Advanced Alignment-Based Scheduling with Varying Production Rates for Horizontal Construction Projects

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ABSTRACT: Horizontal construction projects such as oil and gas pipeline projects typically involve repetitive-work activities with the same crew and equipment from one end of the project to the other. Repetitive scheduling also known as linear scheduling is known to have superior schedule management capabilities specifically for such horizontal construction projects. This study discusses on expanding the capabilities of repetitive scheduling to account for the variance in production rates and visual representation by developing an automated alignment based linear scheduling program for applying temporal and spatial changes in production rates. The study outlines a framework to apply changes in productions rates when and where they will occur along the horizontal alignment of the project and illustrates the complexity of construction through the time-location chart through a new linear scheduling model, Linear Scheduling Model with Varying Production Rates (LSM_{VPR}). The program uses empirically derived production rate equations with appropriate variables as an input at the appropriate time and location based on actual 750 mile natural gas liquids pipeline project starting in Wyoming and terminating in the center of Kansas. The study showed that the changes in production rates due to time and location resulted in a close approximation of the actual progress of work as compared to the planned progress and can be modeled for use in predicting future linear construction projects. 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. In addition, the graphical format lets 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.

Key Words: project scheduling, linear scheduling method, pipeline construction project, production rate, project planning

1. INTRODUCTION

Project scheduling is one of the fundamental components in project management besides cost, quality and scope. The advancement in project scheduling techniques and approaches has led to the emergence and utilization of tools such as bar charts and critical path method (CPM). Although these techniques are the most widely accepted tools in scheduling projects, they lack detail especially in scheduling horizontal construction projects such as oil and gas pipeline construction projects and might not be the optimal scheduling solutions. Typically, horizontal construction projects are characterized by the use of continuous, linear-type work activities which involve the same crew and equipment from one end of a project to the other. In these types of construction projects, the main concern is assessing the rate of progress or production rates of the work activities rather than their sequence. In this regard, linear scheduling method has proved to have better potential than bar charts and critical path method (CPM) in scheduling horizontal construction projects.

Linear scheduling method (LSM) is an effective scheduling technique that supports the continuous utilization of resources based on time-location chart. LSM has the ability to portray the changes of production rates along with a multitude of graphical capabilities. These graphics and intuitiveness will support the construction personnel to better visualize the plan of action and easily communicate the plan with other project participants. LSM allows a) visual (2-D) representation of the job, b) ability to show the gaps and obstacles in a project which aids in managing risks, and c) better capability for analyzing claims. Various studies have been conducted in predicting production rates based on simulation, probability and regression analysis (Chao Skibniewski 1994, Smith 1999, Kuo 2004, O'Connor and Huh 2005, Jiang and Wu 2007). However, there is not significant research conducted in determining when and where production rates change along a project's alignment.

This study presents a framework to apply temporal and spatial changes in production rates along a horizontal alignment of a project supported by empirically derived production equations. This study shows the capabilities of linear scheduling that accounts for the variance in production rates by developing a Linear Scheduling Model with varying Production Rates (LSM_{VPR}) to illustrate the complexity of construction through a time-location chart. The developed model has the ability to utilize readily available data or variables such as weather and terrain information for predicting linear schedules. This allows project teams to better understand how and when the production variables affect the construction progress throughout the length of a project. In addition, it allows the scheduler to analyze the impact of various routes and/or start dates for construction and the corresponding impact on schedule. Furthermore, the construction team can visualize obstacles in a project due to a new feature, Activity Performance Index (API) which colors the linear schedule chart by time and location to indicate the variation in predicted production rate from desired production rate.

2. BACKGROUND

Nowadays, the Critical Path Method (CPM) uses a network logic diagram to display interdependencies between activities which make it one of the most widely accepted scheduling techniques. However, the CPM has certain limitations on certain aspects in scheduling linear projects. Some of these limitations include: difficulty to accurately model the continuity of resources; arbitrary division of repetitive activities from location to location; no indication of activity rates of progress; and loss of information on the location of the current work being performed (Mattila and Park, 2003, Hamerlink and Rowings 1998, and Chrzanowski and Johnston 1986). The term linear scheduling method (LSM) was first introduced to the highway construction industry by Johnston (1981). He utilized production rates, activity interruptions, buffers, calendar considerations, and project resources to develop linear schedules for highway construction projects. In 1986, Chrzanowski, Jr. and Johnston (1986) added to Johnston's previous work by comparing and contrasting CPM and LSM utilizing an as-built highway schedule. Nine years later, Harmelink (1995) developed a model of linear scheduling in conjunction with an AutoCAD-based program. His work focused on proving that computerization of linear scheduling is possible and illustrating procedures to identify the controlling activity path in the schedule. Figure 1 shows some of the academic works conducted in the application of LSM and production rates in the horizontal construction industry.

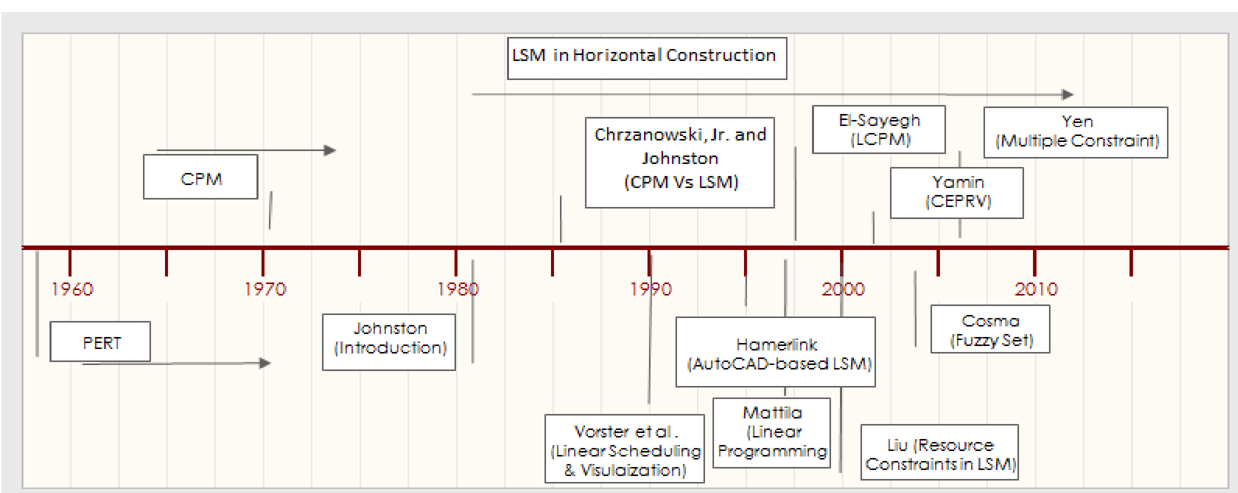

Figure 1 Application of LSM in Horizontal Construction

In 1998, El-Sayegh developed a windows-based software package named "Linear Construction Planning Model" (LCPM) which comprises of deterministic and probabilistic models for calculating resource-based linear schedules based on user input and Monte Carlo simulation respectively. Liu (1999) defined a method for evaluating resource constraints in linear schedules by utilizing a heuristic approach in scheduling resources that allows the user to input certain criteria to support decisions on resource usage and allocation. Yamin (2001) developed an approach to analyze the cumulative effects of production rate variability (CEPRV) on linear activities in highway projects. Other linear scheduling model studies include Vorster et al. (1992), Mattila (1997), Harmelink & Rowings (1998), Herbsman (1999), Cosma (2003), and Yen (2005). It is important to note that LSM can also be applied to vertical constructions such as multiunit housings and high rise buildings (referred as point-based scheduling), however this study primarily focuses on location-based (alignment-based) scheduling projects.

3. LSM SOFTWARE PROGRAMS

A search for software packages capable of producing alignment-based linear scheduling revealed commercially available products such as Chainlink (England), LinearPlus (England), Spider Project Professional (Russia), TILOS (England/Germany), and Time Chainage (England). Table 1 illustrates comparisons of these programs on a set of criteria (based on data input and interface, output capabilities and adaptability) in scheduling pipeline construction projects. Based on the comparisons, Linear Plus and TILOS displayed the most potential for use by the pipeline industry in the US. In particular, 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. While Chainlink, Spider Project, Time Chainage offer excellent solutions for producing linear schedules, they lack some basic features which might make it challenging for acceptance in the U.S. market. For example, Time Chainage would be more advantageous for pipeline contractors in the US 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.

Table 1 – 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

4. LSM_{VPR}

This study presents the development of linear scheduling method with varying production rates (LSM_{VPR}) as a framework for applying temporal and spatial production rate changes in a given horizontal construction project. The LSM_{VPR} uses the concept of *working windows* (WW) which adds the visual nature for linear scheduling. The WW has a similar concept to the working windows of elements in finite element method (FEM) of structural analysis, which requires mesh discretization of a continuous domain into a set of discrete sub-domains.

A working window is a time-space rectangle with a homogenous set of variables that affect the construction production rate. Working windows are areas of time and location for which unique production variables can be assigned. Traditionally, linear schedule depicts the entire time and location when and where the construction is proposed, while in LSM_{VPR} the project's entire time-location chart (TLC) is sliced into a grid of smaller cells on a user-defined interval in which the cells depict the project's working windows represented by WW_{ij}; where *i* denotes the column and *j* denotes the row. LSM_{VPR} is unique in such a way that given the *i* and *j* coordinates for the working window, one can looks up for appropriate production variables to be applied to specific working window. This approach allows both time and location related variables that affect the production rate of the WW to be appropriately and visually modeled in the project schedule. Therefore, working windows display the when and where production variables may change along the linear project.

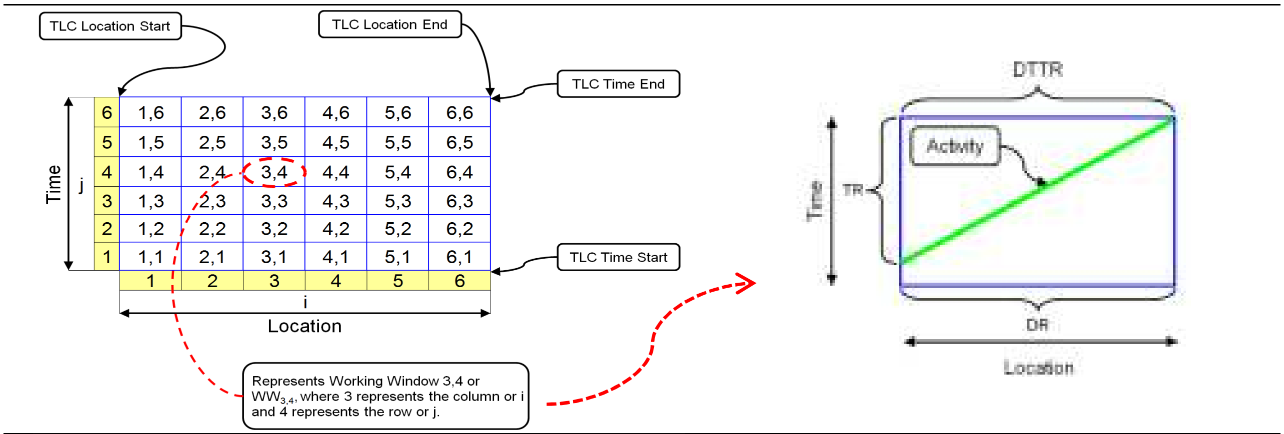

Figure 2 Working Windows on Time-Location Chart

LSM_{VPR} uses terminologies Distance Remaining (DR) and Time Remaining (TR) to depict information necessary for making calculations in developing a linear schedule. The DR is the amount of distance that has not been completed in the current WW when an activity starts in that window, while the TR is the amount of time remaining in the current WW when an activity starts in that window. DR and TR are used to determine the movement of an activity through the linear scheduling chart; the movement from one WW to another WW. A term called Distance Traveled in Time Remaining (DTTR) is also used to compare it with the DR and determine exit location. The LSM_{VPR} uses a forward and backward pass methodology to develop variable production rate linear schedules. The forward pass schedules an activity using the Minimum Lead (ML) specified from an activity input stage. The ML is the minimum separation between activities based on time units. For initial calculation, the Activity Separation (AS) is set to the ML. The AS 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 an activity. During the backward pass, the time difference between every vertex of both activities being scheduled and the preceding one is calculated. This process creates an iterative loop until the minimum separation of time calculated between the two activities is greater than or equal to the Minimum Lead. This looping nature is necessary, due to the possibility of incurring varying production rates for iteration purpose to ensure the ML is satisfied.

Another unique concept introduced in LSM_{VPR} is the Activity Performance Index (API) to provide the user with additional information about the production rates predicted within each working window. The API is a color scheme that indicates the status of production rates on the project. The color indicates the relationship between a user-defined production rate (PR_{UD}) and the calculated production rate (PR_{ij}), which is a most likely rate based on historical data (derived from production rate prediction equations and using LSM_{VPR}). The API is calculated by dividing production rate (PR_{ij}) to the user-defined production rate (PR_{UD}) and associated with a color scheme with red indicating very poor performance, and green indicating favorable performance with regard to the desired production rate. This visual aid helps the scheduler easily determine the time-locations that may be problematic for construction and determining optimal starting locations and dates for the crews along the horizontal alignment, providing a valuable front-end planning tool. Figure 3 shows the overview of the algorithm for LSM_{VPR}.

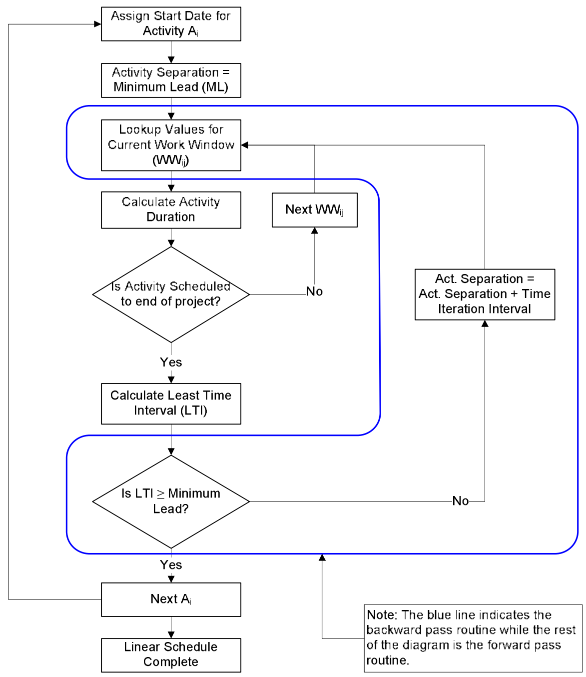

Figure 3 LSM_{VPR} Algorithm

5. DATA COLLECTION

The main objective of the data collection is to incorporate the variables or factors in determining production rates in actual pipeline construction project (Table 2). Field production rate data was obtained from a 750 mile natural gas liquids pipeline project which starts in Wyoming, spanning the Rocky Mountains and terminates in the center of Kansas. The project was broken up into five spreads or segments, each approximately 150 miles in length. Production rate data was acquired on a daily basis by construction inspectors from the progress of construction activities based on a data entry form and coding system developed. The form captures the start and end of each activity along with crew and equipment makeup, length of work done, type of rock encountered as well as a general site condition and ground condition which can aid in the validation of correlating the weather data. Weather data was collected along the length of the project from stations within the National Climatic Data Center (NCDC) network. It should be noted that construction was performed with six day work weeks consisting of ten hour days. The production rate data collected was obtained from activities being performed by similar equipment and similar crew makeup. Once, production rate data is collected through inspectors, it is transferred into MS Excel and stored in a master database.

6. MODEL DEVELOPMENT

Multiple regression models were utilized to develop production rates for major pipeline construction activities. The production variables that were employed in the model include mean temperature, minimum temperature, maximum temperature, average wind speed, maximum wind speed, precipitation, pipe length, number of welders, number of workers, elevation, slope of terrain, work week and holiday schedule. In order to ensure a valid regression analysis and determine a reliable fit, the existence of a large enough sample size is first checked based on power analysis. Then, the distribution is tested to ensure the dependent and independent variables were approximately normally distributed. Box plots were utilized and analyzed the standardized residuals to remove outliers. A regression model is then fit and checked for collinearity among variables selected for the model and the model is validated using coefficient of determination, R^2. Finally, correlations were tested among the activities for the production variables. Regression analysis was performed by utilizing statistical software package SPSS®.

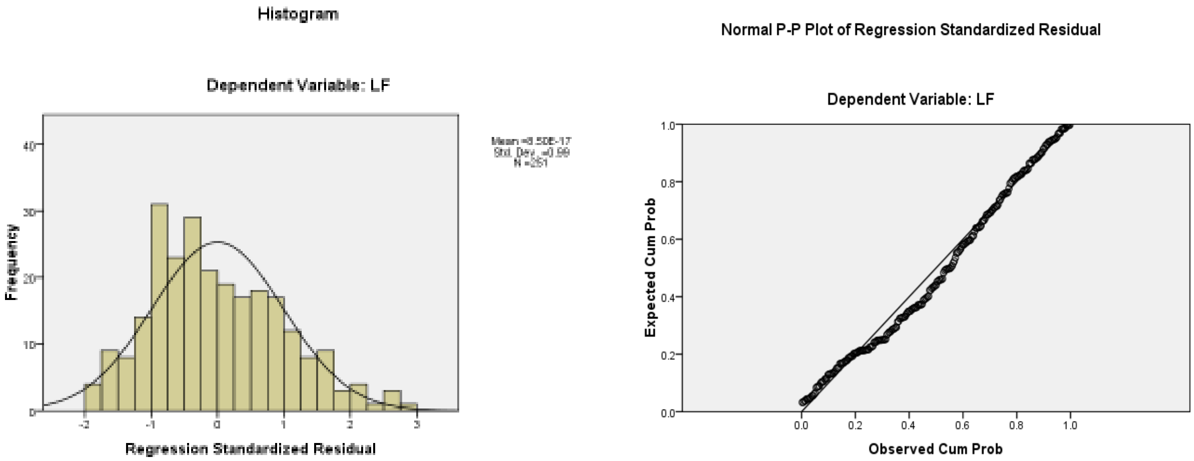

Figure 4 Regression Standardized Residual for Welding Activity

The results reveal that the production variables examined were found only to correlate with the welding activity. The production variables that significantly affect welding activity include maximum temperature, maximum wind speed, precipitation, average pipe joint length, and slope of terrain. This may be attributed to the fact that a) welding is the driving activity for pipeline construction, b) important production variables were not incorporated (or missing), and c) different methods should have been used in measuring progress. The fitted model for welding activity resulted in an R^2 of 0.435 and a p-value of 0.000. Figure 4 shows the distribution and normal p-p plot of regression standardized residual for welding activity. Since welding is typically the driving activity for pipeline projects, all other activities are scheduled to ensure welding continues without interruption. This could cause the production rates of other activities to appear sporadic and disrupt natural correlations which may exist with the given activities had they no tie to welding.

7. VELOCITY 1.0

This study has developed an automated alignment based linear scheduling software program using MS Excel called Velocity 1.0 to process the calculations required for implementing the algorithm utilized in LSM_{VPR}. Sub-routines not accomplished within the workbook are performed in Visual Basic for Applications (VBA) through the use of macros. The program consists of tabs within an Excel workbook that walk the user through the data entry process. An input tab of information for example, is set to determine the overall route input and working times, calculation parameters, and 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. Other tabs include activity tab which is set to allow the user to enter the activities that take place on the project and input additional information about the specific activities and output tab which results in a linear schedule which depicts production rate variance. The output tab includes the start and end parameters of the chart, the interval for both the horizontal and vertical grid, and the activity performance index (API) that is displayed on the chart background. Figure 5 shows a magnified linear schedule output from velocity 1.0.

The color pattern in the background depicts the relationship between the contractor's planned production rate for welding and the expected production rate utilizing LSM_{VPR} via the Activity Performance Index. This allows the user to see an averaged view without the interference of the day to day variances. The schedule displays a red row every seven days depicting the Sundays not worked due to a six day work week selection and a large band of red across the page for the winter holiday. 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 on the first 50,000 feet of the chart which indicates worse weather and terrain conditions for this time and location of the project. The API associated with welding quickly shows the user if the production rate is realistic. The user can continue to adjust the desired production rate down until the API calculation yields a more favorable green background. 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.

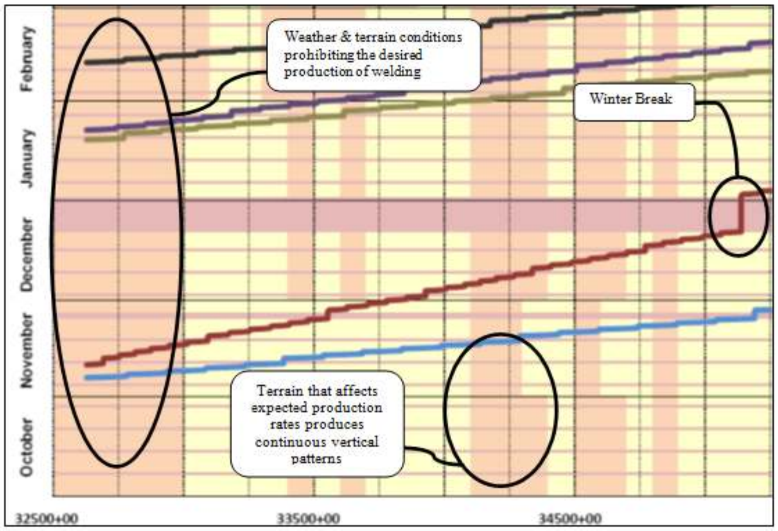

Figure 5 Magnified View of the Linear Schedule developed by Velocity 1.0

8. VALIDATION

The first four spreads of construction data were used to develop the regression models while the fifth spread is utilized for validation of the model. Spread 5 runs 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). Once the project data was input, Velocity 1.0 was run to provide a linear schedule and the output was compared with planned and actual progress of the project. 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. Based on the analysis, the progress and duration calculated using Velocity 1.0 nearly matches that which was actually achieved on the project (Figure 6). 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.

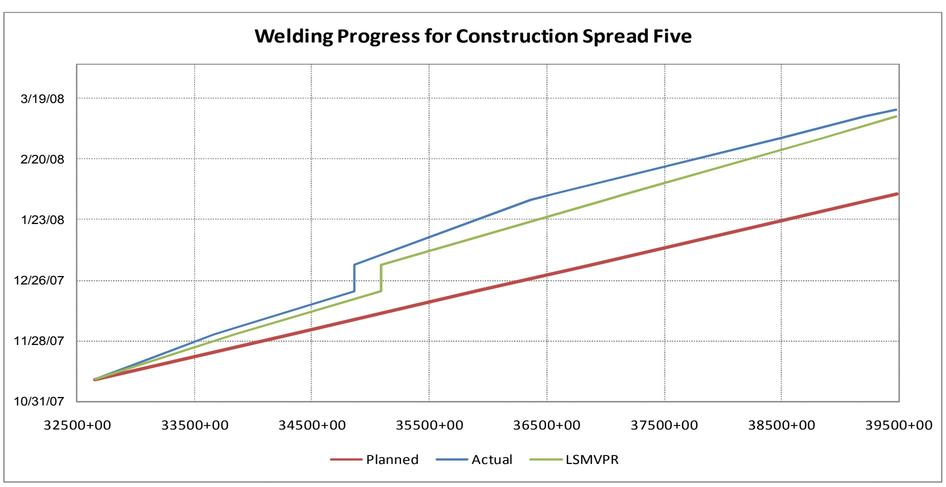

Figure 6 Comparison of Welding Progress for Construction Spread Five

9. SUMMARY & CONCLUSION

The study showed that changes in production rates due to time and location resulted in a close approximation to an actual progress of work as compared to the planned progress and thus can be modeled for use in predicting future linear construction projects. The study developed an automated alignment based linear scheduling software program called Velocity 1.0 based on the Linear Scheduling Model with Varying Production Rates (LSM_{VPR}) framework. The model uses empirically derived production rate equations with appropriate variables as an input at the appropriate time and location based on actual a 750miles pipeline construction project.

LSM_{VPR} allows the scheduler to develop schedule durations based on minimal project information. It also allows the scheduler to analyze the impact of various routes or start dates for construction and the corresponding impact on the schedule. In addition, a graphical format of the model lets 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 provides a project team with the ability to better understand how changes in the project plan and schedule will impact production rates for the project.

The program has laid a foundation for developing linear scheduling that incorporates historical data and variable inputs to allow the user in deriving schedules that indicate changes in production when and where they occur. This model can be applied to other types of horizontal construction project as well. Expanding the abilities of LSM_{VPR} and adding features to Velocity 1.0 by a) collecting additional site data, b) allowing the ability to use multiple crews starting in multiple locations, c) modeling activities moving across the project in both directions, d) incorporating non-linear activities into the scheduling model, e) include additional activity types, f) incorporating Bayesian methods to update the production rate model while construction is in progress would aid future research and the scheduling and detailed analysis of complex linear construction projects.

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