Cost, Schedule, and Time Variances and Integration[1]

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ABSTRACT. This paper derives and demonstrates detailed schedule- and cost-control relationships at the activity/cost-account level with which project managers can budget, track, and control projects. Time variances are introduced to describe differences between scheduled times and actual times for activity and project performance. Variances are the sum of more detailed variances, and variances can be calculated and reported at different levels of detail, whether for activities and cost accounts or for a project as a whole. Activity/cost-account budgets sum to project budgets and variances sum to project variances. A unified nomenclature and parallel budget and variance structures allow integration of cost and schedule control for projects that share common work breakdown structures. Budget, actual, and variance values of cost, progress, and time are combined in a single illustration to demonstrate integration at the activity/cost-account level. Equation development is augmented with computer implementation details for generic spreadsheets or custom applications. Examples are presented for a single element from start to completion and for a project of four elements.

INTRODUCTION

Control is calculating variances between actual measured cost and progress on one hand and target budgets and schedules on the other to determine if operations are being performed as intended. This paper presents equations that describe parallel hierarchical cost and schedule control systems that calculate cost, schedule, and time variances at different levels of detail. For projects on which cost- and schedule-control share a common work breakdown structure (WBS), the equations provide integrated cost, schedule, and time variances for integrated cost- and schedule-control. A construction project may be viewed as a hierarchy of work packages, the lowest or most detailed level of which can be called an elemental work package or element. This paper focuses on elemental work package or element variances and demonstrates how combining element-control data produces project-control data.

BACKGROUND

Cost control is basic to managerial accounting. Schedule control is more recent. Integration of schedule and cost control has been a natural objective of project control systems since the late 1970s. The U.S. Department of Defense basic earned value-based relationships are widely accepted ("Cost and Schedule" 1980). Several authors have presented methods for construction projects (Neil 1982; Bernstein 1983; Murthy 1983; Riggs 1987; Singh 1991). General implementation issues have received attention (Ibbs et al 1987; McConnell 1985; Sears 1981; Teicholz 1987). Control automation and relationships of project control to project integrated data bases have been explored (Abudayyeh and Rasdorf 1991; Rasdorf and Abudayyeh 1991, 1992). The Construction Industry Institute has issued guides for engineering and construction ("Project Control" 1986, 1987). Project management software includes schedule- and cost-control integration (Parade 2.1 from Primavera Systems, Bala Cynwyd, PA). Abu-Hijleh (1991) described detailed cost and schedule integration with a focus on exception reporting. This paper grew from a brief paper presented at the 1991 ASCE Construction Congress (Carr 1991).

Strengths and weaknesses of schedule- and cost-control integration include those of separate schedule and cost control, plus several specifically related to integration. In particular, integration requires that cost

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performance and schedule performance share a WBS (Sears 1981; Teicholz 1987; Rasdorf and Abudayyeh 1991).

The general literature and computer software, except Abu-Hijleh (1991), limit themselves to cost and schedule variances of projects and the activities and cost accounts that make them up. They do not describe detailed element variances. This paper makes three significant contributions to the literature and software design: (1) It presents a more detailed cost- and schedule-variance structure; (2) it presents a time-variance structure that parallels cost- and schedule-variance structures; and (3) it describes links among element schedule, cost, and time variables and variances to implement a more detailed integration of schedule and cost variables, and to introduce and integrate time-variable details if they share a common WBS.

WORK PACKAGE CONTROL

Variances are useful if they are available early enough that problems can be identified and fixed. Partial completion measurements and calculations are easiest to perform for linear and continuous processes that produce a single output, and this is the standard model for cost and schedule control. This paper emphasizes linear operations, but it also integrates discrete processes that are not as easily controlled. (The landscape element in Table 1 is an example of such a lump-sum element.)

BASIC VARIABLES

Integration of data requires a single unit of measure that combines cubic meters with kilograms and cost performance with schedule performance. Cost and schedule variances are therefore reported in dollars. Time variances are reported in days. Activities and cost accounts require a common performance base, and this is furnished by budgeted cost information. Cost control also depends on cost of resources. Schedule control depends on resources used. Therefore, cost and schedule control share budgeted cost, resources, and quantities, and they share actual resources employed and quantities produced. Control requires that budgets be established for elements before their construction begins. During realization of the process, projected quantities are then calculated using actual performance.

The construction process is: resources (R) such as worker hours or equipment hours, constructing output units (U), such as meters or cubic meters, over a duration of time (D), such as days, at a construction cost (C) in dollars. Quantities of these variables are budgeted (subscript b) to be required at completion of the process, scheduled (s), actual (a) to date, or projected (p) at completion of the process based on data to date. A process has a start (S) and its partial completion is percent complete (P).

From this basic vocabulary, we build the following variables: R_b, U_b, D_b, and C_b are the input resources, output units, duration, and costs budgeted to be required to complete an operation; S_s is the scheduled start day; S_a is the actual start day. D_s is the number of days to date since scheduled start of an operation; D_a is the number of days to date since actual start of an operation, where

$$D_a = D_s - (S_a - S_s) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

D_c is the day the operation was completed; and U_s is the units scheduled to be produced to date, where

$$U_s = U_b \frac{\mathrm{Min}(D_s,\, D_b)}{D_b} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

TABLE 1. Project Status at End of Third Period

Variables (1)	Excavate (m³) (2)	Pipe (m) (3)	Backfill (m³) (4)	Landscape (lump sum) (5)	Project (6)
(a) Budget Input					
Units of output, U_b	9,600	1,760	9,424	1.00	–
Cost, C_b (dollars)	81,388	60,800	22,334	31,000	195,522
Resources, R_b	65	400	221	–	–
Scheduled start day, S_s (days)	0	15	40	50	0
Duration, D_b (days)	40	50	30	20	70
(b) Period Budget Calculations					
Days since sched start, D_s (days)	60	45	20	10	60
Units of output scheduled, U_s	9,600	1,584	6,283	0.50	–
BCWS (dollars)	81,388	54,720	14,890	15,500	166,497
Scheduled percent complete, P_s	100	90	67	50	85
Resources scheduled, R_s	64.8	360	147.5	–	–
(c) Period Input					
Actual start, S_a (days)	7	21	35	55	7
Day completed, D_c (days)	58	–	–	–	–
Days since actual start, D_a (days)	51	39	25	5	53
Resources used, R_a	76	326	168	–	–
Units produced, U_a	10,445	1,165	6,941	0.15	–
Actual cost, C_a (dollars)	99,047	46,837	17,944	4,905	168,734
Estimated total quantity, U_p	10,445	1,855	10,366	1.00	–
(d) Work Performed					
Actual percent complete, P_a	100.0	62.8	67.0	15.0	71.2
BCWP (dollars)	81,388	38,190	14,954	4,650	139,183
$BCWP_b$ (dollars)	88,550	40,253	16,450	4,650	149,902
$BCWP_s$ (dollars)	81,388	47,424	18,612	7,750	155,174
ACWP (dollars)	99,047	46,837	17,944	4,906	168,734
(e) Cost Variances To Date (dollars)					
Cost Variance, V_c	(17,659)	(8,647)	(2,990)	(256)	(29,552)
Quantity variance, $V_{c\ quan}$	(7,162)	(2,062)	(1,495)	0	(10,720)
Rate variance, $V_{c\ rate}$	(10,497)	(6,585)	(1,494)	(256)	(18,832)
Resource variance, $V_{c\ res}$	(3,164)	2,674	(952)	(256)	(1,698)
Productivity variance, $V_{c\ prod}$	(7,333)	(9,258)	(543)	0	(17,134)
(f) Projected Cost (dollars)					
At budget unit cost, C_{pb}	88,550	64,083	24,568	31,000	208,201
At actual unit cost, C_p	99,047	74,566	26,800	32,705	233,118

TABLE 1. (Continued)

(1)	(2)	(3)	(4)	(5)	(6)
(g) Projected Cost Variances (dollars)					
Cost variance, V_{cp}	(17,659)	(13,766)	(4,465)	(1,705)	(37,596)
Quantity variance, $V_{cp\ quan}$	(7,162)	(3,283)	(2,233)	0	(12,679)
Rate variance, $V_{cp\ rate}$	(10,497)	(10,483)	(2,232)	(1,705)	(24,917)
Resource variance, $V_{cp\ res}$	(3,164)	4,256	(1,421)	(1,705)	(2,034)
Productivity variance, $V_{cp\ prod}$	(7,333)	(14,739)	(811)	0	(22,883)
(h) Schedule Variances To Date (dollars)					
Schedule variance, V_S	0	(16,530)	65	(10,850)	(27,315)
Start variance, $V_{S\ start}$	0	(7,296)	3,722	(7,750)	(27,315)
Quantity variance, $V_{S\ quan}$	0	(2,062)	(1,495)	0	(3,558)
Rate variance, $V_{S\ rate}$	0	(7,171)	(2,162)	(3,100)	(12,434)
Resource variance, $V_{S\ res}$	0	2,087	(1,619)	–	467
Productivity variance, $V_{S\ prod}$	0	(9,258)	(543)	–	(9,801)
(i) Calculated times (days)					
ATWP	58.00	45.00	20.00	10.00	60.00
BTWP$_S$	51.00	39.00	25.00	5.00	53.00
BTWP$_b$	43.52	33.10	22.10	3.00	–
BTWP	40.00	31.41	20.09	3.00	–
(j) Time Variances To Date (days)					
Time variance, V_t	(18.00)	(13.59)	0.09	(7.00)	–
Start variance, $V_{t\ start}$	(7.00)	(6.00)	5.00	(5.00)	–
Quantity variance, $V_{t\ quan}$	(3.52)	(1.70)	(2.01)	0	–
Rate variance, $V_{t\ rate}$	(7.48)	(5.90)	(2.90)	(2.00)	–
Resource variance, $V_{t\ res}$	(3.88)	1.72	(2.18)	–	–
Productivity variance, $V_{t\ prod}$	(3.60)	(7.61)	(0.73)	–	–
(k) Projected Durations (days)					
Duration, D_p	51.00	62.09	37.34	33.33	81.33
with addition of start delay, D_{ps}	58.00	68.09	32.34	38.33	–
at budgeted units per day, D_{pb}	43.52	52.70	33.00	20.00	–
Completion	58.00	83.09	72.34	88.33	88.33
(l) Projected Time Variances (days)					
Time variance, V_{tp}	(18.00)	(18.09)	(2.34)	(18.33)	18.33
Start variance, $V_{tp\ start}$	(7.00)	(6.00)	5.00	(5.00)	–
Quantity variance, $V_{tp\ quan}$	(3.88)	2.73	(3.25)	0	–
Rate variance, $V_{tp\ rate}$	(7.48)	(9.39)	(4.34)	(13.33)	–
Resource variance, $V_{tp\ res}$	(3.88)	2.73	(3.25)	0	–
Productivity variance, $V_{tp\ prod}$	(3.60)	(12.12)	(1.09)	0	–

Note: Units of measure for variables are shown in parentheses

In Eq. (2) $\min(D_s, D_b)$ is the minimum of D_s and D_b. This constraint prevents units scheduled from exceeding total budgeted units. Other variables are: R_s is the resources scheduled to date, where

$$R_s = R_b \frac{U_s}{U_b} = R_b \frac{\min(D_s, D_b)}{D_b} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

R_a, U_a, and C_a are the actual resources used, units produced, and cost incurred to date; U_p is the projected output units, which equals the latest estimate of total units to be produced; P_s is the scheduled percent complete to date, where

$$P_s = \frac{U_s}{U_b} = \frac{\min(D_s, D_b)}{D_b} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$

P_a is the actual percent complete to date, where

$$P_a = \frac{U_a}{U_p} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

and P_b is the percent complete measured by budgeted quantity, where

$$P_b = \frac{U_a}{U_b} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Because U_a can exceed U_b, P_b can exceed one, though P_a and P_s cannot. For lump-sum elements, for which P_a must be input by a user, and because the number of output units from a lump-sum element is one, $U_a = P_a$, and $U_p = U_b = 1.0$.

PROJECTED COST

Costs can differ from budget, because the quantity of output differs from budget ($U_p \neq U_b$) and/or price per unit of output differs from budget ($C_a/U_a \neq C_b/U_b$). C_{pb} represents C_b adjusted for projected quantity U_p but not for actual unit costs. Therefore, C_{pb} is the projected cost for the projected total units of output at the budgeted cost per unit, where

$$C_{pb} = C_b \frac{U_p}{U_b} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$

For lump-sum elements, which are not measured by units of output, $C_{pb} = C_b$ because $U_p = U_b$. C_p is the total projected cost at completion, which includes adjustment for U_p and for actual unit cost experience. If cost is linearly related to output units, as it is for an owner on a unit price contract or for a prime contractor on a unit price subcontract, C_p is the cost for the projected units of output at the actual unit cost, which can be calculated as

$$C_p = C_a \frac{U_p}{U_a} = \frac{C_a}{P_a} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

For elements for which cost is not linearly related to output units, (7) can be replaced with a nonlinear function or C_p can be input from a separate calculation. Budgeted unit cost can also be used up to a particular percentage complete and (7) used for higher values. For example, use $C_p = C_b$ for $P_a \leq 10\%$ and (7) for $P_a > 10\%$, if one is concerned that early costs are not an accurate predictor of later costs.

VALUE VARIABLES

Work is valued at budgeted cost, C_b. As work is performed, its value is earned in proportion to its percentage of completion, P_a, and its earned value is its budgeted cost of work performed (BCWP).

Therefore, actual progress is measured by earned value, *BCWP*. Scheduled progress is budgeted cost of work scheduled, (*BCWS*), measured by value associated with the percentage of completion scheduled, P_s. *BCWP* can differ from *BCWS* because projected quantity differs from budget ($U_p \neq U_b$), the actual start differed from the scheduled start ($S_a \neq S_s$), and units performed per day differ from those budgeted ($U_a/D_a \neq U_b/D_b$). $BCWP_b$ denotes *BCWP* if projected quantity were the same as budgeted ($U_p = U_b$). $BCWP_b$ is *BCWS* if budgeted rate of output units per day were the same as actual output units per scheduled day ($U_a/D_a = U_b/D_b$) and scheduled start were the same as actual ($S_a = S_s$). $BCWP_s$ denotes *BCWP* if projected quantity were the same as budgeted and if actual rate of units output per day were the same as budgeted ($U_a/D_a = U_b/D_b$). $BCWP_s$ is *BCWS* if scheduled start were the same as actual ($S_a = S_s$). In transition from *BCWS* to *BCWP;* we see $BCWP_s$ recognizes change in start; $BCWP_b$ recognizes changes in start and rate of output; and *BCWP* recognizes changes in start, rate of output, and quantity.

$$\text{BCWS} = C_b \frac{U_s}{U_b} = C_b P_s \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (9)$$

$$BCWP = C_b \frac{U_a}{U_p} = C_b P_a \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (10)$$

$$BCWP_b = BCWP \qquad \text{if } U_p = U_b \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (11a)$$

$$BCWP_b = BCWS \qquad \text{if } \frac{U_a}{D_a} = \frac{U_b}{D_b}, \ S_a = S_s \cdot \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (11b)$$

$$BCWP_b = C_b \frac{U_a}{U_b} = C_b P_b \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (11c)$$

$$BCWP_s = BCWP \qquad \text{if } \frac{U_a}{D_a} = \frac{U_b}{D_b}, \ U_p = U_b \quad \dots \dots \dots \dots \dots \dots \dots \quad (12a)$$

$$BCWP_s = BCWP_b \qquad \text{if } \frac{U_a}{D_a} = \frac{U_b}{D_b} \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (12b)$$

$$BCWP_s = BCWS \qquad \text{if } S_a = S_s \cdot \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (12c)$$

$$BCWP_s = C_b \frac{\min(D_a, D_b)}{D_b} \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (12d)$$

$$ACWP = C_a \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (13)$$

Because P_a can exceed one, $BCWP_b$ can be greater than C_b. Therefore, $BCWP_b = BCWP$ for $U_p = U_b$ is only true for $U_a \leq U_b$, and not where output passes U_b and $U_a > U_b$.

COST VARIANCES

Cost variance, V_c, is the difference between actual cost of producing the output units to date, U_a, and budgeted cost to produce the percentage of completion, P_a, which is the difference between budgeted and actual cost to produce output units to date:

$$V_c = BCWP - ACWP = C_b \frac{U_a}{U_p} - C_a = C_b P_a - C_a \quad \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (14)$$

Variance equations are formulated so that a favorable variance is positive and an unfavorable variance is negative. Thus, (14) is positive when actual cost is less than budgeted ($C_bP_a > C_a$) and negative when actual cost exceeds budgeted ($C_bP_a < C_a$). Cost variance is due to change in projected output quantities and change in cost per unit of output. The change in unit cost is a rate change, due to change in cost per unit of resource and change in productivity of resources. Each of these changes has a variance, as reflected in the following:

- Cost quantity variance, $V_{c\ quan}$, is the cost variance due to difference between budgeted quantity and projected quantity:

$$V_{c\ quan} = C_bU_a\left(\frac{1}{U_p} - \frac{1}{U_b}\right) \quad = C_b\frac{U_a}{U_p} - C_b\frac{U_a}{U_b}$$

$$= C_b(P_a - P_b) = BCWP - BCWP_b \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (15)$$

- Cost rate variance, $V_{c\ rate}$, is the cost variance from the difference between budgeted and actual unit costs:

$$\text{Vc rate} = U_a\left(\frac{C_b}{U_b} - \frac{C_a}{U_a}\right) = C_b\frac{U_a}{U_b} - C_a = C_bP_b - C_a = BCWP_b - ACWP \cdots\cdots\cdots (16)$$

- Cost resource variance, $V_{c\ rate}$, is the cost variance due to the difference between budgeted and actual cost per unit of resources (where cost per unit of resource $= C / R$)

$$V_{c\ res} = R_a\left(\frac{C_b}{R_b} - \frac{C_a}{R_a}\right) = C_b\frac{R_a}{R_b} - C_a = C_b\frac{R_a}{R_b} - ACWP \cdots\cdots\cdots\cdots\cdots\cdots (17)$$

- Cost productivity variance, $V_{c\ prod}$, is the cost variance due to the difference between budgeted and actual productivity (where productivity equals units of output per unit of resources input):

$$V_{c\ prod} = C_b\frac{R_a}{U_b}\left(\frac{U_a}{R_a} - \frac{U_b}{R_b}\right) = C_b\left(\frac{U_a}{U_b} - \frac{R_a}{R_b}\right) = BCWP_b - C_b\frac{R_a}{R_b} \cdots\cdots\cdots\cdots (18)$$

Cost variance equals cost quantity variance plus cost rate variance (where cost rate variance equals cost resource variance plus cost productivity variance). Calculation of cost resource variance and cost productivity variance requires data on budgeted and actual resources, which may not be available due to lack or complexity of resource information. Therefore, when resource data are not available, cost rate variance can be calculated but cost resource and productivity variances cannot.

On lump-sum and unit-price contracts, the client's cost variances will be the contractor's revenue variances. The contractor's cost variances will differ from the client's, because the contractor's costs differ from the client's, except for a cost-reimbursable contract. Therefore, as quantities of pay items in a unit-price contract change, the client's cost quantity variances and the contractor's revenue quantity variances will be equal, and the contractor will have its own cost quantity variances. The contractor's resulting income quantity variances will depend on the relative differences between its cost variances and revenue variances. (Further explanation of contractor revenue and income variances is beyond the scope of this paper.)

Cost variances anticipated at completion can be projected from experience to date. Examples are projected cost variance, V_{cp}, projected cost quantity variance, $V_{cp\ quan}$, and projected cost rate variance, $V_{cp\ rate}$:

$$V_{cp} = C_b - C_p \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (19)$$

$$V_{cp\ quan} = C_b - C_{pb} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (20)$$

$$V_{cp\ rate} = C_{pb} - C_p \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (21)$$

Projected cost variance variables equal their respective cost variances to date divided by P_a. For example, projected cost quantity variance equals cost quantity variance divided by P_a. Therefore, projected cost variances are easily calculated from their cost variance to date counterparts. As with cost variances to date, projected cost variance equals projected cost quantity variance plus projected cost rate variance (where projected cost rate variance equals projected cost resource variance plus projected cost productivity variance).

SCHEDULE VARIANCES

Schedule variance, V_s, is the difference between the earned value of work performed and that which was scheduled, as represented by:

$$V_s = BCWP - BCWS = C_b \frac{U_a}{U_p} - C_b \frac{U_s}{U_b} = C_b(P_a - P_s) \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (22)$$

Schedule variances are positive when actual output exceeds scheduled output, because that is favorable. The difference between actual and scheduled percent complete has the range $-1 \leq P_a - P_s \leq 1$. Therefore, schedule variance can range from $-C_b$ to C_b, but its absolute value cannot exceed budgeted cost. At completion of an operation, $P_a = 100\%$, and the operation cannot be behind schedule. Therefore, a completed operation, even if completed late, cannot have a negative, unfavorable schedule variance. An operation completed ahead of schedule will have a positive, favorable schedule variance that decreases to zero when its scheduled completion date is reached.

Schedule variance is from variance in time when the operation starts, variance in projected output quantity, and variance in rate of units produced per day. A variance in rate of units produced per day is due to variance in resources input per day and in productivity of those resources.

Schedule start variance, $V_{s\ start}$, is the schedule variance due to the difference between scheduled and actual start time, $S_s - S_a = D_a - D_s$, given quantity and rate were as budgeted:

$$V_{s\ start} = C_b \frac{S_s - S_a}{D_b} = C_b \frac{D_a - D_s}{D_b} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (23)$$

However, as with schedule variance, the absolute value of schedule start variance cannot exceed C_b, even though the absolute value of $S_s - S_a = D_a - D_s$ can exceed D_b. Schedule start variance is greater than or equal to zero when $D_a = D_b$, because actual start will not have delayed the operation. Therefore, schedule start variance must be adjusted,

$$V_{s\ start} = C_b \frac{\min(D_a, D_b) - \min(D_s, D_b)}{D_b} = C_b \frac{\min(D_a, D_b)}{D_b} - C_b P_s$$

$$= BCWP_s - BCWS \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (24)$$

- Schedule quantity variance, $V_{s\ quan}$, is the schedule variance due to the difference between projected and budgeted total quantity of output units:

$$V_{s\ quan} = C_b \frac{U_a}{U_p} - C_b \frac{\min(U_a, U_b)}{U_b} = C_b(P_a - P_b) = BCWP - BCWP_b \cdots\cdots\cdots (25)$$

$$= \text{Cost quantity variance}$$

- Schedule rate variance, $V_{s\,rate}$, is the schedule variance due to the difference between actual and scheduled units of output per day:

$$V_{s\,rate} = \min(D_a, D_b)\frac{C_b}{U_b}\left[\frac{U_a}{\min(D_a, D_b)} - \frac{U_b}{D_b}\right]$$

$$= C_b\left[\frac{U_a}{U_b} - \frac{\min(D_a, D_b)}{D_b}\right] = BCWP_b - BCWP_s \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (26)$$

[Use of $\min(D_a, D_b)$ in place of D_a here and for schedule resource variance, creates a positive rate variance that balances the negative quantity variance when $U_p \geq U_b$. It also balances the same term in start variance such that schedule variance equals start variance plus quantity variance plus rate variance.]

- Schedule resource variance, $V_{s\,res}$, is the schedule variance due to the difference between actual and budgeted units of resource input per day.

$$V_{s\,res} = \min(D_a, D_b)\frac{C_b}{R_b}\left[\frac{R_a}{\min(D_a, D_b)} - \frac{R_b}{D_b}\right] = C_b\frac{R_a}{R_b} - BCWP_s \quad\cdots\cdots\cdots\cdots\cdots (27)$$

which does not equal cost resource variance

- Schedule productivity variance, $V_{s\,prod}$, is the schedule variance due to the difference between budgeted and actual units of resources input per unit of output:

$$V_{s\,prod} = C_b\frac{R_a}{U_b}\left(\frac{U_a}{R_a} - \frac{U_b}{R_b}\right) = C_b\left(\frac{U_a}{U_b} - \frac{R_a}{R_b}\right) = BCWP_b - C_b\frac{R_a}{R_b} \quad\cdots\cdots\cdots\cdots (28)$$

which equals cost productivity variance.

Schedule variance equals schedule start variance plus schedule quantity variance plus schedule rate variance (where schedule rate variance equals schedule resource variance plus schedule productivity variance). Calculation of schedule productivity variance and schedule resource variance requires data on budgeted and actual resources, which may not be available due to lack of or complexity of resource information. Therefore, when resource data are not available, schedule rate variance can be calculated, but schedule productivity and resource variances cannot.

As stated earlier, a completed operation, even if completed late, cannot have a negative, unfavorable schedule variance. An operation completed ahead of schedule will have a positive, favorable schedule variance, which will decrease day by day until its scheduled completion is reached, after which its schedule variance will be zero. Eq. (22) for schedule variance converges linearly on zero as P_s approaches $P_a = 100\%$, and (24) for schedule start variance converges on zero as actual days reach budgeted days. However, the equations for schedule quantity, rate, resource, and productivity variances do not necessarily converge on zero as an operation is completed on time or late nor, if completed early, as the calendar reaches scheduled completion. Therefore, in implementing these equations, one must set them to zero at completion, as defined by $U_a = U_p$ and $P_a = 100\%$. These variances at completion can be made to converge to zero at or after early completion by multiplying them by Δ, which equals the ratio between the number of days remaining to scheduled completion and the number of days early the operation finished, defined by

$$\Delta = \max\left(\frac{1 - P_s}{1 - P_{sc}}, 0\right) \quad \text{for } U_a = U_p \text{ or } P_a = 100\% \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (29)$$

where P_{sc} = value of P_s when operation was completed

$$P_{sc} = \frac{D_c - S_s}{D_b} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (30)$$

Fig. 1(a) provides a graphic view of value and quantity variables, projected costs, cost variances, and schedule variances. All variances are unfavorable, which presents a conceptually consistent view and helps demonstrate projections beyond schedule and budget. Cost unit variables are shown on the vertical axis, and quantity unit variables are on the horizontal axis. Crosses in circles show the base of the calculations. Point (U_b, C_b) establishes the budget line, which is the solid line extending from the origin $(0, 0)$. The dashed extension from this point shows projected performance if budgeted output rate was followed to projected quantity U_p. Point $(U_a, ACWP = C_a)$ shows actual performance, and the dashed line from that point projects future performance at actual output rate to date. A third dashed line from point $(U_a, C_b R_a/R_b)$ projects future performance at actual productivity to date, if resource variance were zero. A fourth dashed line shows projected rate of earned value, at actual output rate to date. This terminates at total value C_b, point (U_p, C_b), which is the value earned when the element is completed. Cost and schedule variables are integrated, showing cost rate variance and quantity variance making up cost variance, and schedule rate variance, start variance, and quantity variance making up schedule variance. Projected cost variances are shown at the upper right. Schedule variances are not projected, because they will be zero at completion, particularly because completion is later than scheduled. Crosses show important intersections of cost and quantity variables. For example, a horizontal extension from $BCWS$ intersects the budget line at U_s and the earned value line at $P_s U_p$.
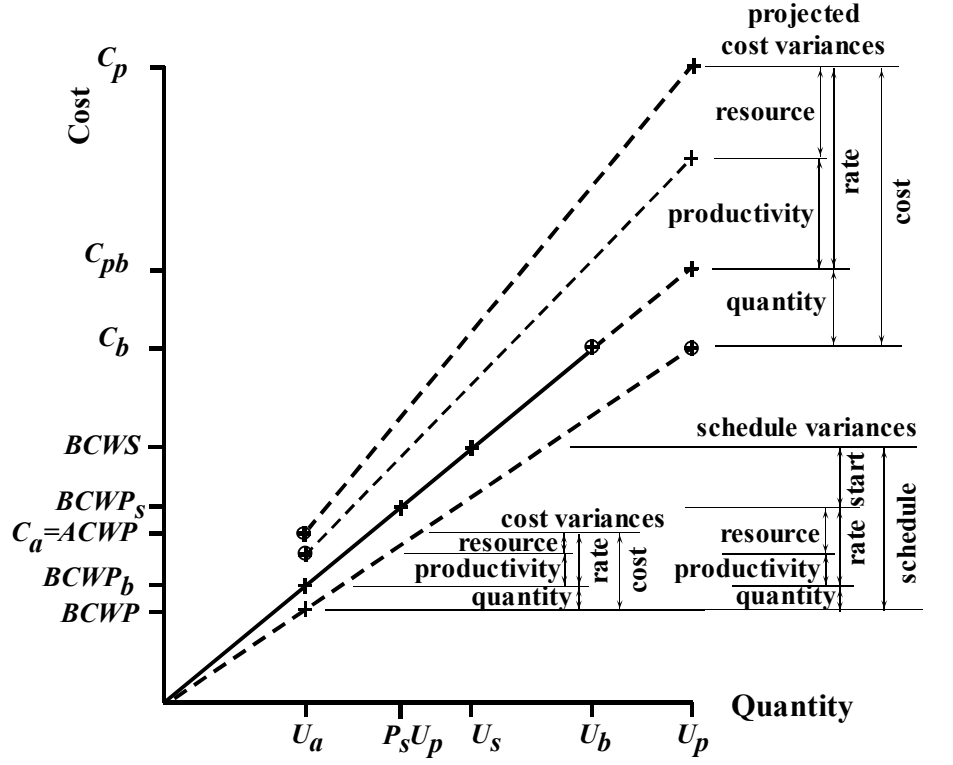
TIME VARIABLES

A systematic description of time relationships can be established for schedule control in parallel with the cost and schedule relationships described above. In this time system, work is measured against its budgeted or scheduled time, D_b. As work is performed, its completion is considered earned in proportion to its percentage of completion, P_a, in the same manner as earned value. The work's earned time is its budgeted time of work performed, $BTWP$, in parallel with $BCWP$ in the cost control system. $BTWP$ can differ from $BTWS$ because projected quantity differs from budget $(U_p \neq U_b)$, the start differed from that scheduled $(S_a \neq S_s)$, and the units performed per day differ from those budgeted $(U_a/D_a \neq U_b/D_b)$. The number of days since scheduled start is the actual time for work performed, $ATWP$:
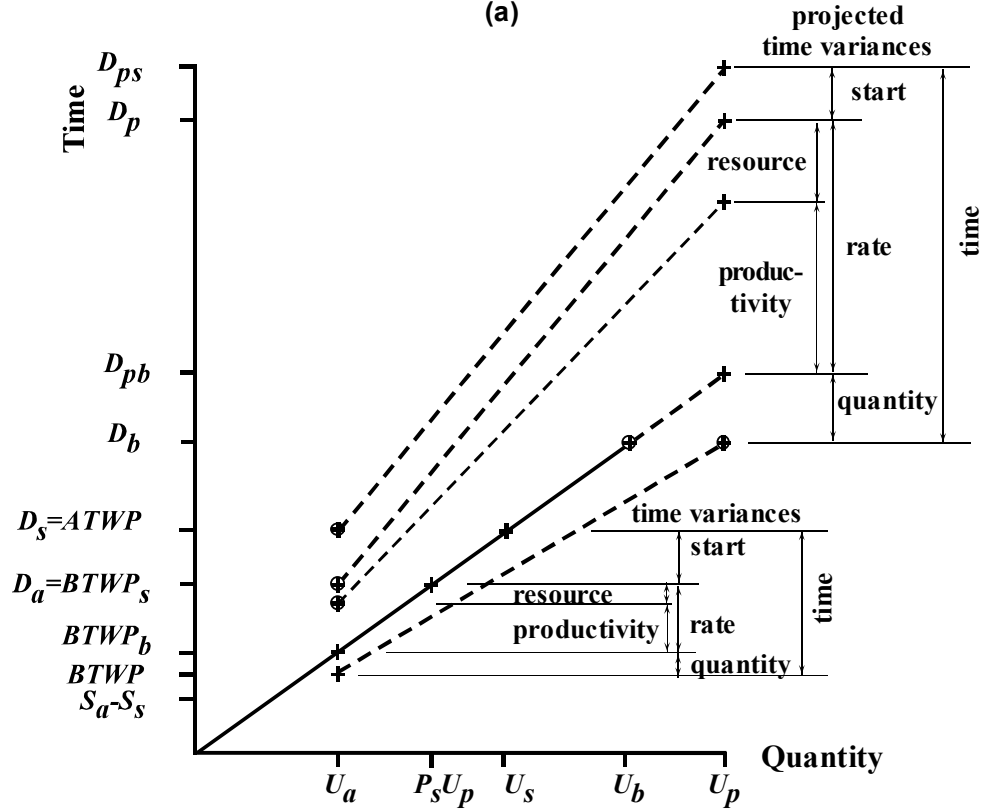
$$ATWP = \min(D_s, D_c - S_s) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (31)$$

$$BTWP = U_a \frac{D_b}{U_b} \frac{U_b}{U_p} = D_b \frac{U_a}{U_p} = D_b P_a \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (32)$$

$BTWP_s$ is $ATWP$ after adjustment for difference between actual and scheduled start (i.e., for $S_a - S_s = D_s - D_a$) but without adjustment for projected units of output (i.e., for U_p) or for actual rate:

$$BTWP_s = ATWP - (D_s - D_a) = \min(D_s, D_c - S_s) - (S_a - S_s) = \min(D_a, D_c - S_a) \cdots\cdots\cdots\cdots \quad (33)$$

FIG. 1. Variances (a) Cost and Schedule Variances: and (b) Time Variances

$BTWP_b$ is budgeted time for work performed if projected total units of output were those budgeted [i.e., substitute $U_p = U_b$ in (32)]:

$$BTWP_b = D_b \frac{U_a}{U_b} = D_b P_b \ \dotfill (34)$$

As with $BCWP_b$, $BTWP_b$ can exceed D_b where $U_a > U_b$.

TIME VARIANCES

Time variance, V_t, is the difference between budgeted time to produce the percentage of completion, P_a, represented by $D_b P_a$ and actual time to produce the output units to date U_a. Time variance is negative when time exceeds budget, which can be called a delay or a lag. A positive time variance is a lead. Time variances are measured in time, whereas cost and schedule variances are measured in money.

Time variance is the number of days between scheduled time and actual time to perform work to date:

$$V_t = BTWP - ATWP = D_b \frac{U_a}{U_p} - D_s = D_b P_a - D_s \dotfill (34)$$

Time variance is due to variance in operation starting, variance due to a change in projected output quantity, and/or variance due to rate of units produced per day. A time variance due to rate of units produced per day is due to variance in resources input per day and/or in productivity of those resources. These time variances are as follows:

- Time start variance, $V_{t\ start}$, is the difference between scheduled and actual start:

$$V_{t\ start} = S_s - S_a = D_a - D_s = BTWP_s - ATWP \dotfill (35)$$

- Time quantity variance, $V_{t\ quan}$, is the difference between scheduled and actual number of days to perform current percent complete at budgeted number of units per day:

$$V_{t\ quan} = D_b \frac{U_a}{U_p} - D_b \frac{U_a}{U_b} = D_b (P_a - P_b) = BTWP - BTWP_b \dotfill (36)$$

- Time rate variance, $V_{t\ rate}$, is the difference between number of days to perform units to date at budgeted and actual number of units per day:

$$V_{t\ rate} = U_a \left(\frac{D_a}{U_a} - \frac{D_b}{U_b} \right) = D_a - D_b \frac{U_a}{U_b} = BTWP_s - BTWP_b \dotfill (37)$$

- Time productivity variance, $V_{t\ prod}$, is the time rate variance due to the difference between budgeted and actual units of resources input per unit of output:

$$V_{t\ prod} = U_a \frac{D_b}{R_b} \left(\frac{R_a}{U_a} - \frac{R_b}{U_b} \right) = D_b \left(\frac{R_a}{R_b} - \frac{U_a}{U_b} \right) = D_b \frac{R_a}{R_b} - BTWP_b \dotfill \ (38)$$

- Time resource variance, $V_{t\ res}$, is the time rate variance due to the difference between budgeted and actual units of resource input per day:

$$V_{t\ res} = R_a \left(\frac{D_a}{R_a} - \frac{D_b}{R_b} \right) = D_a - D_b \frac{R_a}{R_b} = BTWP_s - D_b \frac{R_a}{R_b} \dotfill (39)$$

Time variance equals time start variance plus time quantity variance plus time rate variance (where time rate variance equals time productivity variance plus time resource variance). Time variances remain after element completion, unlike schedule variances which converge on zero. However, time variances of different operations cannot be summed to provide a project time variance. Instead, project time variance is

the time variance in completion of the last operation in the project, most of which is usually contained in that operation's time start variance.

PROJECTED DURATIONS AND TIME VARIANCES

Projected duration, D_p, can differ from budget, because the quantity of output differs from budget ($U_p \neq U_b$) and/or the rate of units of output per day differs from budget ($U_a/D_a \neq U_b/D_b$). D_{pb} represents D_b adjusted for projected quantity U_p but not for actual output rate. D_{ps} represents the projected time from scheduled start S_s to projected completion. The projected values are described by:

- Projected duration for total projected units of output at budgeted effort:

$$D_{pb} = D_b \frac{U_p}{U_b} \cdots\cdots\cdots (40)$$

- Projected duration to perform total projected units of output:

$$D_p = D_a \frac{U_p}{U_a} = \frac{D_a}{P_a} \cdots\cdots\cdots (41)$$

- Projected duration for total projected units of output plus difference between actual and scheduled start:

$$D_{ps} = D_a \frac{U_p}{U_a} + (D_a - D_s) = D_p + (D_a - D_s) = D_p - V_{t\ start} \cdots\cdots (42)$$

Time variances anticipated at completion can be projected from experience to date, in the same manner as cost variances can be projected, except for time start variances, which do not change once an element has started.

- Projected time variance, V_{tp}, is the number of days between scheduled time and projected time to complete the activity:

$$V_{tp} = D_b - D_a \frac{U_p}{U_a} - (D_s - D_a) = D_b - D_p - (D_s - D_a) = D_b - D_{ps} \cdots\cdots (43)$$

- Projected time quantity variance, $V_{tp\ quan}$, is the difference between the budgeted and projected number of days to perform the entire activity at the budgeted number of units per day:

$$V_{tp\ quan} = D_b - D_b \frac{U_p}{U_b} = D_b \left(1 - \frac{U_p}{U_b}\right) = D_b - D_{pb} \cdots\cdots (44)$$

- Projected time rate variance, $V_{tp\ rate}$, is the difference between the budgeted and projected number of days to perform the budgeted number of units:

$$V_{tp\ rate} = D_b \frac{U_p}{U_b} - D_a \frac{U_p}{U_a} = U_p \left(\frac{D_b}{U_b} - \frac{D_a}{U_a}\right) = D_{pb} - D_p \cdots\cdots (45)$$

As with projected cost variances, projected time variance variables equal their respective time variances to date divided by P_a, with the exception of start time variances. Therefore, projected time variances are easily calculated from their time variance to date counterparts. For example, projected time resource variance equals time resource variance divided by P_a. Time start variance is an exception, of course, because (1) If an operation has not started, there is no calculation for its projected start; and (2) once it is started, its time start variance is known and constant. As with time variances, projected time variance equals time start variance plus projected time quantity variance plus projected time rate variance (where

projected time rate variance equals projected time productivity variance plus projected time resource variance).

Fig. 1(b) is a graphic view of time and quantity variables, time variances, and projected time variances, in a format parallel to Fig. 1(a). All time variances are unfavorable. Time variables are on the vertical axis, in parallel with the cost variables in Fig. 1(a). The horizontal axis quantities are identical. Two points provide a base. Point (U_b, D_b) establishes the budget or schedule production line, shown solid from origin. Its dashed extension projects output to U_p at the budgeted output rate. Point (U_a, ATW = $_s$) shows time from scheduled start to date for actual output. Its dashed line with vertical intercept $S_s - S_a$ projects the to date output rate to completion time, D_{ps}. A parallel dashed line, which has vertical intercept at the origin, projects total duration, D_p. A fourth dashed line from point (U_a, $D_b R_a/R_b$) projects future performance at actual productivity to date, if resource variance were zero. A fifth sloped dashed line, with vertical intercept at origin, starting at (U_a, BTWP) indicates earned completion relative to projected quantity, U_p, and earned time. To date and projected time rate variance, time start variance, and time quantity variance sum to time variance. Crosses show important intersections of time and quantity variables. For example, a horizontal extension from ATWP intersects the budget line at quantity U_s, and it intersects the earned completion line at $P_s U_p$.

Obvious parallels among variances provide a base for their integration. A negative schedule variance parallels a negative time variance. An increased rate of output improves both. Schedule variances and time variances have resource and productivity rate variables, start variables, and quantity variables. Integration with cost variances is also expected, given that cost and schedule have the same magnitude of productivity and quantity variances. Therefore, one expects some manner of conversion among variances.

Cost variables, cost variances, and schedule variances in Fig. 1(a) plus time variables and variances in Fig. 1(b) are plotted against identical quantities. This provides a base for a graphic representation of cost, schedule, and time in Fig. 2. Consider the vertical cost axis of Fig. 1(a) and the vertical time axis of Fig. 1(b) to be folded about or rotated about the common horizontal quantity axis to produce Fig. 2, which shows the cost axis vertical and the time axis horizontal. A solid budget line slopes up from the origin, point (0, 0), to budgeted cost and duration, C_b and D_b. A dashed extension of the budget line projects the cost and duration, C_{pb} and D_{pb}, the operation would have at its projected quantity if its unit costs and output units per day and start were as budgeted. Dots mark important intersections of cost and time variables. Horizontal projections from the cost variables and vertical projections from the time variables would intersect the budget line at dots and show the common budget base of cost and schedule with time. *BCWP* intersects with *BTWP*, *BCWP$_b$* intersects with *BTWP$_b$*, *BCWP$_s$* intersects with *BTWP$_s$*, and *BCWS* intersects with *ATWP*. Intersections occur between a cost variable and a time variable in Fig. 2 where those variables have intersected a common quantity variable in Fig. 1. The intervals among the vertical cost variables are the cost and schedule variances of Fig. 1(a), and the intervals among the horizontal time variables are the time variances of Fig 1(b). The intersections at the budget line show schedule variances are proportional to time variances. Cost quantity variance equals schedule quantity variance; therefore, cost quantity variance is also proportional to time quantity variance. Cost rate variance is not proportional to time rate variance, though they share a common relationship to productivity, because only cost rate variance contains cost resource variance, and time rate variance contains rate of resources used.

A dashed line from point ($S_a - S_s$, 0) through point (*ATWP, ACWP*) has the slope of actual costs per day, and it projects cost and time at completion, C_p and D_{ps}. A parallel dashed line from the origin projects to final duration, D_p. Its horizontal offset is the time start variance, and its vertical offset is the budgeted cost of work scheduled for the time interval of the time start variance, *BTWP$_b$−BCWP$_s$*. The upper right portion of Fig. 2 shows integration of projected cost variances and time variance. Projected cost quantity variance and time quantity variance are proportional, but cost rate variance and time rate variance are not. Of course, projected schedule variances are not shown, because they are zero.

PIPING EXAMPLE

Table 2 shows reports for five periods for pipe. The first section shows budgeted values for pipe. These provide the base against which performance is measured, and they do not change with time. Pipe did not start in the first period (column 2) ending day 20, though it was scheduled to start day 5. Therefore, in period 1, pipe has a schedule variance and time variance due to a delayed start, but it has no cost variance or other schedule variance or time variance, though its estimated quantity has changed from the budget.

Pipe starts day 21, in period 2, and it is completed day 83, in the period 5. The example shows information flow during project progress, reporting values to date and projected at completion. Cost variances and some time variances grow, but changes in projected cost variances and time variances are more subtle. Schedule variances grow, then converge to zero as the element is completed after scheduled completion. The schedule start variance after four periods is zero, though the activity is not finished. Because $D_a = 59 > D_b = 50$, the activity would be finished despite the delayed start if its rate and quantity were as budgeted. Table 2 provides data that can significantly aid cost and schedule control as well as provide information of current and projected status.

Input of resource data allowed calculation of cost, schedule, and time resource variance as well as cost, schedule, and time productivity variance. Schedule variance goes to zero when pipe is finished in period five. However, pipe time variance and its contributions of start, resource, productivity, and quantity are retained. Projected values of cost and time variances converge on values at completion, which are retained.

PROJECT EXAMPLE

Table 1 shows project status at the end of three periods of 20 days for a project of four elements. Negative values are shown in parentheses. Excavation, pipe, and backfill are elements that have single measurable outputs, and landscape is lump-sum, represented by a quantity of one unit. Column 3 of Table 1 reports on the third period of pipe, which is column 4 of Table 2. P_a shows excavation is complete, and its $D_c = 58$ shows it was completed on day 58. Because it is complete, its projected values are the same as its values to date, and its schedule variances are zero.

Landscape demonstrates how a lump-sum element and an element without resource input can be represented. Because its quantity is one unit, which is typical of a lump-sum element, its units scheduled and produced is its percent complete. Resource information is not available, which is common for lump-sum elements, which may have complex, mixed resource inputs. Therefore, its resource and productivity variances are not defined. As a lump-sum element, with a unit quantity, it has no quantity variance, although its cost changes.

Element costs sum to provide project *BCWS, BCWP,* and *ACWP*. Project percent complete based on earned value is its earned value divided by its total budgeted cost, $\Sigma_{i=1,n} BCWP_i / \Sigma_{i=1,n} C_{b_i}$, where *n* is the number of elements in the project. Element cost and schedule variances sum to project variance, which provides a top down view of overall cost and schedule performance. Element times do not sum to project time, as is demonstrated in sections *i* through *l* in Table 1. Instead, project duration is the difference between the earliest start of an element and the latest finish of an element. Project time variance is the difference between project scheduled finish and projected or actual finish.

TABLE 2. Period Report for Pipe

Variables	Period				
	1	2	3	4	5
(1)	(2)	(3)	(4)	(5)	(6)
(a) Period Budget Calculations					
Days since project start (days)	20	40	60	80	100
Days since sched start, D_S (days)	5	25	45	65	85
Units scheduled, U_S (meters)	176	880	1,584	1,760	1,760
Resources scheduled, R_S (crew hours)	40	200	360	400	400
BCWS (dollars)	6,080	30,400	54,720	60,800	60,800
Scheduled percent complete, P_S	10.0	50.0	90.0	100.0	100.0
(b) Period Input					
Actual start, S_a (days)	–	21	21	21	21
Day completed, D_c (days)	–	–	–	–	83
Days since actual start, D_a (days)	0	19	39	59	62
Resources used, R_a (crew hours)	0	157	326	495	520
Units produced, U_a (meters)	0	533	1,165	1,776	1,867
Estimated total quantity, U_p (meters)	1,768	1,855	1,855	1,864	1,867
(c) Work Performed					
Actual percent complete, P_a	0	28.7	62.8	95.3	100.0
BCWP (dollars)	0	17,471	38,190	57,926	60,800
$BCWP_b$ (dollars)	0	18,414	40,253	61,359	64,487
$BCWP_S$ (dollars)	0	23,104	47,424	60,800	60,800
ACWP (dollars)	0	22,838	46,837	70,784	74,435
(d) Cost Variances To Date (dollars)					
Cost Variance, V_C	0	(5,368)	(8,647)	(12,858)	(13,635)
Quantity variance, $V_{C\,quan}$	0	(943)	(2,062)	(3,433)	(3,687)
Rate variance, $V_{C\,rate}$	0	(4,424)	(6,585)	(9,424)	(9,948)
Resource variance, $V_{C\,res}$	0	1,041	2,674	4,417	4,668
Productivity variance, $V_{C\,prod}$	0	(5,465)	(9,258)	(13,841)	(14,616)
(e) Projected Cost (dollars)					
At budget unit cost, C_{pb}	61,071	64,083	64,083	64,404	64,487
At actual unit cost, C_p	61,071	79,480	74,566	74,296	74,435
(f) Projected Cost Variances (dollars)					
Cost variance, V_{cp}	(271)	(18,680)	(13,766)	(13,496)	(13,635)
Quantity variance, $V_{cp\,quan}$	(271)	(3,283)	(3,283)	(3,604)	(3,687)
Rate variance, $V_{cp\,rate}$	0	(15,396)	(10,483)	(9,892)	(9,948)
Resource variance, $V_{cp\,res}$	0	3,623	4,256	4,636	4,668
Productivity variance, $V_{cp\,prod}$	0	(19,019)	(14,739)	(14,528)	(14,616)

TABLE 2. (Continued)

(1)	(2)	(3)	(4)	(5)	(6)
(g) Schedule Variances To Date (dollars)					
Schedule variance, V_S	(6,080)	(12,929)	(16,530)	(2,874)	0
Start variance, $V_{S\ start}$	(6,080)	(7,296)	(7,296)	0	0
Quantity variance, $V_{S\ quan}$	0	(943)	(2,062)	(3,433)	0
Rate variance, $V_{S\ rate}$	0	(4,690)	(7,171)	559	0
Resource variance, $V_{S\ res}$	0	775	2,087	14,400	0
Productivity variance, $V_{S\ prod}$	0	(5,465)	(9,258)	(13,841)	0
(h) Calculated times (days)					
ATWP	5.00	25.00	45.00	65.00	68.00
BTWP$_S$	0.00	19.00	39.00	59.00	62.00
BTWP$_b$	0.00	15.14	33.10	50.46	53.03
BTWP	0.00	14.37	31.41	47.64	50.00
(i) Time Variances To Date (days)					
Time variance, V_t	(5.00)	(10.63)	(13.59)	(17.36)	(18.00)
Start variance, $V_{t\ start}$	(5.00)	(6.00)	(6.00)	(6.00)	(6.00)
Quantity variance, $V_{t\ quan}$	0.00	(0.78)	(1.70)	(2.82)	(3.03)
Rate variance, $V_{t\ rate}$	0.00	(3.86)	(5.90)	(8.54)	(8.97)
Resource variance, $V_{t\ res}$	0.00	0.64	1.72	2.84	3.05
Productivity variance, $V_{t\ prod}$	0.00	(4.49)	(7.61)	(11.38)	(12.02)
(j) Projected Durations (days)					
Duration, D_p	50.22	66.12	62.09	61.93	62.00
with addition of start delay, D_{ps}	55.22	72.12	68.09	67.93	68.00
at budgeted units per day, D_{pb}	50.22	52.70	52.70	52.96	53.03
Completion	70.22	87.12	83.09	82.93	83.00
(k) Projected Time Variances (days)					
Time variance, V_{tp}	(5.22)	(22.12)	(18.09)	(17.93)	(18.00)
Start variance, $V_{tp\ start}$	(5.00)	(6.00)	(6.00)	(6.00)	(6.00)
Quantity variance, $V_{tp\ quan}$	0.00	(2.70)	(2.70)	(2.96)	(3.03)
Rate variance, $V_{tp\ rate}$	0.00	(13.42)	(9.39)	(8.96)	(8.97)
Resource variance, $V_{tp\ res}$	0.00	2.22	2.73	2.98	3.05
Productivity variance, $V_{tp\ prod}$	0.00	(15.64)	(12.12)	(11.95)	(12.02)

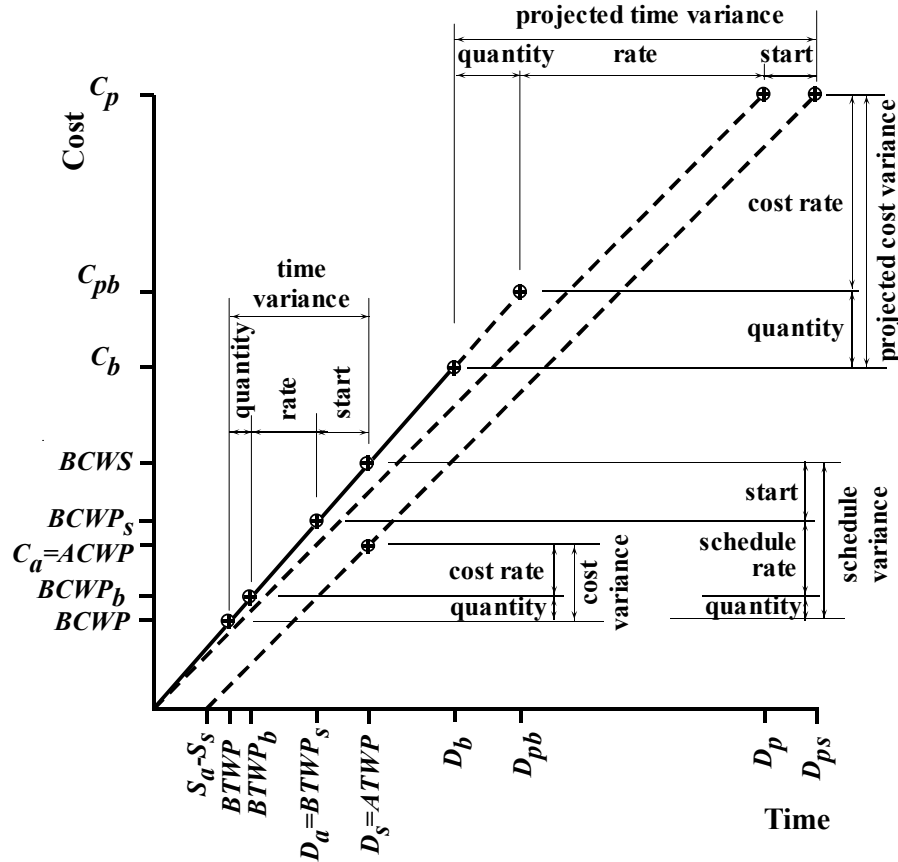Note: Units of measure for variables are shown in parentheses

FIG. 2. Integration of Cost Schedule, and Time Variances

LEVEL OF DETAIL

Users have a broad choice of level of detail at which to input data and report performance. Top management would want a single period report for all projects that listed each project's cost, schedule, and time variances. One can expect project management to want summarization at least at the system level. Elements can be summarized through any typical work breakdown system to report variances at different amounts of detail for foundation, structural, electrical, piping, and other systems. More detailed reporting can be focused on systems or elements that have large unfavorable variances. Obviously, the level of detail that can be reported is limited to the level of detail of input. A company can input and report different levels of detail for different systems, depending on who is responsible for system performance, performance uncertainty, or ease of obtaining data.

The primary function of project control is to identify unacceptable performance to focus management attention on projects, systems, and elements that can benefit from more detailed analysis. The level of detail described here can provide a quick path to understanding performance and a quick start to detailed analysis and problem solving to improve future performance.

This depth of detail also provides detailed documentation for settling disputes. Cost and schedule variance, in themselves, provide little information on cause that can document responsibility. With greater detail, one can document impact of quantity, resource use, resource cost, and productivity. Schedule variance also has a weakness in claim analysis, because schedule variance becomes zero when an activity or project is completed. However, time variance will capture and retain activity and project delay or lead times and the impact of quantities, resources, and productivities on delays or leads.

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CONCLUSIONS

Cost control and schedule control are important tools for managing projects. Cost and schedule performance share common variables on which an integrated view of cost, schedule, and time variances can be built if they share a common WBS. When represented in earned value units, the element quantity, rate, productivity, start, and resource variances can be summed to provide project quantity, rate, productivity, start, and resource variances. Element time variances parallel value variances. However, project time variances are not sums of element time variances, and project time variances are therefore not parallel with project cost and schedule variances. Earned value integration at the element level is paralleled by integration at the project level.

APPENDIX I.   REFERENCES

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Appendix II.   Notation:
The following symbols are used in this paper.

$ACWP$ = actual cost of work performed;
$ATWP$ = actual time for work performed;
$BCWP$ = budgeted cost of work performed;
$BCWP_b$ = $BCWP$ [for condition that $U_p = U_b$];
$BCWP_s$ = $BCWP$ [for condition that $U_p = U_b$ and $S_a = S_s$];
$BCWS$ = budgeted cost of work scheduled;
$BTWP$ = budgeted time for work performed;
$BTWP_b$ = budgeted time for work performed, if projected total units of output were those budgeted;
$BTWP_s$ = $ATWP$ after adjustment for difference between actual and scheduled start (i.e., for $S_a - S_s$), but without adjustment for projected units of output (i.e., for U_p);
C_a = actual cost incurred to date;
C_b = budgeted cost to complete operation;
C_p = cost for projected units of output at actual unit cost;
C_{pb} = projected cost for projected total units of output at budgeted cost per unit;
D_a = number of days to date since actual start of activity;
D_b = budgeted duration to complete operation;
D_c = day the operation was completed;
D_p = projected duration;
D_{pb} = projected duration for total projected units of output at budgeted effort;
D_{ps} = projected duration for total projected units of output plus difference between actual and scheduled start (i.e., for $D_s - D_a$);
D_s = number of days to date since scheduled start of activity;
n = the number of elements in project;
P_a = actual percent complete to date;
P_b = percentage of budgeted quantity that has been completed;
P_s = scheduled percent complete to date;
P_{sc} = value of P_s when operation was completed;
R_a = actual resources used to date;
R_b = budgeted input resources to complete operation;
R_s = resources scheduled to date;
S_a = actual start day;
S_s = scheduled start day;
U_a = actual units produced to date;
U_b = budgeted output units to complete operation;
U_p = projected output units;
U_s = units scheduled to be produced to date;
V_c = cost variance;
V_{cp} = projected cost variance;
V_s = schedule variance;
V_t = time variance;
V_{tp} = projected time variance;
Δ = ratio of number of days remaining for scheduled completion to number of days early the operation finished.