Window.
```

```
Elseif DTTR > DR Then
```

```
    i = (i + 1)  
    j = j
```

```

ALE = WWLE
ATE = (((DR / CurrentProduction) * WorkHours) + ATS)
ALS = ALE
ATS = ATE

```

'This case occurs when the activity exits the Working Window through the WWTE or the top of the Working Window.

```

Elseif DTTR < DR Then
  i = i
  j = j - 1
  ALE = ALS + DTTR
  ATE = WWTE
  ALS = ALE
  ATS = Sheets("PV Grid").Cells(j, 8)

```

End If

'Write the values of vertices of the activity to the "Vertices" Worksheet

```

x = x + 1
Sheets("Vertices").Cells(x, y).Value = ALE
Sheets("Vertices").Cells(x, y + 1).Value = ATE

```

Loop Until ALE = EndStation

AdditionalLead = 0

```

'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
'XXX Calculate the coordinates of the remaining activities using the same logic as above XXX
'XXX with the inclusion of a loop to determine if the separation between activities has XXX
'XXX been maintained according to the cell on the "Activity" worksheet. XXX
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

For ActivityCount = 1 To ActivitiesTotal - 1

```

Activity = Sheets("Activity").Cells(ActivityCount + 4, 3).Value
ActivityID = Sheets("Activity").Cells(ActivityCount + 4, 1).Value

```

```

x = 2
y = y + 4

```

Sheets("Vertices").Range(Cells(2, y), Cells(5000, y + 1)).ClearContents

```

InitialLead = Sheets("Activity").Cells(ActivityCount + 3, 19).Value
Lead = InitialLead + AdditionalLead
ALS = StartStation

```

```
ATS = Sheets("Vertices").Cells(2, y - 3).Value + Lead
```

```
i = Sheets("Setup").Cells(9, 14).Value
```

```
j = Application.Match(CDbI(ATS), Worksheets("PV Grid").Range("H:H"), -1)
```

```
Sheets("Setup").Cells(12, 14).Value = j
```

```
Sheets("Vertices").Cells(x - 1, y).Value = ActivityID
```

```
Sheets("Vertices").Cells(x - 1, y).Value = ActivityID
```

```
Sheets("Vertices").Cells(x - 1, y + 1).Value = Activity
```

```
Sheets("Vertices").Cells(x, y).Value = ALS
```

```
Sheets("Vertices").Cells(x, y + 1).Value = ATS
```

```
Do
```

```
CurrentProduction = Worksheets(ActivityID).Cells(j, i).Value
```

```
WWLE = Sheets("PV Grid").Cells(472, i + 1)
```

```
WWTE = Sheets("PV Grid").Cells(j, 8) + WorkHours
```

```
DR = WWLE - ALS
```

```
TR = WWTE - ATS
```

```
DTTR = CurrentProduction * TR
```

```
If DTTR = DR Then
```

```
    i = i + 1
```

```
    j = j - 1
```

```
    ALE = WWLE
```

```
    ATE = WWTE
```

```
    ALS = ALE
```

```
    ATS = Sheets("PV Grid").Cells(j, 8)
```

```
Elseif DTTR > DR Then
```

```
    i = (i + 1)
```

```
    j = j
```

```
    ALE = WWLE
```

```
    ATE = (((DR / CurrentProduction) * WorkHours) + ATS)
```

```
    ALS = ALE
```

```
    ATS = ATE
```

```
Elseif DTTR < DR Then
```

```
    i = i
```

```
    j = j - 1
```

```
    ALE = ALS + DTTR
```

```
    ATE = WWTE
```

```
    ALS = ALE
```

```
    ATS = Sheets("PV Grid").Cells(j, 8)
```

```
End If
```

```

x = x + 1
Sheets("Vertices").Cells(x, y).Value = ALE
Sheets("Vertices").Cells(x, y + 1).Value = ATE

```

```

Loop Until ALE = EndStation

```

```

CountVerticies = Application.WorksheetFunction.CountA(Range("Range" & ActivityCount
+ 1))

```

```

RowRank = 2
ColumnRank = y - 2

```

```

'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
'XXX  Writes the unique set of vertices from consecutive activities to column y-2      XXX
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

```

For Small = 1 To CountVerticies

```

```

    CurrentSmall = Application.WorksheetFunction.Small(Range("Range" & ActivityCount
+ 1), Small)

```

```

    PreviousSmall = Sheets("Vertices").Cells(RowRank - 1, ColumnRank)
    If CurrentSmall = PreviousSmall Then
        RowRank = RowRank
    Else: Sheets("Vertices").Cells(RowRank, ColumnRank).Value = CurrentSmall
        RowRank = RowRank + 1
    End If

```

```

Next Small

```

```

TotalNoVerticies = Application.WorksheetFunction.CountA(Range(Cells(2, y - 2),
Cells(5000, y - 2))) + 1

```

```

If ActivityCount = 1 Then
    Sheets("Vertices").Range(Cells(2, y - 1), Cells(TotalNoVerticies, y - 1)).Formula =
"=(IF(C2=Setup!$C$8,VLOOKUP(C2,E:F,2,FALSE),((C2-
INDEX(E:E,MATCH(C2,E:E,1)))/(INDEX(E:E,MATCH(C2,E:E,1)+1)-
INDEX(E:E,MATCH(C2,E:E,1))))*(INDEX(F:F,MATCH(C2,E:E,1)+1)-
INDEX(F:F,MATCH(C2,E:E,1))+INDEX(F:F,MATCH(C2,E:E,1))))-
(IF(C2=Setup!$C$8,VLOOKUP(C2,A:B,2,FALSE),((C2-
INDEX(A:A,MATCH(C2,A:A,1)))/(INDEX(A:A,MATCH(C2,A:A,1)+1)-
INDEX(A:A,MATCH(C2,A:A,1))))*(INDEX(B:B,MATCH(C2,A:A,1)+1)-
INDEX(B:B,MATCH(C2,A:A,1))+INDEX(B:B,MATCH(C2,A:A,1))))"
    Else
        Sheets("Vertices").Range("D2").copy Destination:=Range(Cells(2, y - 1),
Cells(TotalNoVerticies, y - 1))
        Worksheets("Vertices").Calculate
    End If

```

```

        SmallestLead = Application.WorksheetFunction.Small(Range(Cells(2, y - 1),
Cells(TotalNoVertices, y - 1)), 1)
        Sheets("Vertices").Cells(1, y - 1).Value = SmallestLead

```

```

'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
'XXX Checks the difference between the required lead and the minimum difference          XXX
'XXX calculated between the current activity and the previous activity.                XXX
'XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

```

If SmallestLead >= InitialLead Then
    ActivityCount = ActivityCount
    AdditionalLead = 0
    SmallestLead = 0
Elseif SmallestLead < InitalLead - 10 Then
    AdditionalLead = AdditionalLead + 10
    ActivityCount = ActivityCount - 1
    y = y - 4
    i = Sheets("Setup").Cells(9, 14).Value
    j = Application.Match(CDbl(ATS), Worksheets("PV Grid").Range("H:H"), -1)
    'Sheets("Vertices").Range(Cells(2, y), Cells(5000, y + 1)).ClearContents
Else
    AdditionalLead = AdditionalLead + 1
    ActivityCount = ActivityCount - 1
    y = y - 4
    i = Sheets("Setup").Cells(9, 14).Value
    j = Application.Match(CDbl(ATS), Worksheets("PV Grid").Range("H:H"), -1)
    'Sheets("Vertices").Range(Cells(2, y), Cells(5000, y + 1)).ClearContents

End If

```

```

Next ActivityCount

```

```

End Sub

```

Update Activity Production Rates Routine

```

Sub UpdateProdRates()
'
Application.ScreenUpdating = False

'Define starting variables
Dim x As Integer
Dim y As Integer
Dim WorkingDay As Integer
Dim ActivityTotal As Integer

```

```
Dim ActivityCount As Integer
Dim HowtoCalcProd As String
Dim ActivityID As Variant
Dim AverageProdRate As Single
```

```
ActivityTotal = Sheets("Activity").Range("X4").Value - 1
ActivityCount = 0
```

```
For ActivityCount = 0 To ActivityTotal
```

```
    HowtoCalcProd = Sheets("Activity").Cells(ActivityCount + 4, 2).Value
    ActivityID = Sheets("Activity").Cells(ActivityCount + 4, 1).Value
```

```
    'Check to see if the production rate is calculated by an average or with a regression equation
    'If it is with the average, loop through the activity's production rates
```

```
    If HowtoCalcProd = "Average" Then
```

```
        For y = 0 To 365
```

```
            AverageProdRate = Sheets("Activity").Cells(ActivityCount + 4, 4).Value
```

```
            WorkingDay = Sheets("PV Grid").Cells(450 - y, 13).Value
```

```
            Sheets(ActivityID).Cells(450 - y, 28).Value = AverageProdRate * WorkingDay
```

```
        Next y
```

```
        Sheets(ActivityID).Range("AB85:AB450").Copy
```

```
        Destination:=Sheets(ActivityID).Range("AC85:AFU450")
```

```
    'If the activity's production rate is calculated with a regression equation, assign variables
    'and loop through the activity's production rates
```

```
    Else
```

```
    'Define variables for production rates calculated from regression equations
```

```
    Dim PV1 As Single
```

```
    Dim PV2 As Single
```

```
    Dim PV3 As Single
```

```
    Dim PV4 As Single
```

```
    Dim PV5 As Single
```

```
    Dim PVConstant As Single
```

```
    Dim Data1 As Variant
```

```
    Dim Data2 As Variant
```

```
    Dim Data3 As Variant
```

```
    Dim Data4 As Variant
```

```
    Dim Data5 As Variant
```

```
    Dim ProductionVariables As String
```

```
    Dim CurrentProductionRate As Double
```

```
    'Assign regression coefficients and constant
```

```

PV1 = Sheets("Activity").Cells(ActivityCount + 4, 5).Value
PV2 = Sheets("Activity").Cells(ActivityCount + 4, 6).Value
PV3 = Sheets("Activity").Cells(ActivityCount + 4, 7).Value
PV4 = Sheets("Activity").Cells(ActivityCount + 4, 8).Value
PV5 = Sheets("Activity").Cells(ActivityCount + 4, 9).Value
PVConstant = Sheets("Activity").Cells(ActivityCount + 4, 15).Value

For y = 0 To 365
For x = 0 To 825

    WorkingDay = Sheets("PV Grid").Cells(450 - y, 13).Value

    If WorkingDay = 0 Then
        Sheets(ActivityID).Cells(450 - y, 28 + x).Value = 0
    Else
        ProductionVariables = Sheets("PV Grid").Cells(450 - y, 28 + x).Value

        Data1 = Left(ProductionVariables, 3)
        Data2 = (Mid(ProductionVariables, 5, 2))
        Data3 = (Mid(ProductionVariables, 8, 6))
        Data4 = (Mid(ProductionVariables, 15, 5))
        Data5 = (Mid(ProductionVariables, 21, 2))

        CurrentProductionRate = WorkingDay * (PV1 * Data1 + PV2 * Data2 + PV3 * Data3 +
PV4 * Data4 + PV5 * Data5 + PVConstant)
        check1 = PV1 * Data1
        check2 = PV2 * Data2
        check3 = PV3 * Data3
        check4 = PV4 * Data4
        check5 = PV5 * Data5

        If CurrentProductionRate < 0 Then
            Sheets(ActivityID).Cells(450 - y, 28 + x).Value = 0
        Else
            Sheets(ActivityID).Cells(450 - y, 28 + x).Value = CurrentProductionRate
            Sheets(ActivityID).Cells(450, 26).Value = 999
        End If
    End If

Next x
Next y

End If

Next ActivityCount

End Sub

```


API Routines (Update & Clear Background Color)

Sub ColorUpdate()

Application.ScreenUpdating = False

Dim Name As String

Dim x As Integer

Dim y As Integer

Dim ProdRate As Single

Dim DesiredProdRate As Single

Dim Ratio As Single

Dim ProdRateFive As Single

Dim ProdRateFour As Single

Dim ProdRateThree As Single

Dim ProdRateTwo As Single

Dim ProdRateOne As Single

Dim ProdRatePercentFive As Single

Dim ProdRatePercentFour As Single

Dim ProdRatePercentThree As Single

Dim ProdRatePercentTwo As Single

Dim ProdRatePercentOne As Single

'Set Colors for Assignment to Ratios of Production Rates

ProdRateFive = Sheets("Drop Down Ranges").Range("M2").Value

ProdRateFour = Sheets("Drop Down Ranges").Range("M3").Value

ProdRateThree = Sheets("Drop Down Ranges").Range("M4").Value

ProdRateTwo = Sheets("Drop Down Ranges").Range("M5").Value

ProdRateOne = Sheets("Drop Down Ranges").Range("M6").Value

ProdRatePercentFive = Sheets("Linear Schedule").Range("uW459").Value

ProdRatePercentFour = Sheets("Linear Schedule").Range("uW460").Value

ProdRatePercentThree = Sheets("Linear Schedule").Range("uW461").Value

ProdRatePercentTwo = Sheets("Linear Schedule").Range("uW462").Value

ProdRatePercentOne = Sheets("Linear Schedule").Range("uW463").Value

Name = Sheets("Setup").Range("I13")

DesiredProdRate = Sheets("Setup").Range("I14")

Sheets("Color").Cells(450, 28).Value = Name

For y = 0 To 365

For x = 0 To 825

```
ProdRate = Sheets(Name).Cells(450 - y, 28 + x).Value
Ratio = ProdRate / DesiredProdRate
```

```
'Select case to determine color number to apply
```

```
    Select Case Ratio
        Case Is > ProdRatePercentTwo
            ColorValue = ProdRateOne
        Case Is > ProdRatePercentThree
            ColorValue = ProdRateTwo
        Case Is > ProdRatePercentFour
            ColorValue = ProdRateThree
        Case Is > ProdRatePercentFive
            ColorValue = ProdRateFour
        Case Is <= ProdRatePercentFive
            ColorValue = ProdRateFive
```

```
    End Select
```

```
Sheets("Color").Cells(450 - y, 28 + x).Value = ColorValue
```

```
Next x
Next y
```

```
Call BackgroundColor
```

```
End Sub
```

```
Sub BackgroundColor()
```

```
'
```

```
' This macro updates the colors of the cells on the Linear Schedule based on the values of the Color tab.
```

```
' The cells have a direct match, in that the cell referenced from the Color tab is the colorindex for
```

```
' the same cell in the Linear Schedule.
```

```
'Set variable types
```

```
Dim x As Integer
```

```
Dim y As Integer
```

```
Application.ScreenUpdating = False
```

```
For y = 0 To 365
```

```
For x = 0 To 825
```

```
CellColor = Sheets("Color").Cells(450 - y, 28 + x).Value  
    Sheets("Linear Schedule").Cells(450 - y, 28 + x).Interior.Color = CellColor
```

```
Next x  
Next y
```

```
End Sub
```

```
Sub ClearBackground()  
,
```

```
' This macro clears the background of all cells in the Linear Schedule Chart
```

```
Application.ScreenUpdating = False
```

```
Sheets("Linear Schedule").Range(Cells(450, 28), Cells(85, 853)).Interior.Pattern = xlNone
```

```
End Sub
```

VITA

Gregory A. Duffy, PE, PLS, PMP

Candidate for the Degree of

Doctor of Philosophy

Dissertation: LINEAR SCHEDULING OF PIPELINE CONSTRUCTION PROJECTS
WITH VARYING PRODUCTION RATES

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Indianapolis, Indiana on July 5, 1976; the son of Patrick A. and Martha J. Duffy.

Education: Received Bachelor of Science in Construction Management from Oklahoma State University, Stillwater, Oklahoma in May 2002; received Bachelor of Science in Civil Engineering from Oklahoma State University, Stillwater, Oklahoma in May 2003; received Master of Science in Civil Engineering from Oklahoma State University, Stillwater, Oklahoma in December 2003; completed requirements for Doctor of Philosophy in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May 2009.

Experience: Project Controller for Willbros Engineers Inc., 2007 to present; Director of Engineering and Surveying for Tanner Consulting LLC, 2006 to 2007; Adjunct Professor for Oklahoma State University, 2004 to 2007; Project Manager for Stillwater Engineering, 2001 to 2006; Project Engineer for Stillwater Engineering, 1998 to 2001.

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Name: Gregory A. Duffy

Date of Degree: May, 2009

Institution: Oklahoma State University

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Title of Study: LINEAR SCHEDULING OF PIPELINE CONSTRUCTION PROJECTS
WITH VARYING PRODUCTION RATES

Pages in Study: 158

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Scope and Method of Study: The purpose of this research was to expand the capabilities of linear scheduling to account for varying production rates in pipeline construction when and where they occur. This new linear scheduling model, Linear Scheduling Model with Varying Production Rates (LSM_{VPR}) had two objectives. The first of these objectives was to outline a framework to apply changes in production rates when and where they occur along the horizontal alignment of the project. The second objective was to illustrate the difficulty or ease of construction through the time-location chart.

Findings and Conclusions: This research showed that the changes in production rates due to time and location can be modeled for use in predicting future construction projects. The model created for this purpose is the Linear Scheduling Model with Varying Production Rates. Using LSM_{VPR} allows the scheduler to develop schedule durations based on minimal project information. The model also allows the scheduler to analyze the impact of various routes or start dates for construction and the corresponding impact on the schedule. The graphical format allows the construction team to visualize the obstacles in the project when and where they occur due to a new feature called the Activity Performance Index (API). This index is used to shade the linear scheduling chart by time and location with the variation in color indicating the variance in predicted production rate from the desired production rate.

ADVISER'S APPROVAL: Dr. Garold Oberlender
