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Invited Paper

[PROC. OF JSCE No. 425/IV-14 (Infrastructure Planning and Management) January 1991]

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CONCEPTUAL APPROACH FOR COST/SCHEDULE INTEGRATION IN PROJECT CONTROL SYSTEMS

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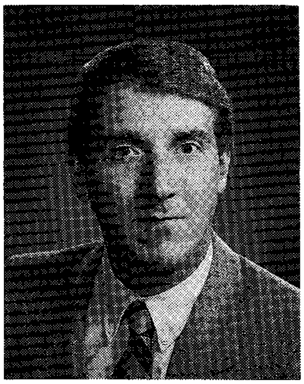

1. INTRODUCTION

Cost and scheduling systems have traditionally been designed and used as separate entities, each geared towards processing different information and meeting independent targets. Though complex, important interrelationships exist between cost and time, most contractors employ fragmented commercial application programs for these management processes. A few larger firms employ self-developed, relational systems that require major amounts of "care and feeding".

The absence of systems that link cost and schedule data in a manner transparent to the user complicates management's evaluation of project performance. Project managers frequently attempt to relate these two data sets to measure interactivity between cost and schedule for work methods analysis or change impacts. The hopes of system integration are that a better picture of a project status can be achieved and that it can be attained more quickly with less effort. Why then isn't integration practiced more commonly ? What solutions offer promise to this important problem ? What general research directions offer promise for successful implementation ?

This paper addresses these questions. It first discusses benefits and obstacles that underlie any integration effort. The discussion then critically examines a selection of integration models that have been proposed in the last few years. The relevant merits and circumstances for using these alternative models are simultaneously examined. Concluding the article is a "performance specification" for the ultimate cost-schedule model. To do this, the paper draws upon information gathered through extensive interviews with construction professionals as well as an analytical examination of the system models. The purpose of these interviews was partly to identify implementation difficulties that complicate efforts to achieve

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Keywords : cost/schedule control, project control, work breakdown structure, system integration

cost/schedule integration. They were also conducted to enhance our own vision of a proposed cost/schedule integration model that uses planning-level information as a basis and which utilizes the powerful object-oriented programming paradigm.

2. THE EVASIVE GOAL OF INTEGRATION

Historically the issue of cost and schedule integration has been extensively studied in both academia and industry. Yet no successful examples exist of functional integration of cost and schedule control systems. Here "successful, functional, integrated model" means a usable (computer) system that automatically links cost account and schedule activity information. This is principally due to the implementation difficulties, and less so to theoretical flaws. The main problem is prohibitive data recovery and maintenance cost. As a project proceeds increasing demands are placed on managers. As the field staff struggles to maintain control and meet deadlines, the new system is gradually neglected. Without timely updates and maintenance, it quickly loses its viability and is set aside.

Because integration is often implemented at the request of the client rather than because the contractor sincerely wants it, commitment lags and the effort fails. Numerous examples can be found of companies that coupled cost and schedule control systems because of client contractual stipulations, and then allowed to expire during that one project which prompted its creation, let alone subsequent jobs.

When questioned about the lack of integration between cost and schedule control systems, the answer was often in the form of one of two questions. One response was : Why would anyone want to integrate them ? The second and more common response was : Given the amount of effort needed to integrate them, is it really worth it ? There seems to be strong sentiment that the required effort is not worthwhile, indeed prohibitive. A large part of this sentiment is misperception because the benefits and costs have not been clearly articulated.

(1) Integration benefits

To understand the issues surrounding effective integration systems and how one might proceed to develop a usable system, it is instructional to catalog the benefits and costs of such an effort. Different people understandably see different advantages in an integrated approach, depending on their particular interests, experiences and responsibilities. Taken together, potential advantages include :

- Synchronization of cost and schedule planning and control. This means in part that everyone is working with the same facts and assumptions.
- Single point data entry. Single-point progress updating would reduce project control costs in turn reducing total project costs. Alternatively, the same amount of money could be spent on other aspects of project control, sharpening overall job management.
- Better trending and forecasting of work in progress since many indirect ramifications are incorporated in the analysis.
- Improved time-cost tradeoff evaluations.
- Diagnosic evaluation of schedule delay or acceleration impacts on cost as well as improved analysis of the effects on schedule due to cost and labor changes.
- Easier generation of time-phased budgets and resource-loaded schedules. Better cash flow analysis, budget planning and resource management are byproducts of these "intelligent" budgets and schedules.

These benefits have the potential to justify the investment required to build and maintain this type of integration. Still, significant obstacles stand in the way of achieving meaningful and functional integration between cost and schedule.

(2) Obstacles to integration

Two obstacles to cost/schedule integration can be readily identified :

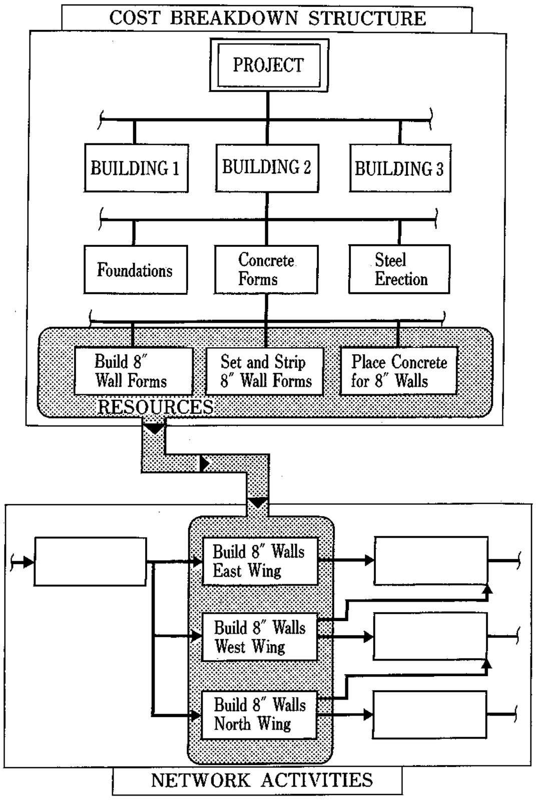
a) The organizational dimension Historically, cost and scheduling control responsibilities have been assigned to different and independent functional groups or personnel within the contractor's organization. The result is that these functionally independent groups traditionally have approached project control from different perspectives and with clearly different goals. They also collect their data with different accuracies and at different times. Given the mutual independence of the two groups, no real incentive usually exists for either to coordinate its operations and data with the other.

b) The level of detail dimension An increased level of detail is usually associated with cost/schedule integration, along with a corresponding increase in data collection, handling, analysis and storage. This has added cost implications which have to be viewed in contrast to the added control value of increased detail. This leads to enunciation of our first general control principle.

> Planning and control principle #1 : Designing any information system requires that its level of detail be set so that the benefits are greater than the costs of capturing, verifying, using and maintaining that information.

The limitation of practical information handling is extremely important within the context of a construction project. Work is broken down to cutoff levels that represent the levels of smallest detail that the contractor is capable of and interested in tracking and managing.

Cost engineers and schedulers usually work with different work breakdown structures; see Fig. 1. Though generalizations are tricky, cost breakdowns are oriented more toward similar work classifications while schedules have more of a locational flavor. Some Federal government projects mandate such a common breakdown, as we discuss later, but that is a minority. In the absence of a common breakdown, each side of the corporate organization attempts to optimize the amount of information it uses. Most of the jobsite effort is aimed at generating reliable, auditable and usable project information. The breakdown may also differ because sometimes there is only one level for a schedule.



Adapted From : (Teicholz 1987)

Fig. 1 Dichotomy of cost and schedule breakdown structures.

> Planning and control principle #2 : A common work breakdown structure must be present to unify cost and schedule systems.

Cost managers advocate account consolidation because it reduces data collection costs, facilitates allocation to appropriate cost centers, and smoothes the data for statistical analysis. This philosophy requires consolidating those accounts into higher level accounts for which data collection is going to be difficult. Schedulers track events and their sequence in real-time , so they need measurement events that are discrete, not aggregated.

Some overlap and commonality does exist between cost and schedule information. For instance, resource needs and consumption rates, responsible management, and physical location of the work are normally strongly implied if not outright specified. In the early stages of planning, both control systems are fed data from the same source information; namely, a detailed estimate. Schedulers take that information and add a time element. Conversely, cost engineers summarize that information into cost centers to form budget control baselines.

A major consideration in this translation process is streamlining and simplifying data collection. Some of that information is bi-directional in that it slips easily between the two data sets with no modification; e. g. the name of the manager responsible for a particular work task. If both systems can be set up to use information at the same level, integration is possible. Actual experience, however, shows that this is not common.

Contractors that attempt to link their cost and scheduling systems are usually faced with the exhausting exercise of mapping the estimate or cost accounts to the schedule activities. If data capture and processing were not concerns, the ideal linking would be in the form of one account to one activity (1 : : 1) mapping. That way the related cost and schedule elements are identified directly and unambiguously. One account to many activities (1 : : M) and many-to-one (M : : 1) account to activity mapping is often necessitated pragmatically because of disparate levels of detail and incompatibility in the cost and schedule breakdown process. Illustrations include mapping work to be performed in different geographic locations, points in time or responsible personnel. The resulting multidirectional links, including many-to-many (M : : N) mappings, hinder cost/schedule interaction. Maintaining the complex maze of links to reflect baseline changes to the cost and schedule elements on both sides of the links becomes difficult, time consuming and frustrating.

> Planning and control principle #3 : Mapping has to be achieved at the most detailed level possible to gain the highest degree of project control.

This entails forcing both the cost and schedule breakdowns to similar forms and levels of detail. Not necessarily identical, but similar. The problem lies in the practical consideration of the level of effort needed for achieving and maintaining such linking. On larger projects 1 000-2 000 control accounts and 3 000-5 000 control activities may be involved. Given that separate, disparate cost and schedule breakdowns are usually used, a 1 : : 1 mapping between accounts and activities is difficult and expensive to manage, especially if created just for construction. The complexity of a mapping approach to integration can be overwhelming.

3. INTEGRATION UNDER C/SCSC

(1) Background

The U. S. Department of Defense (DOD) has long been a major procurer of contract services, both in defense and construction-related contexts. Recognizing the importance of cost/schedule control—and hence the appeal of system integration—it issued a document entitled "Cost/Schedule Control System Criteria" (C/SCSC) outlining monitoring procedures for defense contractor performance. Since the original issue of those 35 criteria in 1967 they have been repeatedly updated (e. g., 1972, 1977, 1987) to account for contract practice improvements. In an effort to insure uniformity in application, the various defense agencies jointly published a more comprehensive description of the criteria under the title "Cost/Schedule Control Systems Criteria Joint Implementation Guide" (JIG) in 1980. Although first introduced and implemented by the military procurement establishment, the criteria have been adopted in full or in part by other governmental agencies and some private companies.

The imposition of the criteria on defense contractors had the following objectives[4] :

1. To merge the activities of planning, task definition, work authorization, budgeting, accounting, and scheduling into one all-inclusive management control system.
2. To require detailed, comprehensive planning which may be quantified and measured along the way.
3. To focus management's attention on earned value.

Of particular interest to this paper's focus are those C/SCSC aspects designed to achieve integrated cost/schedule control.

(2) The relevant criteria

C/SCSC defines a cost account as a management control point at which actual cost can be accumulated and compared to budgeted cost for work performed[2]. A cost account is a natural control point for cost/schedule planning and control since it represents the work assigned to one responsible organizational element on one contract work breakdown structure (CWBS) element.

A CWBS is developed and used by the contractor in accordance with the contract work statement. The criteria require each contractor to use only one WBS to define the work. Cost accounts are the lowest elements displayed in a CWBS. A cost account must combine one CWBS element with one responsible unit in the contractor's organization (Fig. 2). Because a military procurement typically consists of multiple contracts, the Owner, e.g. DOD, develops a project summary work breakdown structure (PSWBS) that merges all contracted (CWBSs) and non-contracted (the owner's WBSs) work. A PSWBS is a summary WBS prepared by the Client for a specific project or program. Typically, it defines project elements through Level 3 shown on Fig. 2. Contract work breakdown structures then extend the PSWBS to the cost account level. Naturally there is no set rule that a job has to be defined to this many levels; these are only guidelines.

C/SCSC also requires that a master project schedule encompassing all contracts be used. This master schedule is developed by the owner and defines major milestones. A project logic network may also be developed by the owner. For each of the project contracts the contractor is responsible for developing a contract master schedule that ties into the project master schedule. S/he is also required to prepare

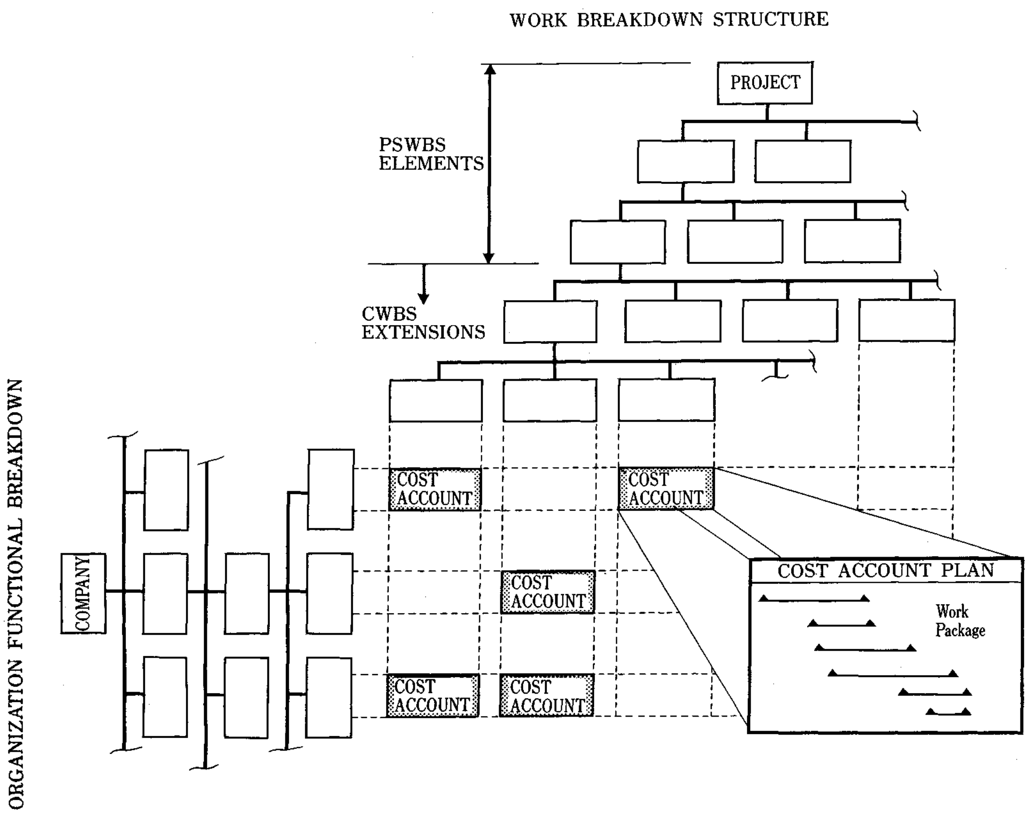


Fig. 2 Work and organization breakdown structures for C/SCSC.

intermediate level schedules for the functional departments and contract work breakdown structure. For each functional or CWBS schedule, a cost account schedule has to identify specific start and end dates. In effect each contractor has to demonstrate the work sequence within the contract period.

Every contractor is also required to establish and maintain a time-phased budget for each cost account in the CWBS. By assigning budgets to scheduled cost accounts, a time-phased budget plan at the cost account and contract levels can be developed. The contract time-phased budget is used as a baseline against which contract performance is measured. C/SCSC further requires that cost accounts be divided into short-span work packages to the extent possible. This assists cost account scheduling. A cost account budget has to distributed between its constituent work packages. This has the effect of increasing the extent to which a contractor has to define discrete budgets. Work packages are also intended to facilitate determination of work progress or earned value.

(3) Government vs. construction contractor control needs

The control needs of the U. S. government and private construction firms are quite different. Systems that abide by the goals of C/SCSC allow government agencies to determine the cost and schedule status of their procurement programs on a monthly basis and better predict final costs. C/SCSC was developed by DOD basically for cost reimbursable major procurement programs. For many contractors, control needs center on competitively bid lump sum, unit price, or guaranteed maximum contracts. Under such contracts, every dollar of direct or indirect cost a contractor saves translates, partially or fully, to extra profit. And spending funds on controls of this type is often viewed as an extravagance.

C/SCSC has prompted modifications of more than one hundred control systems at private firms in the U. S.[4]. The firms include design, project management, construction management, and contractor firms. Many contractors specializing in government projects were forced to modify their underlying systems to meet the validation and reporting requirements of the criteria. Many companies though kept their basic control systems intact, and developed extensions or utilities that allowed their systems to pass the Government's validation process and produce the required reports. A few, including non-defense and hard money ones, incorporated some of the C/SCS concepts in their internal control systems. Those contractors recognized an enhanced control capability in C/SCS that their previous procedures could not provide.

Our investigations have revealed that cost accounts under C/SCSC may be insufficiently detailed for contractor control and data recovery efforts.

Planning and control principle #4 : A planning and control system should support a level of detail that : 1) permits performance monitoring to detect deviations, 2) explains variations in a way that corrective action can be taken, and 3) supports future project planning.

With this overview, the following section illustrates the various details of several prominent integration models.

4. EXAMPLES OF INTEGRATION MODELS

Several proposed models for cost/schedule integration can be found in the published literature. All propose a mapping of one sort or another and often use different terms to describe essentially the same thing. The subtle differences between these approaches include:

- Choice of cost generating elements to be linked to schedule activities, e. g. cost accounts or estimate line items ;
- Creation of a new common denominator control element from the intersection of cost and schedule control elements ; and importantly,
- The level of breakdown advocated, usually on the cost side.

They should be viewed as evolutionary, extensions over time, rather than as separate paradigms or models per se. Also, they were not consciously built upon each other.

(1) Example 1

Sears describes an integration scheme that promises to deliver many desirable functions[11]. These include :

- Giving quantitative cost information about schedule delays.
- Evaluating in-place quantities for cost reporting based on the progress status of the CPM activities.
- Producing a cash flow projection.
- Facilitating time-cost tradeoff evaluations.
- Segregate acceleration costs to support claims and to update historical data bases in an undistorted fashion.

He argued that cost and schedule should receive comparable levels of detailed analysis, and thus advocates a flexible mapping strategy. This entails a model that allows 1 : : 1, M : : 1, 1 : : M, and M : : N mapping between cost accounts and schedule activities. Here cost accounts usually have no durations or location implications and are concerned with a single crew.

Mapping is achieved by associating each account with its related activities and distributing the estimated work quantity among them. Using unit cost and production rates, each linked activity can be resource loaded according to its share of the account's work quantity. This provides the ability to project cash flows.

Sears also describes how in-place quantities for cost reporting can be automatically evaluated from the progress status of CPM activities. For any one account :

COST ACCOUNT 03100.2800
FORM SHAFTS

	ACTIVITY QUANTITY	ACTIVITY PROGRESS	QUANTITY TO DATE
Form Elevator Shaft 1st Floor	3 840 S.F.	80%	3 072 S.F.
TOTALS	3 840 S.F.		3 072 S.F.

Source : (Sears 1981)

Fig. 3 Example of 1 : : 1 mapping.

COST ACCOUNT 03100.2800
FORM SHAFTS

	ACTIVITY QUANTITY	ACTIVITY PROGRESS	QUANTITY TO DATE
Form Elevator Shaft 1st Floor	3 840 S.F.	80%	3 072 S.F.
Form Stair Shaft 1st Floor	2 240 S.F.	100%	2 240 S.F.
Form Pipe Shaft 1st Floor	1 960 S.F.	40%	784 S.F.
TOTAL	8 040 S.F.		6 096 S.F.

Source : (Sears 1981)

Fig. 4 Example of 1 : : M mapping.

COST ACCOUNT 03100.9800
PLACE WALL FORMS
10″ & 12″

COST ACCOUNT 03210.4700
TIE SHEAR WALL
REBAR

QUANTITY TO DATE	ACTIVITY QUANTITY		ACTIVITY PROGRESS	ACTIVITY QUANTITY	QUANTITY TO DATE
1 708 S.F.	4 270 S.F.	Form Elevator Shaft 1st Floor	40%	18 907 LB.	7 563 LB.
1 708 S.F.	4 270 S.F.	TOTALS		18 907 LB.	7 563 LB.

Source : (Sears 1981)

Fig. 5 Example of M : : 1 mapping.

$(Q_j)_{\text{TO-DATE}} = PC_j * (Q_j)_{\text{TOTAL}}$

The "Activity Quantity" represents the activity's share of the account's work quantity. The account's in-place quantity is the sum of Quantity to-date for all related activities. For activities that are mapped to more than one account, this calculation assumes that work under all accounts starts, progresses, and finishes concurrently and at a uniform rate. With substantial activities this assumption can result in erroneous account progress evaluations. The author suggests the use of conventional field measurement of quantities for accounts with such activities. Sear's concept of joint progress updating is demonstrated by example for 1 : : 1, 1 : : M, and M : : 1 mappings in **Fig.** 3-5.

(2) Example 2

A next major step for integration models was proposed by Teicholz[7]. The premise here is that a given cost code may involve the same type of work performed in several locations. From a cost control point of view, separating each location in a different account is not justified because typically the work would be performed by the same crew and foreman, and have (roughly) the same unit productivity. In actuality separation of like work performed in different location causes coding difficulties. Since the same crew may work in more than one location during the same day, it can be difficult for the foreman to allocate the crew's work hours to those various locations. In contrast, task scheduling usually must capture the fact that different locations are involved, because location is often the source of logic dependencies. The result is that each work segment is planned and scheduled as a separate activity.

Teicholz's approach recognizes this and is developed on a flexible mapping between cost accounts and schedule activities. It allows one account to be related to one or more activities, and one activity to be related to one or more accounts (**Fig.** 1). The following mathematical description models this M : : N relationship and the allocation process for the resources from a cost account to its related activities:

Let,

i = index on cost accounts

j = index on activities

r = index on resources ($, manhours, etc.)

$BTOT_{ir}$ = total budget amount of resource r at account i

$BTOT_{ijr}$ = total budget of resource r allocated from account i to activity j

F_{ij} = fraction of account i allocated to activity j (assumed to be the same value for all resources), between 0 and 1

A_i = set of activities related to account i

Then,

$$BTOT_{ijr} = F_{ij} * BTOT_{ir}$$

Where,

$$\sum_{j \in A_i} F_{ij} = 1.0$$

Allocating to-date and remaining amounts is more difficult because each account's status (active, unstarted, finished) must be determined relative to the associated activity. Of course the costs of active work should be assigned only to active activities. This is handled by the following algorithm:

Let,

P_j = to-date time % complete of activity j (expressed in decimal form);

TD_{ir} = to-date amount of resource r at account i;

TD_{ijr} = to-date amount of resource r allocated from account i to activity j;

REM_{ir} = remaining amount of resource r allocated from account i to activity j;

$FTOT_{ir}$ = total forecast final amount for resource r at account i; and

$FTOT_{ijr}$ = total forecast amount of resource r allocated from account i to activity j.

Then

$$TD_{ijr} = TD_{ir} * k_{ij}$$
$$REM_{ir} = FTOT_{ir} - TD_{ir}$$
$$REM_{ijr} = REM_{ir} * m_{ij}$$
$$FTOT_{ijr} = TD_{ijr} + REM_{ijr}$$

Where

$$k_{ij} = P_j * \frac{BTOT_{ijr}}{\sum_{j \in Ai} (P_j) * BTOT_{ijr}}$$

$$m_{ij} = \frac{[1 - P_{ij}] * BTOT_{ijr}}{\sum_{j \in Ai} [1 - P_j * BTOT_{ijr}]}$$

Project Activity Group	Cost Account for Superstructure					
	204.1	204.2	204.3	204.4	204.5	204.6
First Floor	■	■		■		■
Second Floor		■		■		■
Third Floor		■	■	■		■
Fourth Floor		■	■			■
Fifth Floor		■	■			■

Adapted From : (Hendrickson and Au 1989)

Fig. 6 Mapping cost resources to schedule activities.

F_{ij} may be to set equal to the fraction of the work quantity of account i assigned to activity j. This is a meaningful way to allocate resources, but it does require a relatively detailed breakdown of work. In other words, the breakdown must expose, for each cost account, a meaningful physical work quantity that can be used as a unit of measure. This is not always the case though, especially with overhead resources like testing and supervision.

This formulation also explicitly addressed non-linear resource consumption during an activity's duration. Histograms were suggested because there is no one shape for all accounts nor for all resources on a single account. The shape depends on many factors, including whether resources curves are to be used for cash or cost allocations. Usually cash planning is the goal, as is a resource smoothed schedule for labor or equipment resources. It is possible to define sub-profiles for the individual resources as long as their sum equals 1.00.

This approach still may have inaccuracies which can arise from loss of synchronization between the cost and schedule systems. The ability to highlight these inaccuracies is a requisite of the integration effort. This linkage can be used to identify some potential data errors for screening and correction before formal reporting to management, too. Teicholz maintains that this flexible approach, despite its potential inaccuracies, represents a superior compromise to the 1: :1 mapping form.

(3) Example 3

Another approach connects cost and schedule by assigning the resources in each cost category or account to schedule activities, which in turn creates work elements[6]. A work element represents a resource in a particular cost category associated with a particular schedule activity. Work elements can be thought of as a cell in a two-dimensional matrix ; see the shaded box in Fig. 6. One dimension represents cost accounts and the other schedule activities. The matrix's work elements are uniquely indexed by the cost account that contains the relevant resource and the associated schedule activity.

This approach requires accumulating costs at a highly disaggregated level of detail which results in more precise, detailed project control. Simultaneously, an activity's cost can be calculated as the sum of all work elements costs appearing in that corresponding matrix row. Project cash flow can be generated and updated to reflect schedule changes.

This model, which is conceptually similar to the first one, faces difficult implementation problems. Until automated data capture mechanisms arrive it will be impractical to sustain the required data collection effort. Recent developments in computer-based technologies do justify some optimism about increased automation of field data recovery and reporting.

(4) Example 4

Grobler defines a common denominator for cost/schedule integration by use of PEC's (Primitive Element of Construction)[5]. These "atoms" are produced when a take-off line item, or some portion thereof, is assigned on a percentage basis to a scheduling activity. Take-off line items are a logical choice in this proposed object-oriented integration scheme because they can provide :

- Association between data and physical objects.

Table 1 PEC assignment process.

Description		Attributes						Assignment to Activities					
		Formwork		Rebar		Concrete							
		Quant.	Detail	Quant.	Detail	Quant.	Detail	Act.	%	Act.	%	Act.	%
0300 Superstructure													
0340 Concrete columns													
Floor 2		ft^2		lb		yd^3							
12×12	12	480		1 512		4.44		210	50	211	50	—	—
15×15	12	600		3 262		6.94		210	50	211	25	212	25
24×15	4	260		1 260		3.70		—	—	211	50	212	50
Floor 3													
12×12	12	432		1 361		4.00		310	25	311	25	312	50
15×15	12	540		2 126		6.35		310	25	311	50	312	25
24×15	4	234		1 134		3.22		—	—	311	50	312	50

Source : (Grobler 1988)

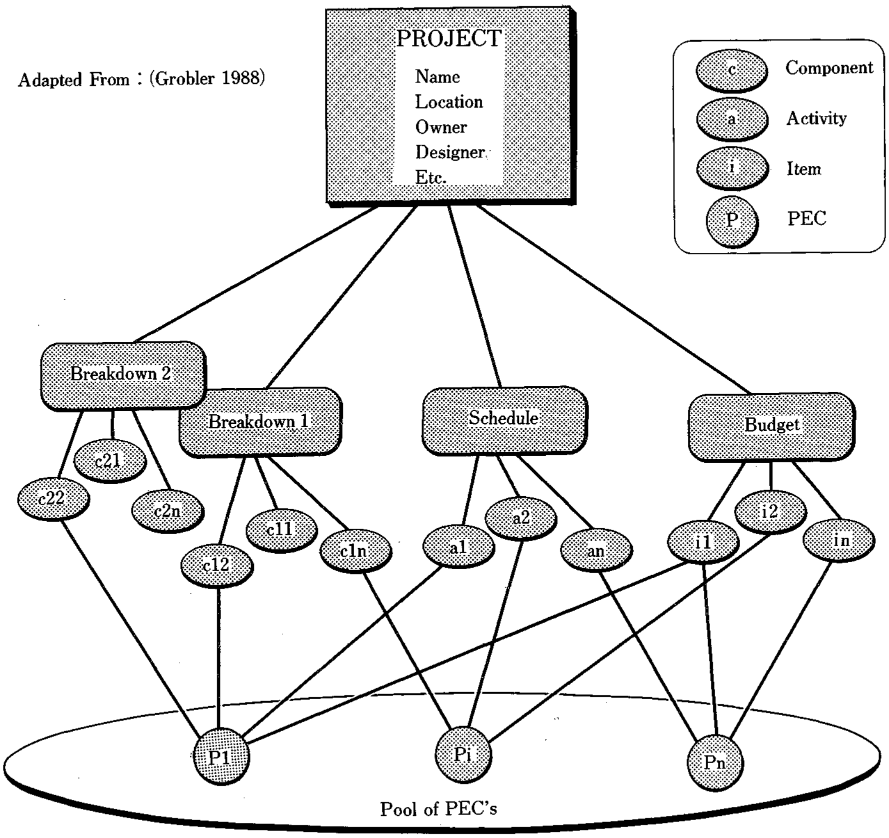


Fig. 7 Pool of PEC's.

- Task definition associated with a specific crew type or types.
- Potential association with cost.

In this model a take-off line item represents a number of objects. Each object represents a unit or item of work. An example might be a 12″×12″ concrete column. To integrate cost and schedule, the objects or work items represented by each take-off item have to be assigned to one or more schedule activities. Table 1 depicts the assignment process. Each assignment creates a PEC. PEC's ideally:

- Associate a task with a crew type and other required resources.
- Link a task with an object (or group of objects) which is (are) in turn associated with a representation

of the design model.

- Correspond the task to time.
- Do not aggregate tasks which are priced differently in the estimating process.
- Can be part of only one scheduling activity.

Using the object-oriented programming software technique[9], PEC's can be thought of as the lowest common denominator building block from which everything else is constructed. A project fundamentally would consist of a pool of PEC's shared by the different breakdown structures, schedules, etc. (Fig. 7). Thus the PEC becomes the lowest level control unit.

While Grobler illustrated how the allocation of PEC's to schedule activities is accomplished, he did not address how the allocation to cost accounts would be performed. For the link between cost accounts and schedule activities to exist, PEC's have to be allocated to cost accounts as well. Even if PEC's are allocated to cost accounts, it is not clear how that would result in a meaningful integration of cost and schedule performances. In addition, there is no discussion of how resources associated with PEC's are distributed over the time spans of schedule activities.

This model more than the others is susceptible to the data capture problem because a tremendous increase in the volume of data is involved. It does provide a conceptual link to much of the current research activity in design.

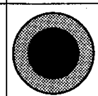
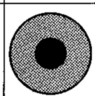
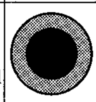
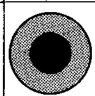
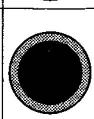
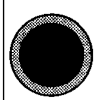
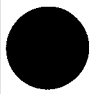
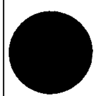
5. PRACTICAL APPLICATIONS

To summarize various features of the different integration models discussed in the previous section, Table 2 is presented. While most of the table's contents are self explanatory, the "Mapping Effort" and "Data Recovery Effort" columns deserve elaboration. For each example, the size of the black-filled bubble directly corresponds to the level of effort required. The shaded bubble in the background of the black bubble represents the ratio of the effort required by the specific example to that required by the most cumbersome example (Example 4).

More than anything else, this chart is meant to compare the effort required by each of the four approaches. They reflect our subjective evaluation. This format was selected in lieu of a quantitative indicator because we believe it is more straightforward and encompassing.

These approaches all provide flexible M : : N mapping between cost and schedule elements. Flexibil-

Table 2 Comparing the key features of various cost/schedule integration models.

Feature / Example	Common Work Breakdown	Cost-Related Entity	Mapping Type (Cost Entity-to-Activity)	Basis of Mapping	Resource Distribution Over Time	Mapping Effort	Data Recovery Effort	Comments
Example 1 (Sears)	NO	Cost Account	Many-to-Many	Activity's share of account's work quantity	Uniform			Perceived benefits are very worthwhile, but need to be demonstrated
Example 2 (Teicholz)	NO	Cost Account	Many-to-Many	Activity's share of account's work quantity	-Uniform -Bell -Front-end			Has been implemented in real life control system. It was used on one project only
Example 3 (Hendrickson and Au)	NO	Cost Account Resource	Many-to-Many	Activity's share of account's resource	Uniform			Mapping produces work elements which are the unifying entities between cost and schedule
Example 4 (Grobler)	NO	Take-off Line Item	Many-to-Many	Activity's share of line item's number of objects (quantity)	Uniform			Mapping produces PECS which are the unifying entities between cost and schedule

ity is a primary concern of most industry professionals. Although flexibility usually has positive connotations, that is not necessarily the case here. Without a common work breakdown for control accounts and activities, the schedule will inevitably include activities that encompass work falling under two or more cost accounts. Similarly, more than one activity will involve resources from the same account. Disparity in the levels of cost and schedule breakdown has a similar effect.

The C/SCSC concept has received more attention precisely because of this problem. Proponents argue that a common framework is necessary for true system integration. None of the schemes reviewed here explicitly proposes such. Part of the difficulties associated with mapping between cost and schedule could be directly attributable to the lack of a common breakdown. C/SCSC requires that such a common breakdown be used although integration currently takes place at such a high level of summarization that it is of minimal value for field control.

The reason for this relates back to Principle #1. If work packages are generated solely for construction control, the benefits available limit the amount of effort that can justifiably be expended in developing the control framework. However, if this control framework were used more fully throughout the entire project lifecycle—extending from the earliest stages of project planning all the way through the facility's operational management stage—a more detailed framework could be developed and level of control exercised.

One other point which arose in our investigation is that the management styles of companies and individuals vary radically. Some organizations maintain extremely detailed information, while other successful, large companies only use scheduling and control systems as demanded by the client. Even the same company's use will change depending upon who the client and the project manager are. That leads to another general principle :

> Planning and control principle #5 : Systems must be flexible to accomodate information needs of managers that change during from project-to-project and even during a single project.

One key here may be graphic displays of information which more quickly and easily allow a manager to grasp the general meaning of a set of data.

6. A MANIFESTO FOR FUTURE PLANNING AND CONTROLS RESEARCH

Having reviewed current industry practices and the research of others who have worked on this problem, we believe there are important research directions that should be pursued to bridge cost and schedule. We are now prepared to articulate them as a Manifesto for Synthesizing Planning and Control Systems. This vision is presented in Table 3.

We subscribe to the notion that the work package is a convenient, powerful paradigm by which to accomplish this integration goal. It is a compact, reasonably well-understood concept that could be adapted for integration purposes. What is lacking at this time is a mechanism that describes how cost and schedule information from different stages of a project can be joined. A promising solution can be seen from the substantial body of knowledge that has been developed in the building process model field. Sanvido's work is representative, though it is at a very high level of abstraction and decision-making compared to what is needed here[10].

Table 3 Research agenda for synthesizing planning and control systems.

RESEARCH AGENDA FOR SYNTHESIZING PROJECT PLANNING AND CONTROLS
Step 1 : Develop Individual Process Models for : * Cost Estimating & Control * Schedule Generation & Control * Work Packaging
Step 2 : Relate the Individual Process Models to a More General Integrated Project Process Model and to Each Other
Step 3 : Computerize and Verify the Deterministic Cost/Schedule Synthesis Model
Step 4 : Incorporate Probabilistic Considerations
Step 5 : Computerize and Verify the General Model

Research Task ♯1 : Define an integrated cost/schedule process model using representative work package models for the different project development phases.

This will necessarily require that individual process models first be developed for the individual cost estimating, scheduling and work packaging functions. Once these individual functions are defined, they should be unified. We anticipate that compromises will have to be made in this formation which means that the efficacy of the individual function process models will be somewhat sacrificed.

The object oriented programming paradigm shows promise as a powerful tool for acheiving this objective[9]. This paradigm has the ability to define objects that can carry and define their own methods and procedures. For instance, a heating system object could carry design-level performance information as well as trigger an estimating method reflecting the level of detail available at that point in time.

Fig. 8 demonstrates the evolutionary work package definition process that we envision, with links all the way back into the earliest project planning activities. Figs. 9-12 detail examples at each of four planning-design-construction phases. Each of these project stages is identified with a characteristic goal of the work packaging definition effort. Also there is a narrative definition of the work scope and salient parametric information such as cost and schedule.

Each of these work packages representing the different phases has a pointer linking it to other packages, both in that phase and in adjacent phases. This particular representation is hierarchical, the most common occurrence in construction. For instance there is a planning package that scopes the functional needs (Fig. 9) and it has five pointers to subsequent work packages in preliminary design. Similarly, there is a series of tagged work packages in preliminary design that lead to detail design requirements. Each level refines the information requirements and information available for control of that work package. What is crucial about this model is the process knowledge that allows extrapolation or decomposition up and down this hierarchy.

Given that there is a definite need for a process model specifically oriented to integrated cost-schedule planning and control, a key question becomes how to identify and define the grammar that links cost information across the phases[8]. That is,

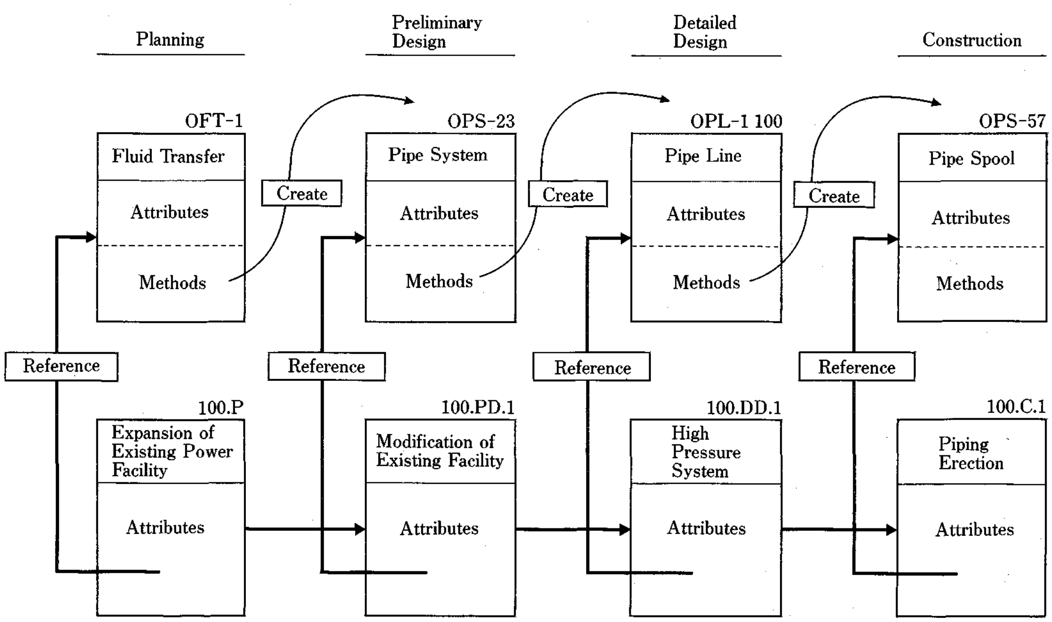


Fig. 8 Evolutionary definition of work packages and unification objects.

Expansion of an Existing Power Facility	100.P
Planning	
Functional Need Definition	
Work Package Definition : Determine Functional Needs, Overall Scope, Budget, Milestone Schedule, etc. Process Technology : Modified Fossil Fuel Processing Related Work Packages : In Preliminary Design : 100.PD.1, 100.PD.2 100.PD.3, 100.PD.4, 100.PD.5 Estimate Type/Amount : Class Z/$45 000 - 70 000 Schedule : Complete Conceptual Planning By May 31, 1984 Responsibilities : Planner : PG&E/Berkeley Engineering	

Fig. 9 Planning work package.

Modification of Existing Facility	100.PD.1
Preliminary Design	
Detailed Functional Need Definition	
Work Package Definition : Scope Definition, Including Alteration of High Pressure System Preliminary System Definition : Develop P&ID Related Work Packages : In Detailed Design : 100.DD.1, 100.DD.2, 100.DD.3, 100.DD.4 Estimate Type/Amount : Class F,X,Y/$50 000 - 75 000 Schedule : Develop P&IDs By Aug.31,1984 Responsibilities : Designer : Berkeley Engineering	

Fig. 10 Preliminary design work package.

High Pressure Steam	100.DD.1
Detailed Design	
System Definition	
Work Package Definition : Design of Pipe Spool HPS-XY12, Including Analysis And Mat'l Specification Component Definition : Steam Supply For Reheat Unit Related Work Packages : In Construction : 100.C.1, 100.C.2, 100.C.3, 100.C.4, 100.C.5 Estimate Type/Amount : Class C,D,E/$100 000 - 125 000 Schedule : Release To Field By Oct. 1, 1984 Responsibilities : Designer : DeAnn Tyler	

Fig. 11 Detailed design work package.

Piping Erection	100.C.1
Construction	
Component Installation	
Work Package Definition : Install Spool HPS-XY12-L110 Crew/Equipment Definition : P/F-4 Estimate Type/Amount : Class A,B/$110 000 Schedule : Start Nov.7,1984 Finish Jan.13,1985 Responsibilities : SUP'T : Zachary Tyler	

Fig. 12 Construction work package.

Research Task #2 : Define the semantic relationships which connect these phase-based work packages as they progress through various project phases.

Fig. 9-12 illustrate the types of critical information that must be provided at each phase. This means that the methods and procedures that are followed in moving across these project phases must be explored and modeled. Research in planning and controls semantic process modeling is already underway by this investigation team[3),8)]. An important corollary is :

Research Task #2A : Define the knowledge—including methods and behaviors—that defines the "boundary conditions".

When, for instance, is a distillation process best served by a settling tank as opposed to an agitating mechanism ? Capacity and flow levels, and chemical and thermodynamic properties are definitely involved, so this new model must have some "deep knowledge" capabilities.

Finally, there is the broad issue of probabilistic representation. The process modelers to-date have largely ignored uncertainty in their representations. This is not acceptable in the cost and scheduling domains, and probably not any domain.

Research Task #3 : Verify this model, preferably by computerizing it.

As with all good research, the theory should be substantiated and calibrated with actual experimental data.

Research Task #4 : Layer a probabilistic representation over the deterministic process model.

Research Task #1 addressed a process model for general, deterministic conditions as a way to simplify the problem. Clearly this is insufficient for the long-term. Rather a more accurate model is needed to describe the vagaries of projects. Probabilistics and influence diagrams can be useful for this task.

An initial step in understanding these variations should be to study practices in significantly different industries ; e. g. building construction and industrial plant erection. A study of this nature would provide insight into such issues as WBS definition, data collection practices and organizational structures.

The research proposed here will not by itself directly address the data capture problem repeatedly stressed in this paper. But with electronic representations of design and increased emphasis on system integration becoming commonplace, the information needed to create these linkages would largely be available. These representations would then be available at little incremental cost and effort.

Research Task #5 : Computerize and verify the general model.

For the same reasons as explained under Task #3.

7. SUMMARY AND CONCLUSIONS

Companies and individuals have traditionally created segregated environments of decision making. The result is that we have islands of decision making with different people making different decisions for different purposes. Coordination between these islands of decision makers is absent, creating information exchange gaps.

Market pressures are now driving industry toward improving productivity through integration and automation. Completely independent cost and schedule systems are ineffective and wasteful of scarce corporate resources, including personnel which will be a critical resource over the next 20 years. There are data for estimating, accounting, scheduling, claim analysis, etc. All that data can be considered to be basically one set of data. Traditionally, the practice has been to have specific and separate files serve each application. Duplication and inefficiency cannot be avoided in such an approach. A more desirable scenario is one central set of data that serves all applications or functions. Such an approach requires reconsidering the way work is broken down and planned, and the way information is collected, organized and stored. One central data set for all project functions is appealing though a distant reality.

An intermediate step toward the penultimate integrated data base will probably be database "islands" that "display centralized behavior"[1]. That is, a number of data/information-bases that are in the eyes of the user connected seamlessly, though in fact may actually be separate. With an integrated repository of data, the goal of integrating various applications or functions becomes possible.

Cost/schedule integration will ultimately be achieved. It will come as a byproduct of the larger quest of integrated project design, planning and execution. The potential payback of the larger goal is simply significant enough to prompt a fresh look at how the industry conducts its business. In our judgement some form of an object-oriented representation based on early project definition activity and needs will be the key. The solution will lie not in just coding certain physical components and typical construction tasks. Rather, the major research task will be to define how the object unification process transpires. When that happens, the cost and schedule will have moved much closer toward being technically integrated.

APPENDIX—NOTATION

A_i=set of activities related to account i;

$BTOT_{ijr}$=total budget amount of resource r allocated from account i to activity j;

$BTOT_{ir}$=total budget amount of resource r at account i;

F_{ij}=Fraction of account i allocated to activity j (assumed to be the same value for all resources), between 0 and 1;

i=index on cost accounts;

j=index on activities; and

PC_j=Activity j's percent complete

$(Q_j)_{TO\text{-}DATE}$=Quantity of work for activity j completed to-date

$(Q_j)_{TOTAL}$=Total quantity of work for activity j

r=index on resources ($, manhours, etc.).

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(Received December 14 1990)