Project Duration Increase from Rework [1]

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Abstract

The introduction of Earned Schedule (ES), as an extension of Earned Value Management, led to the discovery of schedule adherence (SA). With SA, project managers can observe how closely the project execution follows the planned schedule, by monitoring the Schedule Adherence Index (SAI). SA provides methods for identifying tasks that may have performance restricted by impediments or process constraints, and other tasks that may experience rework in the future. As well, calculation methods have been created, utilizing SAI, for determining the rework generated from performing tasks out of their planned sequence. Thus, project managers have facility to assess the cost impact of rework. Rework obviously impacts project cost, but it must, also, increase project duration. This paper takes another step in the evolution of ES. A method is developed for determining the duration increase caused by rework.

Introduction

Earned Schedule (ES) has been in existence since 2003 [Lipke, 2003]. Over time ES has been recognized globally by inclusion in various standards for project management, Earned Value Management (EVM) and scheduling [PMI, 2011], [PMI, 2017], [ISO, 2018], [PMI, 2019]. As such, it is presumed the reader has a working knowledge of both EVM and ES. Thus, reviews of these management methods are not discussed. Should the reader require more background, see the PMI Practice Standard for EVM referenced previously, and the book *Earned Schedule* [Lipke, 2009].

The concept of schedule adherence (SA) is another matter; even now, it is not well known and is not prevalent in application. The concept was introduced in 2004 [Lipke, 2004], only a year after the seminal paper on ES. At that time, the idea of SA could not be taken up and readily applied. It depended upon understanding ES for which very few were aware and thus, certainly had no idea of SA.

[1] How to cite this paper: Lipke, W. (2020). Project Duration Increase from Rework; *PM World Journal*, Vol. IX, Issue IV, April.

With the general acceptance of ES as a recognized extension to EVM, it is timely to re-introduce SA and more fully utilize the management facility it offers. SA extends ES to project management methods for identifying tasks likely to be performance impeded or constrained and those having a potential of rework. As well, it provides methods for computing the portion of earned value (EV) that moves the project toward completion, termed “effective earned value.”

In 2011, the approach for forecasting the total cost of rework from lack of SA was developed [Lipke, 2011]. Having the ability to compute the cost impact of rework, in turn, provides project managers reason to increase attention to managing schedule performance and improving planning.

Although facility has been available for calculating the schedule performance impacts of rework, it hasn’t been fully recognized, and therefore not employed. A recent paper presented SA derived schedule analysis methods, in an attempt to further propagate the application of ES and encourage greater project control of schedule performance [Lipke, 2020].

Even so, the application of SA from its introduction several years ago, primarily, has focused on the impact to project cost. This article provides a review of SA, and then presents a method for computing the project duration increase caused by the accrual of rework. As the reader will discover, if he/she is applying SA analysis, it is a simple matter to compute the increase to project duration.

Schedule Adherence

Figure 1 provides a visual for discussing the concept of schedule adherence. The tasks to the left of the vertical ES time-line, not completely darkened, are those possibly experiencing impediments and constraints (I/C), or poor process discipline. The darkened tasks to the right of the ES line indicate performance resulting from voids identified by the I/C tasks. Frequently, those darkened tasks to the right are executed without complete information. The performers of these tasks must necessarily anticipate the inputs expected from the incomplete preceding tasks; this consumes time and effort and has no associated earned value. Because the anticipated inputs are very likely misrepresentations of the future reality, the work accomplished (EV accrued) for these tasks usually contains significant amounts of rework. Complicating the problem, the rework created for a specific task will not be recognized for a period of time. The eventual rework will not be apparent until all of the inputs to the task are known or its output is recognized to be incompatible with the requirements of a subsequent task.

This conceptual analysis leads to the measurement of schedule adherence. By determining the EV for the tasks performed congruent with the project schedule, a measure can be created. The adherence to schedule characteristic, P, is described mathematically as a ratio:

$$P = \Sigma\ EV_k / \Sigma\ PV_k$$

PV_k represents the planned value for a task associated with ES. The subscript "k" denotes the identity of the tasks from the schedule which comprise the planned accomplishment, either completed or in-work. The sum of all PV_k is equal to the EV accrued at the status point, AT. EV_k is the earned value for the "k" tasks, limited by the value attributed to the planned tasks, PV_k. Consequently, the value of P, or P-Factor, represents the proportion of the EV accrued which exactly matches the planned schedule.

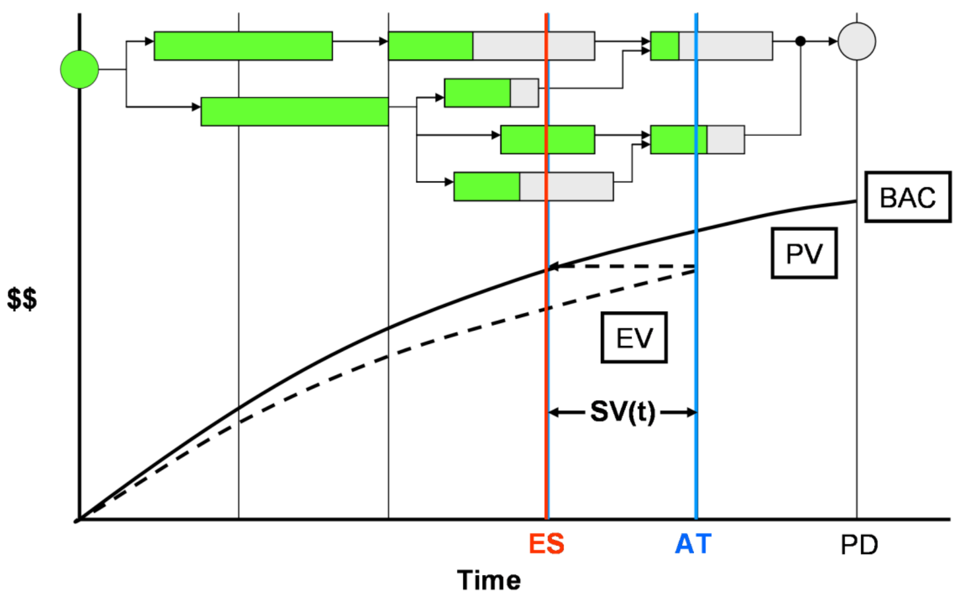

Figure 1. Actual versus Planned Performance

When the value for P is much less than 1.0, indicating poor schedule adherence, the project manager has a strong indication the project will have rework at some point in the future. Conversely, when the value of P is very close to 1.0, the project manager (PM) can feel confident the schedule is being followed and that milestones and interim products are being accomplished in the proper sequence.

Rework Calculation

The diagram shown in figure 2 is provided to aid the understanding for computing rework. EV(p) represents the portion of the EV accrued that is in agreement with the schedule; whereas, EV(r) is the portion for which rework is probable. The fraction of EV(r) requiring rework is EV(-r). For notation simplicity in the subsequent discussion, R is substituted for EV(-r).

At each status point, the amount of rework from performing work out of sequence is given by the following equation:

$$R = EV(-r) = f(r) \times EV(r) = f(r) \times (1 - P) \times EV$$

where f(r) is the function for determining the portion requiring rework. Other representations are possible[2], however the one presently in use is:

$$f(r) = 1 - C \times e\verb|^|(-0.5 \times (1 - C))$$

where C is the fraction complete of the project; C equals EV divided by the planned project budget, i.e., Budget At Completion (BAC).

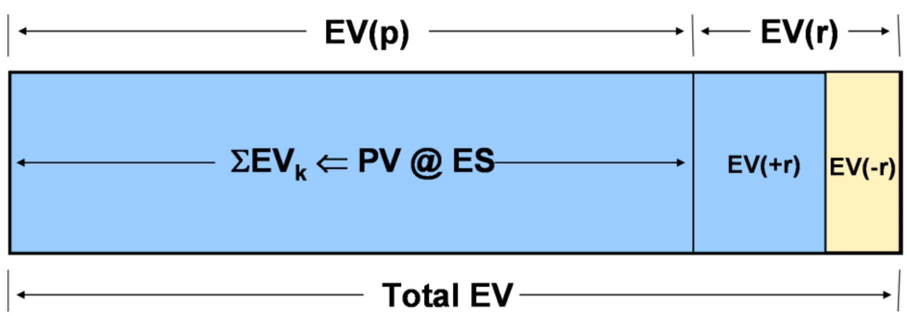

Figure 2. Rework Diagram

The value of R is made useful by the indicator, Schedule Adherence Index (SAI). SAI is defined as R divided by work remaining:

$$SAI = R / (BAC - EV)$$

[2] The general equation is given by f(r) = 1 – C^n × e^(-m × (1 – C)); where C is fraction complete of the project (EV/BAC), e is natural number (base “e”), ^ signifies an exponent follows, and n and m are curve shaping variables. The conditions for f(r) follow: when C = 0, f(r) = 1; when C= 1, f(r) = 0.

The indicator is useful for detecting trends and is, therefore, an indicator by which a manager can gauge his or her actions taken. The interpretation of the indicator is straight forward. When SAI values increase with each successive status evaluation, schedule adherence (SA) is worsening. Conversely, when SAI decreases with time, SA is improving.

Having SAI provides the ability for calculating the rework created within a performance period along with the cumulative effects from imperfect SA. Additionally, it provides computational capability for forecasting the total rework from the lack of schedule adherence. Rework within a performance period is computed through a trapezoidal approximation technique, illustrated in figure 3.

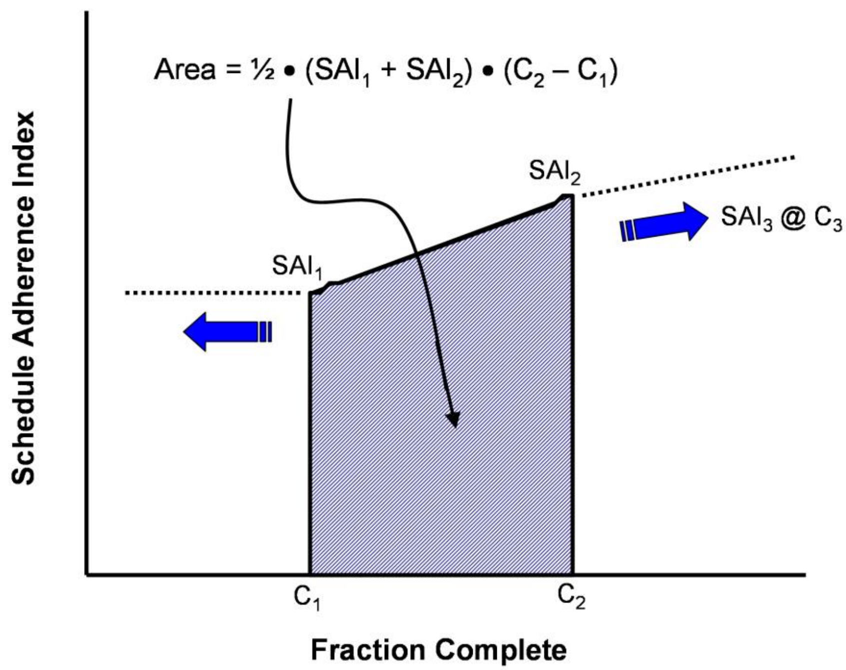

Figure 3. Area Calculation Method

For the graphical depiction, the area computed for each period is in terms of cost of rework per unit of budget. Thus, to obtain the rework cost for any period, the computed area is multiplied by BAC:

$$R_p(n) = BAC \times [½ \times (SAI_n + SAI_{n-1}) \times (C_n – C_{n-1})]$$

where n is the performance period of interest, and the initial and last index values, SAI_0 and SAI_N, are equal to 0.0.

With the methodology established for computing the cost of rework for any period, it becomes a trivial matter to calculate the cumulative cost. The cumulative accrual of rework (R_{cum}) generated from imperfect SA is the summation of the periodic values: $R_{cum} = \Sigma\, R_p(n)$.

The method for forecasting the total rework caused by performance deviations from the schedule is very similar to the formula used for forecasting final cost from EVM. The formula for the total rework forecast (R_{wk}) is

$$R_{wk} = R_{cum} + SAI \times (BAC - EV)$$

This formula makes possible, for each project status point, the computation of total rework forecast from imperfect schedule execution.

Duration Increase

To determine project duration increase caused by rework from poor schedule adherence is a difficult and complex problem. To analyze the problem a simulator was constructed. The simulator varies periodic EV performance randomly. Then, utilizing the P-Factor to induce rework, the lengthening of the project duration can be observed. The output of the simulator includes: project duration with and without rework, total rework, total rework percent, duration increase, duration increase percent, average of the P-Factor over the project execution, and SPI(t) at completion. Definitions for the output terms are listed here:

- Project duration with rework (D_w)
- Project duration without rework (D_o)
- Duration Increase (DI) = D_w minus D_o
- Duration Increase Percent (DI%) = DI divided by project Planned Duration (PD)
- Rework Percent (R_{wk}%) = R_{wk} divided by Budget at Completion (BAC)
- Schedule Performance Index (time), SPI(t), at completion = PD divided by D_w

Simulation Description

Ten project simulations are executed simultaneously. Each has the same set of input variables: BAC, PD, specific multipliers for the periodic EV, specific probabilities for selecting particular multipliers, and an initial value for the P-Factor. The outputs of each simulation are entered to a table and then averaged to become a record representing a specific set of inputs.

For all of the simulations, BAC = 100 and PD = 50. These entries establish the base periodic value for EV at 2.00. Three sets of multiplying factors were applied to the base EV to generate early, on-time, and late finish outcomes. The multiplying factors are:

Early: 0.75, 1.00, 1.75
On-Time: 0.50, 1.00, 1.50
Late: 0.25, 1.00, 1.25

Thus, for clarity, the periodic values used in the simulation for the Early Scenario are 1.50, 2.00, and 3.50.

Each scenario performance (early, on-time, late) was skewed in the simulations by the probability of occurrence given each of the multiplying factors. Three sets of probabilities were applied:

Negative: 0.40, 0.45, 0.15
Un-biased: 0.25, 0.50, 0.25
Positive: 0.15, 0.45, 0.40

The first number in each of the probability sets applies to the first number in the scenario sets. The 2^{nd} number applies to the 2^{nd} number, etc. For example, using the Early scenario and the Negative probability, there is 40% probability that multiplier 0.75 will be applied, a 45% probability that multiplier 1.00 is used, and a 15% probability that multiplier 1.75 occurs in the random selection. For this combination, the execution is set up by the multipliers to have the simulated project finish early. However, the probabilities applied randomly to the multipliers skew the execution toward longer duration. Applying the 3 probability sets to the 3 scenarios yields 9 conditions for the 10 performance simulations, thereby providing a good range of outcomes for examination.

The P-Factor was varied during the simulations of the 9 conditions. That is, P was initialized at a value less than 1.00 and subsequently increased monotonically through the simulated performance to 1.00 at completion. This process mimics the trend of P to increase during execution to its final value (1.00).

Six different levels of rework (16%, 13%, 10%, 7%, 4%, 1%) were controlled in the simulations by the P-Factor applied. This approach is regarded as acceptable due to the strong correlation of rework to the computed average of the P-Factor across the 10 simulations. The Coefficient of Correlation (r) is determined to be equal to 0.9939. The strength of r is made by referring to table 1. When r is greater than the Critical Value (CV) for 4 degrees of freedom at a specific Level of Significance (α), correlation between the variables is likely [Wagner, 1992].

Level of Significance (α)	0.10	0.05	0.01
Critical Value (df = 4)	0.729	0.811	0.917

Table 1. Critical Values for r (R_{wk}% vs P)[3]

Each of the 9 conditions described above was simulated for each of the 6 levels of rework, creating 54 sets of results for analysis. Each set was averaged across the 10 simulations to obtain the outputs described earlier.

The rework values generated by the simulations required scaling. An adjustment factor was applied to have the simulation generated rework at project completion agree with the forecast output of the SAI and Rework Calculator from the ES website. This was accomplished by utilizing the linear relationship of the rework percent to the average value of the P-Factor.

Output Analysis

Three graphs are presented below, figures 4, 5, and 6. They are plots of R_{wk}%, DI%, and SPI(t) versus the P-Factor. The graphs illustrate good, moderate, and poor execution efficiency, as observed from the placement of SPI(t) in each of the figures. The linear relationship between the P-Factor and R_{wk}% discussed previously is seen in each chart. An extremely significant observation taken from these graphs is that rework is not a consequence of schedule performance efficiency. Regardless of the SPI(t) value, the line representing R_{wk}% appears in the exact same location in each graph. This was expected from the theory of schedule adherence and is verified by the output of the simulations.

Also observed in figures 4, 5, and 6, is a seeming negative relationship between SPI(t) and DI%; as SPI(t) becomes larger, DI% decreases. The possible correlation was examined by constructing six graphs, one for each of the controlled values of rework. DI% vs SPI(t) data were plotted, using results recorded for the 9 conditions. The

[3] The Critical Values shown throughout are available from the following URL:
https://www.radford.edu/~jaspelme/statsbook/Chapter%20files/Table_of_Critical_Values_for_r.pdf

correlation of DI% to SPI(t) is indicated in table 2. The statistical CVs for the linear fit with df = 7 at their corresponding α are shown in table 3. The only result not strongly indicating correlation is for the rework parameter of 1%.

Rework	16%	13%	10%	7%	4%	1%
r value	.9769	.9728	.9625	.9698	.8443	.5454

Table 2. Coefficient of Correlation (DI% vs SPI(t)

Level of Significance (α)	0.10	0.05	0.01
Critical Value (df = 7)	0.584	0.666	0.798

Table 3. Critical Values for r (DI% vs SPI(t)

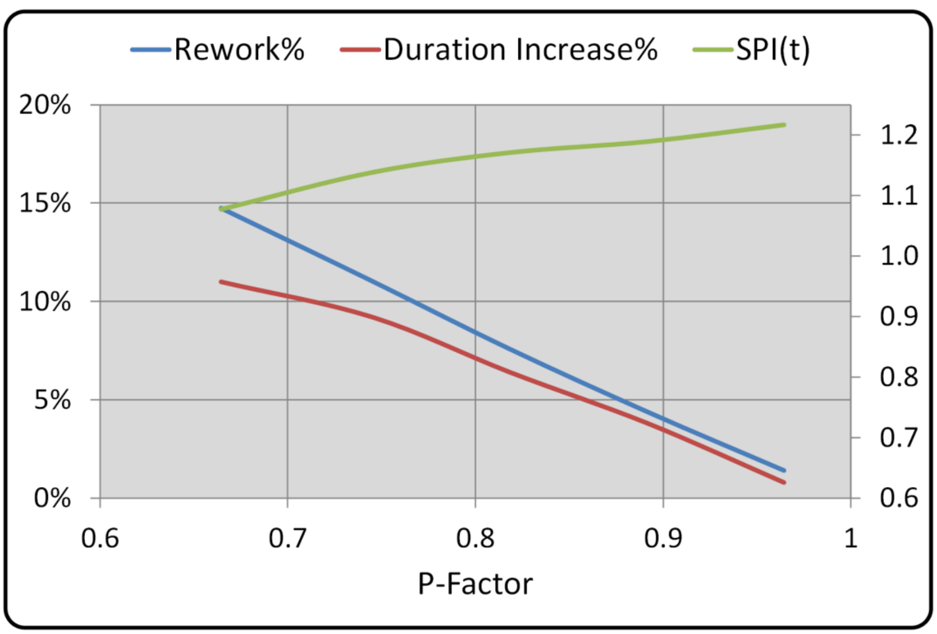

Figure 4. Good Efficiency

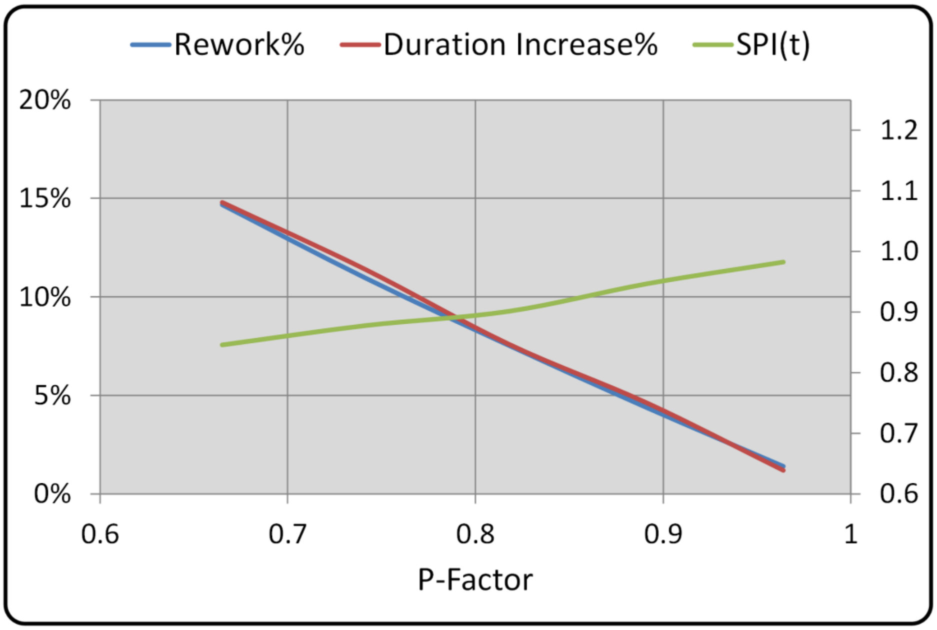

Figure 5. Moderate Efficiency

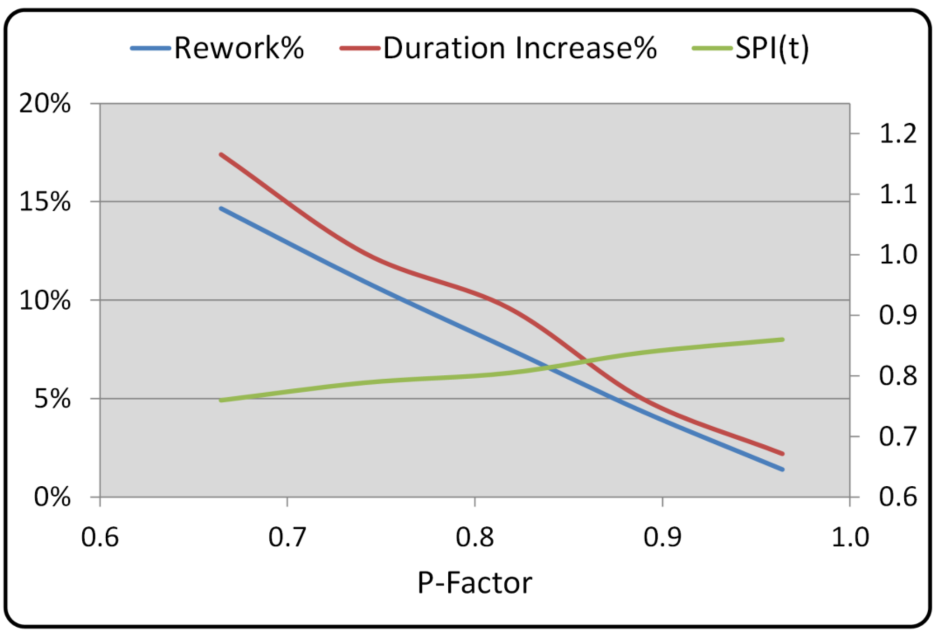

Figure 6. Poor Efficiency

Duration Increase Calculation

Because good correlation is established, prediction is possible. The six parametric models are formulated in table 4 and their graphical representation is shown in figure 7. With its poor correlation, there is some question concerning the 1% model. However, from inspection of the graph and the slope of the formula, it is readily deduced that error from its prediction would be very small.

At this point, take care to note that because the R_{wk}% is the forecast value for project completion, the DI% determined is then likewise a forecast at completion. Moving forward, the normal definition, SPI(t) = ES/AT, is substituted hereafter for the "at completion" definition used in development of the DI% models. The substitution is justified by the assumption, generally made in forecasting, that the SPI(t) determined during execution will continue to project completion.

There is a significant issue in applying the models. The correlation of DI% with SPI(t) has been determined for 6 levels of rework only. Should the rework percentage forecast be a value different from one of the six, its linear model for DI% and SPI(t) is not defined. Certainly, more predictive models could be created for various values of R_{wk}%, but the number needed becomes impractical.

An alternative is the application of interpolation. The two project performance status values needed for the calculation are SPI(t) and forecast R_{wk}%. With the value of SPI(t), the DI% can be computed for each of the 6 parametric models. The R_{wk}% reported establishes which two of the parametric rework percent plots are to be used for the interpolation. The forecast for DI% can then be computed.

For clarity, let's assume the values reported are: SPI(t) = 0.850, and R_{wk}% forecast = 14%. Because 14% lies between, the DI% values for R_{wk}% parameters of 13% and 16% are determined. Their notation is identified as $DI\%_{13}$ and $DI\%_{16}$, respectively. Substituting the value of SPI(t) into the models and making the calculation, $DI\%_{13}$ = 14.14%, and $DI\%_{16}$ = 16.46%.

The interpolated result can then be computed, as follows:

$$DI\% = DI\%_{13} + (DI\%_{16} - DI\%_{13}) \times (14\% - 13\%)/(16\% - 13\%)$$

$$= DI\%_{13} + (DI\%_{16} - DI\%_{13}) \times 1/3$$

Substituting the values for $DI\%_{13}$ and $DI\%_{16}$ completes the calculation:

$$DI\% = 14.14\% + (16.46\% - 14.14\%) \times 1/3 = 14.91\%$$

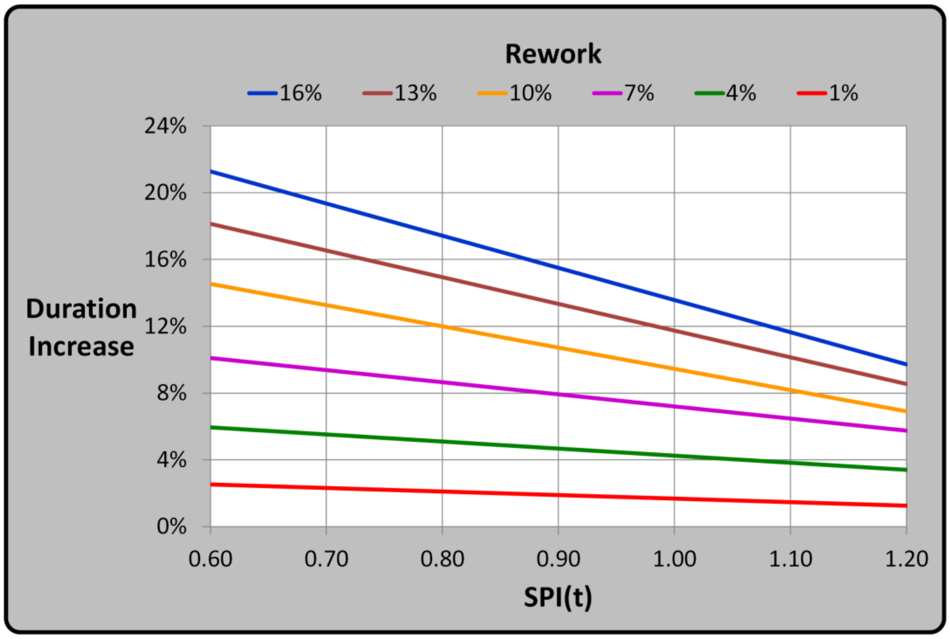

Figure 7. Parametric Models

Rework%	Models
16%	$DI\%_{16} = 0.3284 - 0.1927 \times SPI(t)$
13%	$DI\%_{13} = 0.2773 - 0.1599 \times SPI(t)$
10%	$DI\%_{10} = 0.2217 - 0.1272 \times SPI(t)$
7%	$DI\%_{7} = 0.1445 - 0.0725 \times SPI(t)$
4%	$DI\%_{4} = 0.0849 - 0.0424 \times SPI(t)$
1%	$DI\%_{1} = 0.0380 - 0.0212 \times SPI(t)$

Table 4. Parametric Models

Although interpolation is a simple solution, and is believed to provide sufficient accuracy for project management decisions, it is limited to $R_{wk}\%$ values less than 16%. A solution having greater range, with less complexity, and less error is desirable.

Returning to figure 7 and table 4, it is observed that as R_{wk}% increases the intercept and the slope values for the associated DI% model increase, as well. Should a relationship exist between these variables, the ability to forecast DI% from any R_{wk}% value less than 16% can be made without the error implicit in the interpolation method. As well, should the relationship be strong, it would be reasonable to believe that the range could be extended somewhat beyond the 16% limitation.

The graphs in figure 8 are plots of intercept and slope values from table 4 versus their associated R_{wk}% values. The graphs were made using the origin as a 7th data point. It is a reasonable assumption that both the intercept and slope should equal 0.0 when R_{wk}% equals 0.0. As shown, the r values for intercept (0.9960) and slope (0.9932) are extremely close to 1.0, indicating a very strong linear relationship. This is verified by comparison to the CVs for df = 5 provided in table 5.

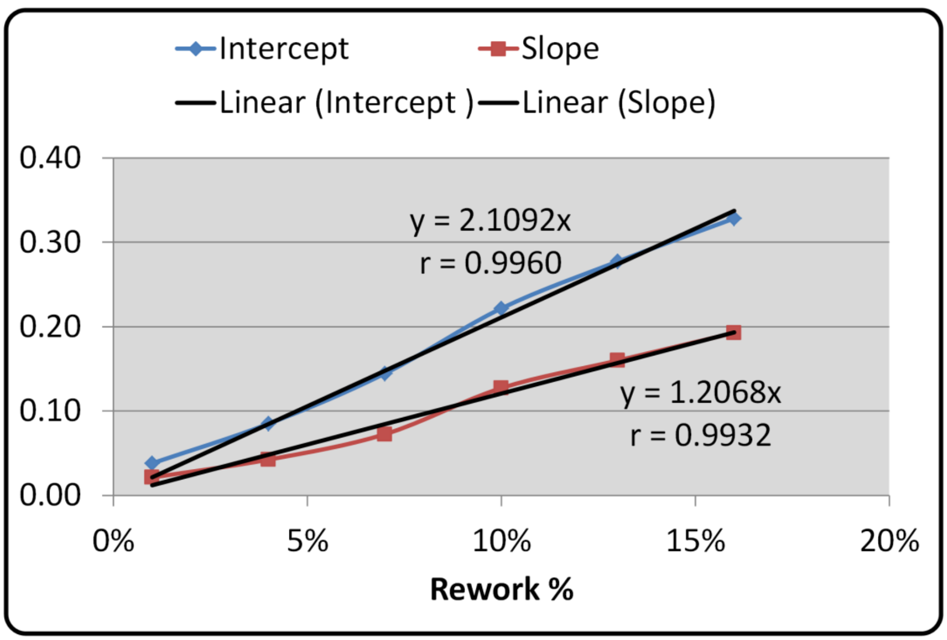

Figure 8. Linear Model

Level of Significance (α)	0.10	0.05	0.01
Critical Value (df = 5)	0.669	0.755	0.875

Table 5. Critical Values for r (Linear Model)

From the equations shown in figure 8 and below, the DI% forecasting model can be derived:

Intercept (I) = $2.1092 \times R_{wk}\%$
Slope (S) = $1.2068 \times R_{wk}\%$

To begin, the general construct for the linear model, taken from table 3 is:

$$DI\% = \text{Intercept} - \text{Slope} \times SPI(t)$$

Substituting the mathematical relationships for I and S into the form yields the following equation:

$$DI\% = 2.1092 \times R_{wk}\% - (1.2068 \times R_{wk}\%) \times SPI(t)$$

Using the $R_{wk}\%$ and SPI(t) values from the previous numerical example, the derived linear model can be compared to the interpolation result:

$$\begin{aligned} DI\% &= 2.1092 \times 14\% - 1.2068 \times 14\% \times 0.850 \\ &= 15.15\% \end{aligned}$$

The two computation methods produce values that are very close, 15.15% versus 14.91%. Certainly the linear model is easier to use and likely has less error.

The model does have limitations. When SPI(t) is equal to 1.74776 (2.1092 divided by 1.2068), DI% equals 0.0 for any $R_{wk}\%$ value. As well, when SPI(t) is greater than 1.74776, nonsensical negative values are computed for DI%. Although SPI(t) greater than or equal to 1.74776 is possible, it is very seldom achieved. The model is expected to provide good results when $R_{wk}\% \leq 20\%$ and SPI(t) < 1.74776.

As a reminder, multiplying DI% by PD computes the forecast duration increase. Then, by subtracting DI from D_w, D_o is determined. From these simple calculations, the project manager is informed of when the project could have completed if rework was avoided. Having this knowledge promotes better planning and schedule execution.

To encourage application of the analysis method, the ability to compute duration increase has been added to the *SAI & Rework Calculator*. The title for the calculator has been changed to *SAI, Rework, and Duration Increase Calculator*. The new calculator will be made available for download from the ES website (www.earnedschedule.com).

Summary/Conclusion

The concept of Schedule Adherence, derived from ES analysis, provides methods for assessing the impact of performing project tasks out of their planned sequence. When out of sequence performance occurs, it is probable that rework will be required at some future time. Thus far, the attention to rework has primarily been concerned with analyzing the increase to project cost. There has been little effort to understand the rework impact to schedule performance.

To understand and examine the impact of rework on project duration, simulation of project performance was created. Three sets of EV multipliers and three sets of probabilities were applied to create nine duration performance conditions, ranging from extremely early to very late completion. Each of the nine conditions was iterated for six levels of P-Factor induced rework, from 1% to 16% at 3% intervals. The 54 combinations of rework and performance conditions were simulated simultaneously for 10 projects and subsequently averaged for analysis.

From the sets of results recorded, two correlations were observed: R_{wk}% to the P-Factor, and DI% to SPI(t). The correlation of R_{wk}% to the P-Factor was determined to be very strong, r = 0.9939. This correlation demonstrated that rework is not a consequence of schedule performance efficiency, a finding in agreement with SA theory.

The DI% to SPI(t) correlation was tested for each of the six rework percentages examined. Strong correlations were observed for all with the exception of the 1% rework parameter; however, the error from application of the 1% model was determined to be insignificant. Utilizing the linear fit models an interpolation method was described for calculating DI% from two project status measures, R_{wk}% and SPI(t). The calculation method was demonstrated using notional data.

Subsequently, it was discovered that the six models can be represented by a single formula for DI%, thereby overcoming the error induced by interpolation. Although not mathematically supported, it is believed the forecasting range of the linear model formula can be extended to values of R_{wk}% greater than 16%. As well, application of the linear model is limited to SPI(t) values less than 1.74776.

To promote management application for assessing the impact of rework on project duration, the *SAI, Rework, and Duration Increase Calculator* has been created and is to be made available on the ES website.

Final Thoughts

Mathematically, the forecasting range of a linear fit is limited to the end points of the data. Without even considering the work discussed in this article, it is logical to make the assumption that DI% is linearly related to R_{wk}%. Therefore, it makes some sense to believe that the range for the DI% formula can be extended, and especially when the correlation coefficients for I and S are so close to 1.0. However, the proposed model remains unproven. Application and further research is needed to confirm its ability to reliably forecast duration increase.

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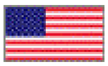

Walt Lipke retired in 2005 as deputy chief of the Software Division at Tinker Air Force Base, where he led the organization to the 1999 SEI/IEEE award for Software Process Achievement. He is the creator of the *Earned Schedule* technique, which extracts schedule information from earned value data.

Credentials & Honors:

- Master of Science Physics
- Licensed Professional Engineer
- Graduate of DOD Program Management Course
- Physics honor society - Sigma Pi Sigma (ΣΠΣ)
- Academic honors - Phi Kappa Phi (ΦΚΦ)
- PMI Metrics SIG Scholar Award (2007)
- PMI Eric Jenett Award (2007)
- EVM Europe Award (2013)
- CPM Driessnack Award (2014)
- Australian Project Governance and Control Symposium established the annual *Walt Lipke Project Governance and Control Excellence Award* (2017)
- Albert Nelson Marquis Lifetime Achievement Award (2018)