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# An Introduction to the Management Principles of Scheduling

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*Abstract*

This report is intended for executives and project managers who need to understand the benefits of scheduling and how they are produced and used. The fundamental concepts of project scheduling are reviewed and an emphasis placed on language and the process inputs and outputs. The scheduling process is discussed in terms of the CPM forward and backward pass techniques and resource leveling techniques.

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# 1 Introduction

Construction project scheduling has evolved into a powerful and complex management tool. The level of expertise for schedulers has risen considerably; however, the level of understanding of managers and executives who supervise them has lagged. As a result, the proper use of scheduling language and an appreciation of the importance and complexity of the scheduling process have decayed. In order to bridge the growing divide, this report emphasizes the key management aspects of scheduling. Accordingly, the intended audience is an executive or manager who needs to know why scheduling benefits project management and how schedules are produced and used. The topics encompass the basics of scheduling with specific emphasis on language, the inputs to the process, and the outputs. The first section defines scheduling and establishes its utility, describing *what we want* a schedule to do. Appropriately, there is information that must be provided to the process, inputs such as activities, logic, and resources. Because the growth of computer-aided scheduling, the process is largely hidden within the "black box" of scheduling software. However, to gain an appropriate appreciation for what the software do, this discussion explains and illustrates the basics of the process, calculating starts, finishes, and floats, leveling resources, and creating commodity curves. The resulting outputs and a general understanding of their implications are subsequently discussed.

## *1.1 Planning and Scheduling*

Planning establishes *what*, *how*, *where* and *in what order* work will be performed, while scheduling sets forth *who* and *when*. Construction planning is the development of a feasible operational design for completing the work. The process involves the selection of work sequence and methods, and provides information for the scheduling process. Scheduling determines the timing and specific sequence of tasks necessary to carry out the plan. The schedule is a result of the planning process and reflects the selected plan. Therefore, an inability to schedule stems from a reluctance or incapacity to plan.

### 1.1.1 Planning

The construction plan defines the work to be completed and the order in which it will be accomplished. Developing a plan is critical to managing the construction and involves five steps:

1. Determination of the general approach to the project
2. Breaking the project into activities
3. Establishing sequential relationships
4. Presenting the plan graphically as a network
5. Endorsement of the plan by the project team [Clough et al. 2000]

Forming a construction plan is a challenging task, as it requires backward reasoning abilities. Sherlock Holmes noted:

> *"Most people, if you describe a train of events to them, will tell you what the result would be. They can put those events together in their minds, and argue from them that something will come to pass. There are few people, however, who, if you told them a result, would be able to evolve from their own inner consciousness what the steps were*

*which led up to that result. This power is what I mean when I talk of reasoning backward."[Doyle 1930]*

Planning construction projects "requires an intimate knowledge of construction methods combined with the ability to visualize discrete work elements and to establish their mutual interdependence"--backward reasoning [Clough et al. 2000]. A great deal can be learned regarding a project through the planning process. Potential problems are often identified and addressed well in advance of construction.

The plan is graphically displayed as a precedence diagram, which completely and accurately presents the work activities and their interrelationships. To develop a complete network, it is necessary for the planners to visualize and consider the entire project from start to finish. The network clearly shows the sequence of work and is an efficient means of communicating the plan.

### 1.1.2 Scheduling

The scheduling process determines the timing of work activities identified by the planning process and results in a project schedule. The "schedule" means various things depending on its intended use. Typically, it represents sequencing and phasing of individual activities required to complete the work. The schedule is a management tool used to predict project completion, and thereby ensure timely completion by adjusting resources applied to the work.

The initial steps to developing a schedule are

1. Estimating the time required for each activity
2. Computing the time required for project completion
3. Establishing time intervals in which each activity must start and finish
4. Identifying the activities crucial to timely project completion [Clough et al. 2000]

The critical path method (CPM) of scheduling makes use of a single or deterministic time estimate for each activity in the network. Such time estimates can be reasonably generated from prior experience. CPM calculations are then performed to establish the early and late start and finish times for each activity, setting the time window for performance. Critical activities are those lying on the network path requiring the greatest time for completion.

## 1.2 Need for Scheduling

Scheduling provides critical information to owners, architect/engineers, contractors, subcontractors, suppliers, and the public. In general, scheduling answers *who* and *when*, determining the sequence and timing of construction operations. However, a schedule has much more than this apparent utility and the interested parties want to know much more. Schedules have both offensive and defensive uses. Project management teams may use schedules offensively in the following ways:

- To predict the project completion date
- To serve as an effective project control tool
- To avoid liquidated damages
- To manage money by predicting cash flows

- To determine the “time window” of an activity
- To coordinate subcontractors
- To coordinate client-supplied info
- To expose conflicts among trades
- To predict resource demand and improve resource allocation
- To mitigate supply-demand conflicts
- To create an as-built record
- To compute progress payments
- To serve as an effective communication tool

The primary defensive use of a project schedule is to evaluate the time impact of changes, which can also be done after the fact to prove or disprove time-based claims. In general, the schedule is used to provide interested parties information needed to better manage the project. This information is the output of the scheduling process or the application of the outputs.

# 2 Definitions

**Activity** – a single work step with a definable scope of work, an identifiable start and finish, requiring time and typically resources to complete

**Backward Pass** – the process of navigating through a network from finish to start for the purpose of calculating the late start and finish times for each activity

**Bar Chart** – a schedule visualization tool using bars to depict the duration and time at which an activity is performed; commonly used due to their ease of creation and understanding, but failing to demonstrate job logic

**Baseline Schedule** – the target construction schedule based on the contractor’s original understanding of the project and used as the standard by which progress is measured

**Bid Package Schedule** – an intermediate schedule included in the bid package outlining milestones and work tasks

**Commodity Curves** – graphical representations of resource utilization used to monitor project progress

**Critical Path** – the sequential combination of activities requiring the longest time to complete

**Critical Path Method** – a network based management procedure for project planning, scheduling, and time monitoring

**Duration** – the length of time required to complete an activity

**Forward Pass** – the process of navigating through a network from start to finish and calculating the early start and finish times for each activity and the minimum time required to complete the project

**Free Float** – the amount of time the start of an activity can be delayed or its duration extended without delaying the early start of following activities

**Inputs** – information resulting from the planning process and used in the scheduling process

**Job Logic** – technical or non-technical relationships between activities defining the sequence of work

**Lag** – period of time that must pass after the finish of one activity before the following activity may start

**Lead** – period of time that must pass after the start of one activity before the start of the following activity

**Milestone** – significant points in time corresponding to intermediate reference points during the performance of the work, often used to monitor project performance

**Milestone Schedule** – the compilation of milestones identified during the planning process which serves as a master schedule

**Outputs** – information resulting from the scheduling process and used to manage the work

**Planning** – the process of selecting the means, methods, and sequence of work to be used to complete the project

**Precedence Diagramming Method** – a method for diagramming construction activities wherein a single node represents an activity which is logically connected to other activities

**Precedence Network** – a diagram of scheduled activities using job logic to show the interrelations between activities, but failing to depict the time at which the activities are performed

**Process** – the use of scheduling software to perform CPM calculations

**Project Narrative** – a written overview of the project providing a framework for scheduling and construction by defining project scope, basic job logic, major milestones, and the intended general sequence of work

**Relationships** – logical links between activities used to demonstrate work sequence

**Resource** – equipment, labor, or materials required to perform an activity

**Resource Leveling** – process of rescheduling activities such that resource requirements do not exceed resource limits; may result in a project completion delay

**Scheduling** – the process of determining the timing and specific sequence of tasks in order to carry out the planned construction operations

**Smart Relationships** – relationships other than finish-to-start used to better model the construction process, such as start-to-start and finish-to-finish

**Time Window** – time period between the early start time and late finish time for an activity

**Time-Scaled Logic Diagram** – bar chart that incorporates logic links such that both job logic and the time at which activities are performed are depicted

**Total Float** – the maximum amount of time an activity can be delayed from its original early start without delaying the duration of the entire project

**Work Breakdown Structure** – a task-oriented breakdown of activities for organizing and dividing a project into manageable sections using a hierarchical structure

# 3 The Inputs

The inputs are the information necessary to the scheduling process in order to generate the needed results. They include very general information such as the project narrative, basic job logic, and major milestones, and very detailed information such as activity durations, allocated commodities, and applied contract value. Essentially, the inputs to the scheduling process are the outputs of the planning process. Herein is the importance of the planning process: nothing is achieved by planning to a greater level of detail than that required for control and we cannot control to any greater level of detail than that to which we have planned. Therefore, an inability to schedule stems from a reluctance or incapacity to plan. The necessary inputs from the planning process are detailed in the following discussion.

## *3.1 The Big Picture*

### 3.1.1 <u>Project Narrative</u>

The project narrative plan is an important stepping stone for the development of all inputs. The plan outlines the big picture, defining the project scope, the basic job logic, major milestones, and intended general sequence of work. It may include detailed architectural drawings of the project at key points during construction so that the owner has a visual representation of how the project at that point in time. In essence, the project narrative provides a framework for the scheduling and construction of the project.

### 3.1.2 <u>Milestones</u>

Milestones are significant points in time that identify intermediate steps to the accomplishment of work. Milestones may highlight the start and/or finish of an event; accordingly, there are *start milestones* and *finish milestones.* Milestones do not have durations or resources, but should be considered zero duration activities because that is how they are handled when placed in a schedule and computed with CPM. They exist like any other activity, but they do not add to the total project duration. A few examples of milestones are notice to proceed, topping out, building enclosed, substantial completion, and project complete. The compilation of the milestones determined in the Grand Plan creates the Milestone Schedule which serves as a master schedule, setting the parameters of the schedule that eventually becomes the detailed construction schedule [Buttelworth 2005].

### 3.1.3 <u>Work Breakdown Structure</u>

A Work Breakdown Structure (WBS) is a framework for organizing and dividing a project into manageable sections using a hierarchical structure, with each section taking on an increasingly greater level of detail. Moreover, the WBS is a task-oriented breakdown of activities that organizes, defines, and graphically displays the project work. But, the WBS is not a schedule; it only lists work tasks in increasing levels of detail. Figure 1 is an example of a simple WBS. A WBS is the result of top-down planning wherein the entire project is broken down and outlined by work tasks, i.e. excavation, site work, foundations, HVAC rough-in, and interior finishes to a name a few, rather than put together from beginning to end. “The definitions of work tasks represent the necessary framework to permit scheduling of construction activities, along with estimating the resources required by the individual work tasks, and any necessary precedence or required sequence among the tasks” [Hendrickson 2000]. The WBS is one of the most important outputs of the planning process because it uniquely guides the scheduling process by defining and grouping work tasks.

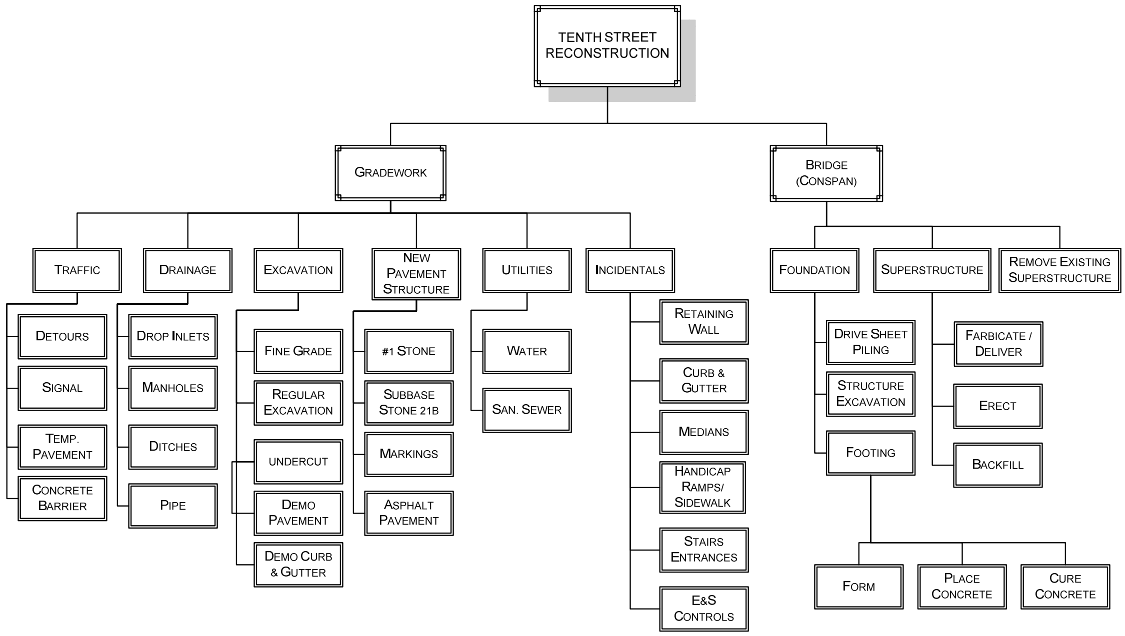



**Figure 1: Example WBS for Tenth St. Reconstruction in Roanoke, VA**

### 3.1.4 Bid Package Schedule

Having established the milestones and WBS, the work is divided into numerous activities that roughly equal the different trade contracts that will be bid out. This produces the Bid Package Schedule, an intermediate step between the very broad milestone schedule and the very detailed construction schedule. The Bid Package Schedule is developed and redeveloped throughout design and into the construction document phase of the design and becomes the basis for the construction schedule.

### 3.1.5 Calendars

Calendar definitions are another important output of planning that significantly influences the construction schedule. Typically, construction projects warrant a workday planning unit and a five-day work week; however, many projects use multiple calendars in order to more accurately represent reality. Scheduling considering multiple calendars is a more effective and efficient way to represent work properties, weather conditions, and resource availabilities. Each calendar can contain a unique workday pattern per week, i.e. 3-day workweek, 5-day workweek, etc. and a unique set of holidays and exceptions [Kim and de la Garza 2005]. These considerations are defined by the company or project. On the other hand, estimating and presenting the effect of weather on construction processes is a difficult task and requires both knowledge of the geographic location in which the work is to be performed and specific experience with the kind of construction operations considered. There are two widely used methods for estimating these effects and adding them to the project schedule. First, a time contingency may be added to the schedule to account for probable weather delays. But the more preferred method for presenting the effects of weather is by employing weather calendars. By determining the anticipated number of work days lost to weather per calendar month, and then taking out those days randomly from the work calendar, the scheduler may lengthen the duration of the affected activities by the number of days removed from the calendar. The use of weather calendars has four major advantages:

1. It automatically adjusts for large changes in the schedule, such as winter to summer
2. It realistically distributes the delay effects of weather over the entire schedule
3. It provides a truer status of the project at each update, allowing for better forward planning

It endures the close scrutiny of owners and public authorities who are often concerned with the amount of contingency added to construction schedules [Clough et al. 2000]

Thus, scheduling with multiple calendars, notwithstanding the added complexity, is practical, and prominent project management software provides the necessary functions to do so with relative ease.

## *3.2 The Details*

### 3.2.1 Activities

Recall that the WBS organized and divided the project into job tasks. At the greatest level of detail, the job tasks become activities - single work steps that have a recognizable beginning and end and require time for their accomplishment. Typically, the extent to which the project is subdivided depends on one of the following practical considerations:

- By area of responsibility
- By category of work as distinguished by craft or crew requirements
- By category of work as distinguished by equipment requirements
- By category of work as distinguished by materials
- By distinct structural elements
- By location on the project
- With regard to the owner's breakdown of the work for bidding or payment purposes
- With regard to the contractor's breakdown for estimating and cost accounting purposes

Notwithstanding their high level of detail, activities are an end result of the planning phase. Most construction companies know what needs to be done in order to complete the work; they know what activities are necessary. The planning phase defines the necessary activities and the scheduling phase determines their sequence and timing. Activities have the following characteristics: they usually consume time and resources, they are assignable and measurable, they have a definable scope of work, and a definable start, finish [Buttelworth 2005].

### 3.2.2 Non-Work Activities

It is important to consider all activities that consume time, even though some activities may not produce an item directly incorporated into the work. These non-work activities are crucial for progression of the work and necessary for completion of the project. Such activities may include obtaining permits or right-of-ways, submitting and reviewing information, and fabrication or delivery of job materials. Non-work activities should be included in the schedule when their completion is required prior to the start of a work activity.

### 3.2.3 <u>Activity Durations</u>

Activities consume time: the length of time they consume is called the *duration*. However, as mentioned previously, activities with zero duration are known as milestones. There are two main factors that must be considered when determining durations: the time available and application of resources to maximize profits. Unfortunately, most projects today do not have the luxury of time. Therefore, activity durations have to be defined based on the available time as defined by the owner. The second most influential factor for determining the duration of an activity is the contractor's profitability. Contractors assign durations and resources to an activity in order to maximize profit by performing the work efficiently. The overall goal is to apply a duration that will allow the work to be performed efficiently and result in a profit. Although these two factors heavily influence the determination of activity duration, there are other factors that may play a role: safety concerns, availability of materials, equipment, and tools, and special conditions and techniques.

After closely considering the influencing factors, the durations must be determined. Whether they are calculated or assigned, durations are intuitive and subjective estimates based on quantity and productivity, gut feeling, past projects, locked-in dates, and/or input from trade contractors. Most activity durations for construction schedules are calculated using the quantity of work that must be accomplished and the productivity rate for the work. The quantity of work is easily determined from a quantity takeoff, found in the bid documents or bid estimate, or from past experience. The productivity rates, however, are not as easily established; they depend on the method of construction, project location, weather, supervision, "learning curve" effect, skill of craft, and the complexity of the task. The two best sources of standard production rates are past experience and estimating guides.

Estimating activity durations does not stop there; the complexity increases by adjusting for time contingency. Concessions for abnormal or random delays are accounted for in a couple ways, the most straightforward being a contingency allowance. If the delay occurrences are recognized as activity specific, a contingency allowance is added in the form of an uncertainty variance to the activity duration [Clough et al. 2000]. But in most cases, an allowance can not be applied to an individual activity. It is impossible to predict which activities are affected by general project delays like accidents, fires, equipment breakdown, and unanticipated site difficulties. Consequently, a general allowance for time contingencies is commonly added to the overall project duration or to the end of specific construction sequences.

In general, the determination of activity durations is a critical part of the planning process, resulting in a vital input to the schedule. Without well defined activity durations, putting the activity time-windows together in the schedule is relatively meaningless.

### 3.2.4 <u>Resource Allocation</u>

Resources are materials, equipment, labor or anything needed to complete an activity. Most activities will require one or more resources; however, not all activities will require resources. For example, schedules often include an activity for cure time, but this activity does not consume resources. Success on construction projects depends on the efficient utilization of limited and costly resources—labor, materials, and equipment. Contractors who minimize waste and re-handling materials, efficiently operate equipment, and maximize labor efficacy have a significant competitive advantage. A construction schedule that does not include resource allocations implies that the contractor has unlimited resources available and has the flexibility to apply all necessary resources to a project change without incurring added costs. However, a resource-loaded schedule illustrates the interdependencies between activities and resources. Moreover, a contractor's jobsite schedule tends to focus on resources rather than activities; therefore, their published master schedules should indicate this.

Once resources are applied to an activity, the project resources should be leveled to improve work efficiency and minimize cost. Resource leveling is the process of smoothing out daily resource demands by shifting the time at which an activity is performed without violating the job logic. To do so effectively, the scheduler must employ resource constraints. No contractor has unlimited resources and the constraints placed on resources should reflect the most likely amount of labor, equipment, and materials available to the contractor under normal conditions. These resource limitations may drive the schedule, changing the critical path.

### 3.2.5 Assign Responsibility and Measure Progress

Activities consume time and resources; therefore, they must be assigned and measured. Assigning activities to responsible parties is imperative because it significantly helps divide the project into manageable pieces, assigning them to the party best suited to perform the work. In addition to determining what an activity is and how long it should take, the assignment tells who is responsible. In order to control the progress of the entire project, the progress of each activity must be measured and the assigned party held responsible for its sufficient progress. Commonly, activities are measured by quantities of materials installed, a percent complete based on a gut feeling or elapsed time. Measuring progress based on the quantities of materials installed, as compared to the planned quantities, is the most effective method, though it requires thorough tracking of installed materials. The other two methods are quick, but significantly less accurate.

### 3.2.6 Assigning Contract Value

Once resources have been added to the activities, their associated contract value is assigned. A cost-loaded plan is the assignment of contract dollar values to work activities; though, not all activities will have a cost associated with them. The benefits of assigning contract value are noteworthy:

- The ability to produce procurement reports indicating the type, quantity, date, and price of a resource need
- Significantly aids project control and earned value cost management
- The updated schedule will reflect the impact of resource changes due to changes in cost or availability
- The updated schedule will identify which activities have begun and finished, the percent complete, and any other activity-related financial information

Essentially, assigning contract value to activities which compose the schedule enables the effective integration of cost and time.

### 3.2.7 <u>Job Logic</u>

Activities have a definable scope of work; each activity is a unique task defined by the complexity of the project and the utility of the schedule. Complex projects may require more activities so that the schedule is communicated effectively. If the project is more or less standard and the schedule is not of great importance, the definition of activities may be broader. For example, a broad activity may be construct footing; but clearly, the activity could be broken into many activities, form footing, place rebar, place concrete, cure concrete, strip forms. The scope of the activity directly affects the defined starts, finishes, and sequence. The broad activity, construct footing, starts when formwork begins and finishes when stripping forms ends.

Once the individual activities and their starts and finishes are defined, job logic is applied to put the pieces together to create an activity network. Job logic is simply the connections between activities, what activities precede and succeed each activity. However, what defines the precedence and succession is not as direct. Most logical relationships are physical connections; ex. foundation walls cannot be built until the footing is complete. Beyond the obvious physical connections, contractors may notice the following non-technical connections:

- Safety – hazards arising when multiple activities are performed concurrently.
- Resources – conflict of available resources precludes simultaneous work.
- Materials – activities with materials that depend on timely procurement.
- Preference – when no other restraints exist, the Contractor elects one activity before another.
- Working Area – the size of the working area will determine the amount of simultaneous work.

With many different means and methods used on a construction project and many subjective sequencing decisions made by the project planner, there is no one correct method for completing a construction project. For example, buildings can either be built from the top-down or bottom up; some contractors place the concrete floor slab before the roof and others vice versa, each with good reason. Clearly, differences between two schedules do not necessarily make one incorrect. Appropriately, the construction schedule hinges on reputable job logic, which uniquely depends on the know-how of the planner. Thus, the validity of the construction schedule relies heavily on the experience of the planner(s) and the care put into establishing the job logic.

### 3.2.8 <u>Relationships</u>

Having determined with job logic which activities precede and succeed each other, *relationships* are applied to define *how* activities are connected. There are four types of relationships between sequenced activities:

- finish-to-start (FS)
- start-to-start (SS)
- finish-to-finish (FF)
- start-to-finish (SF)

The most common and intuitive relationship is the finish-to-start; when one activity finishes, a successive activity can start. However, FS relationships alone do not accurately represent the actual flow of work of a construction project. Smart relationships, those other than FS, can be used to better represent reality. Start-to-start and finish-to-finish relationships are frequently used to better represent the association between activities. A SS relationship is when one activity starts, so can another. An FF relationship is when one activity finishes, so does another. The final and least used relationship type is the start-to-finish, which says that when one activity starts, another activity will finish. This differs from the finish-to-start relationship because the start of an activity causes the finish of the other. Rarely used in construction; the SF is not as intuitive or useful as the other activity relationships.

These two types allow concurrent starts and finishes. They are typically used with leads and lags, which are extra time purposefully placed between activities. For example, HVAC rough-in must begin before plumbing and electrical rough-ins, but the HVAC does not need to finish. This represents a common SS relationship with a lag; the HVAC work can stay ahead of the others without the schedule requiring its completion. Similarly, project closeout on many projects can not and does not finish until a certain number of days have passed since punchout; therefore, the finish of project closeout lags the finish of punchout by the planned difference, this represents a common FF relationship with a lag.

By general rule, a successor lags a predecessor, but a predecessor leads a successor. In essence, a negative lag time is a lead time. Leads and lags are not to be referred to or confused with activity float, which will be discussed in detail later. Leads and lags are purposely set by the project planner in order to better model the actual sequence of work. Once activities are defined and appropriately sequenced and related, the network diagram is drawn to easily and visually demonstrate how a project will be completed.

### 3.2.9 Network Diagram

A network diagram is the graphical representation of a detailed project plan; it illustrates the job logic and basic activity sequencing. In general, a network diagram shows the 'big picture,' what is going to happen and in what order. In this way, it is an accurate, efficient, and reliable review method to prevent any bad logic from getting "lost" in the scheduling software. Thus, it is very important that interested parties understand how to read and evaluate these diagrams. The most popular, powerful, flexible, and effective diagramming method used in the construction industry is the Precedence Diagramming Method (PDM)—used by nearly every scheduling software—due to its ease of creation and use, and due to its incorporation of the four major activity relationships. A single node represents an activity and is logically connected to other activities by a line or arrow, as represented in Figure 2. Like other methods, PDM has rules and standards. Figure 3 shows the standard nomenclature for activities in a precedence network.


**Figure 2: Precedence Diagramming**

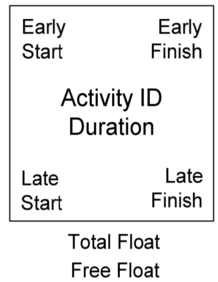



**Figure 3: Standard Precedence Diagramming Nomenclature**

The activities for successful project completion have been identified, their durations determined, and their sequence defined; all that remains is knowing exactly when they will occur, the specific time associated with their sequence. Essentially, the PDM puts the pieces of the plan together, preparing them for the scheduling process. Figure 4 shows an example precedence diagram where the basic job logic is applied in order to sequence the activities. The figure shows a very simple sub-network with very few activities, very straightforward logic, and no smart relationships. Nonetheless, a well-modeled network diagram for even the most complicated project is absolutely necessary. The scheduling of the model is only as effective as the model represents reality. Accordingly, in order that scheduling has any relevance, planning must define inputs that closely model the actual construction of the project.

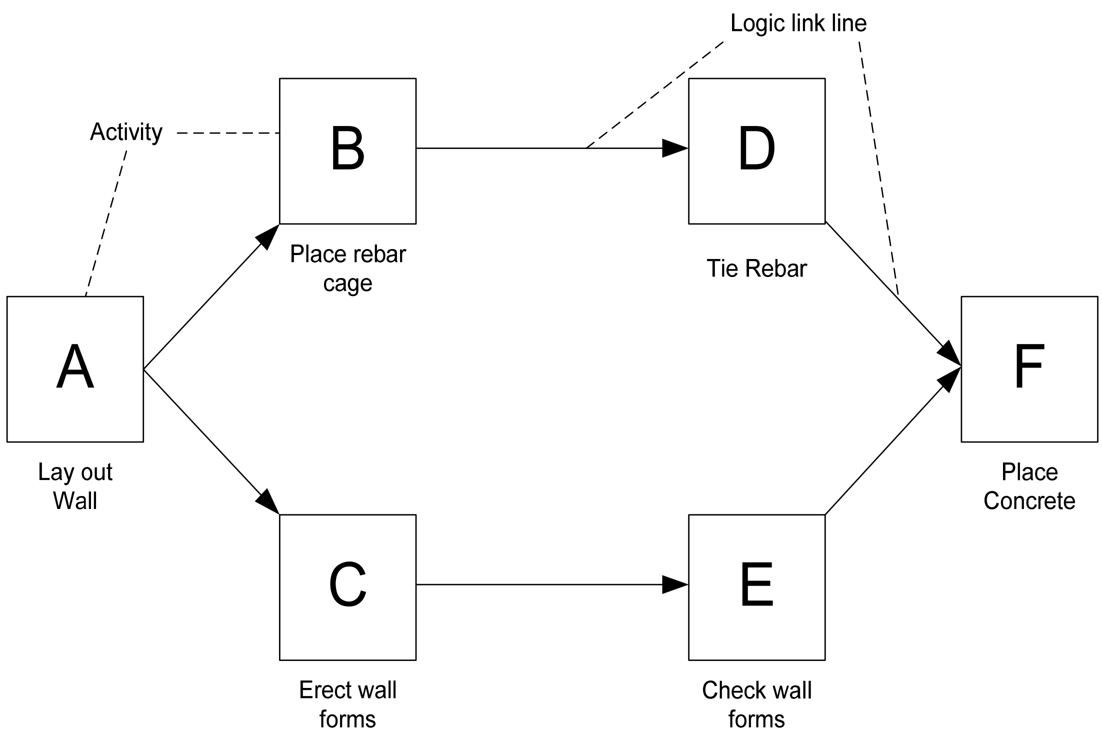



**Figure 4: Example Precedence Network**

# 4 The Process

Once the project network is diagrammed and durations have been assigned to activities, the schedule is ready for calculation. CPM uses a forward and backward pass to calculate the following important scheduling information for each activity: early start (ES), early finish (EF), late start (LS), late finish (LF), and the float. (These topics will be thoroughly discussed in the Outputs section) The starts and finishes determined are in *ordinal* days—time not bound to a calendar or time period, but a unit of time. Thus, the sequential ordinal days are then converted to calendar days, from which a complete construction schedule is developed [Buttelworth 2005].

Scheduling is not an easy process, but with the aid of computer-based software, the tedious and repetitive parts of scheduling are performed instantly. Modern calculations are performed by intelligent computer-based scheduling software. Inside the “black box,” the software performs all the tedious calculations and iterations instantaneously. However, schedules produced by software are only as relevant as the inputs are reflective of the actual construction plan. And, the produced schedule is only as accurate as the software correctly applies the rules of CPM and resource leveling.

## *4.1 Forward Pass*

The forward pass is the process of navigating through a network from start to finish and calculating the early dates for each activity and the completion date of the project [Mubarak 2005]. Specifically, the forward pass through an activity network yields the early start and early finish of each activity and the minimum total project duration. The process assumes that all activities in the network will start as soon as possible; each activity will start just as soon as the last of its predecessors finishes. Furthermore, the activities will finish as soon as possible; thereafter, succeeding activities will start immediately. The process starts with the first activity and time zero. The early finish (EF) is found by simply adding the duration of the activity to its earliest start. The early start (ES) for an activity is the earliest an activity can start; therefore, the early start is the same as the early finish of a preceding activity. However, if more than one activity precedes an activity, the early start comes from the latest finish of all preceding activities. Figure 5 illustrates the ease of the forward pass on a network without smart relationships.

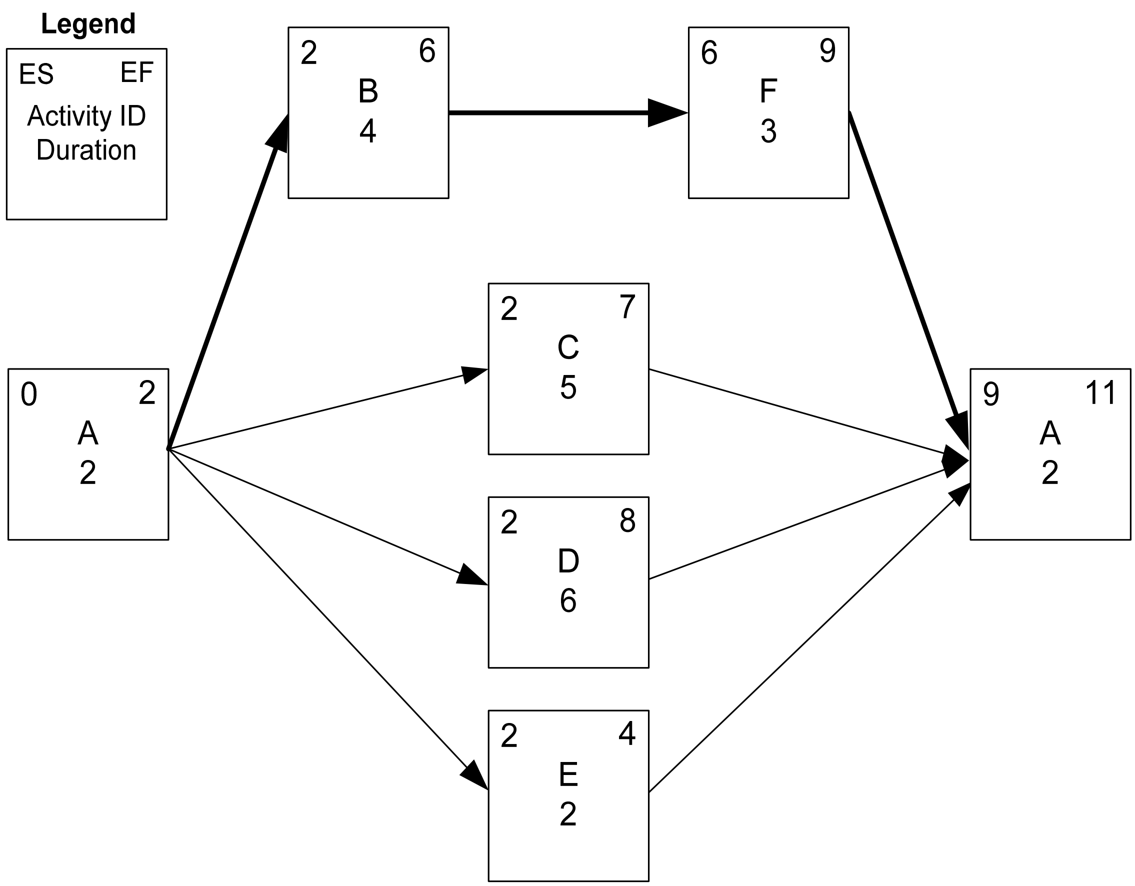



**Figure 5: Basic Forward Pass Example**

Adding SS, FF, SF relationships and leads and lags significantly complicates the process. But, the definitions of early start and finish remain the same. When performing the forward pass with smart relationships and leads and lags, collect all the possible ES for each activity and choose the latest ES from the list. For FF and SF relationships, find the ES by first finding the EF and subtract the activity's duration. Figure 6 demonstrates how the forward pass becomes more complex when relationships and time are added to more realistically model a construction project.

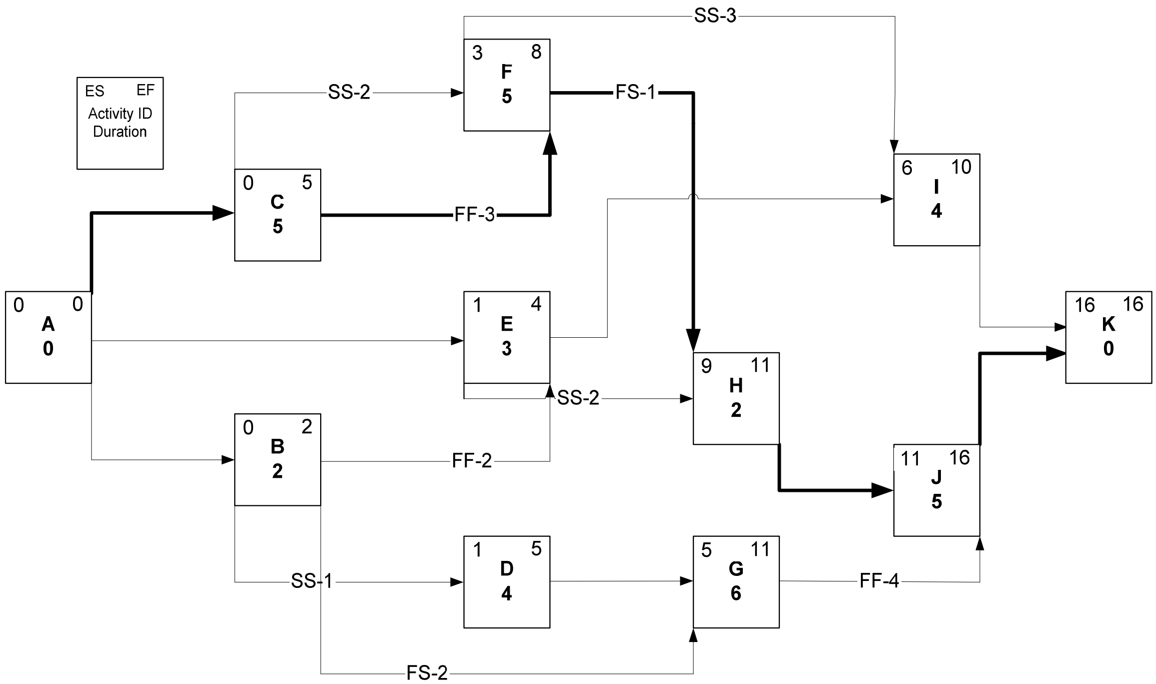



**Figure 6: Forward Pass with Smart Relationships**

If multiple calendars are employed, forward pass calculations follow this rule: if the ES or EF of the successor calculated directly from the predecessor is a non-working day, the early time should be postponed to the next available working date in order to satisfy the minimum time interval. Clearly, multiple calendars add another layer of complexity, making even the simple forward pass time consuming and very complicated.

## *4.2 Backward Pass*

The backward pass is *the process of navigating through a network from finish to start and calculating the late dates for all activities* [Mubarak 2005]. Specifically, the backward pass yields the late start and late finish of each activity and further helps identify the critical path and float times. The backward pass assumes that all activities in the network will start and finish as late as possible; each activity will finish as the earliest of its successors starts. Moreover, the process assumes that all preceding activities will also finish as late as possible. Working backward, from finish to start, the process starts with the final activity and assumes the zero-float convention, which uses the exact number of days calculated by the forward pass as its starting point. The late start (LS) is found by simply subtracting the duration from the LF if there is a single succeeding activity. In the event of multiple successors, the late finish is the earliest late start of all succeeding activities. Figure 7 illustrates the ease of the backward pass on a network without smart relationships.

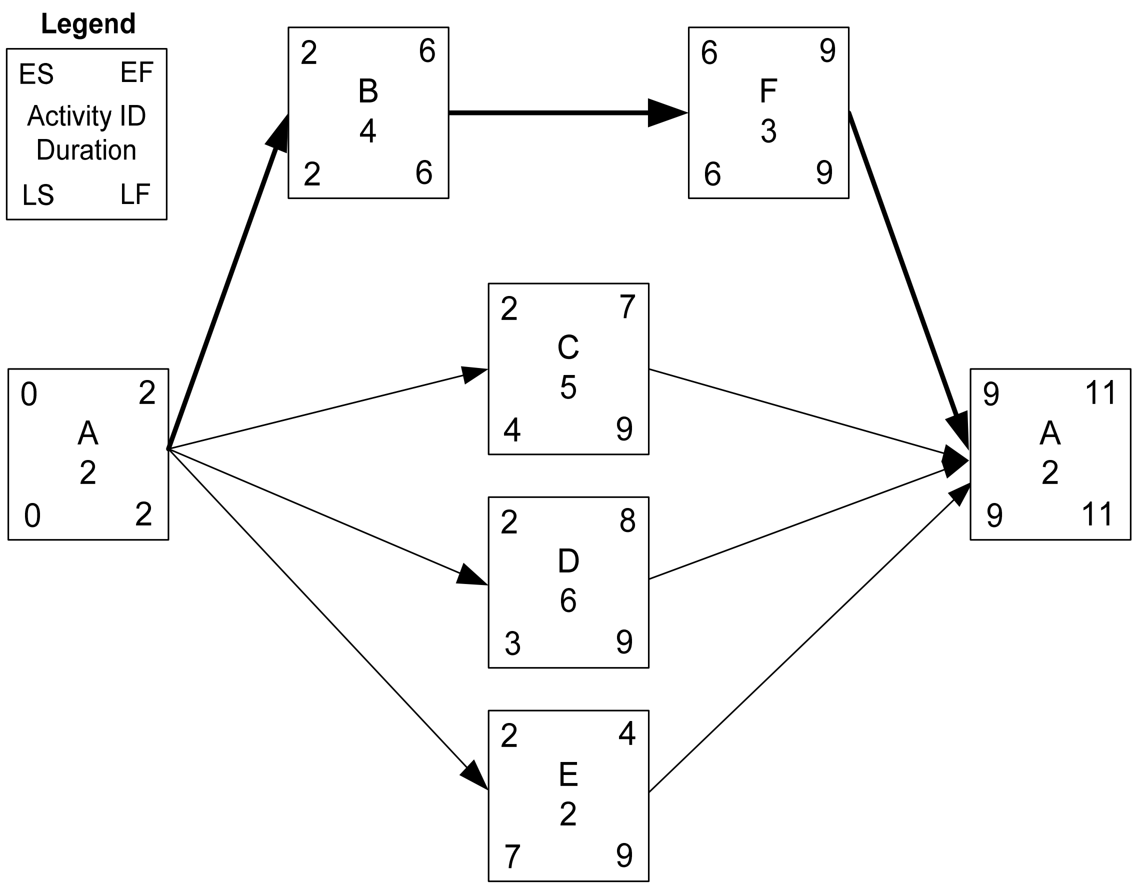



**Figure 7: Backward Pass Example**

Adding SS relationships and leads and lags significant complicates the process. But, the definitions of late start and finish remain the same. When performing the backward pass with smart relationships and leads and lags, collect all the possible LF for each activity and choose the earliest from the list. For SS relationships, find the LF by first finding the LS and adding the activity's duration. Figure 8 demonstrates how the backward pass becomes increasingly more complicated.

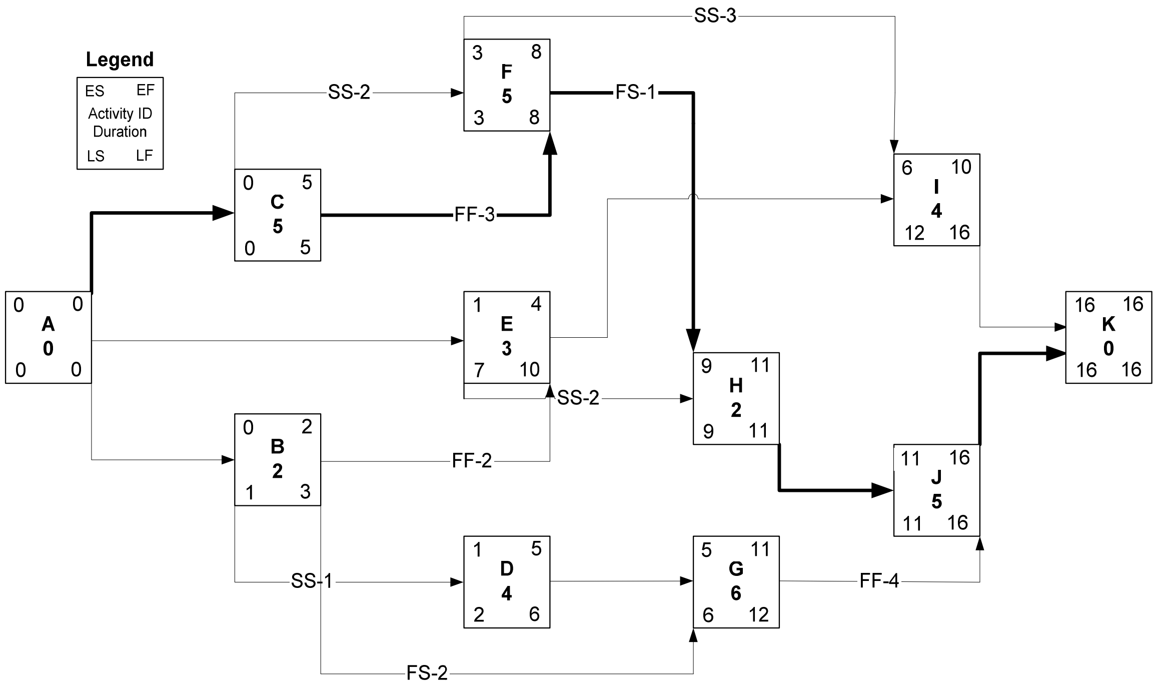



**Figure 8: Backward Pass with Smart Relationships**

Again, if multiple calendars are involved, backward pass calculations follow this rule: if the LS or LF of the predecessor calculated directly from the successor is a non-working day, the late time should be advanced to the previous available working date in order to satisfy the minimum time interval. To reemphasize, multiple calendars add another layer of complexity to even the simplest of CPM calculations, making them very difficult and tedious.

## *4.3 Resource Leveling*

To reiterate, construction project success depends heavily on efficiently utilizing limited and costly resources—labor, materials, and equipment. A resource-loaded schedule demonstrates the interdependencies between activities and resources. Once resources are applied to an activity, the project resources should be leveled (or smoothed) to improve work efficiency and minimize costs. Formally, resource leveling minimizes the fluctuation in daily resource usage throughout the life of the project by shifting non-critical activities within their available float. To smooth resources realistically, the scheduler must employ resource constraints, because no contractor has unlimited resources. The constraints placed on resources should reflect the most likely amount of labor, equipment, and materials available to the contractor under normal conditions. The constraints supersede the original project duration; meaning, the project duration is extended if the constraints can not be met by using the available total float. Hence, these resource limitations may drive the schedule, changing the critical path. Figures 9 and 10 illustrate how leveling resources may or may not extend the project duration.

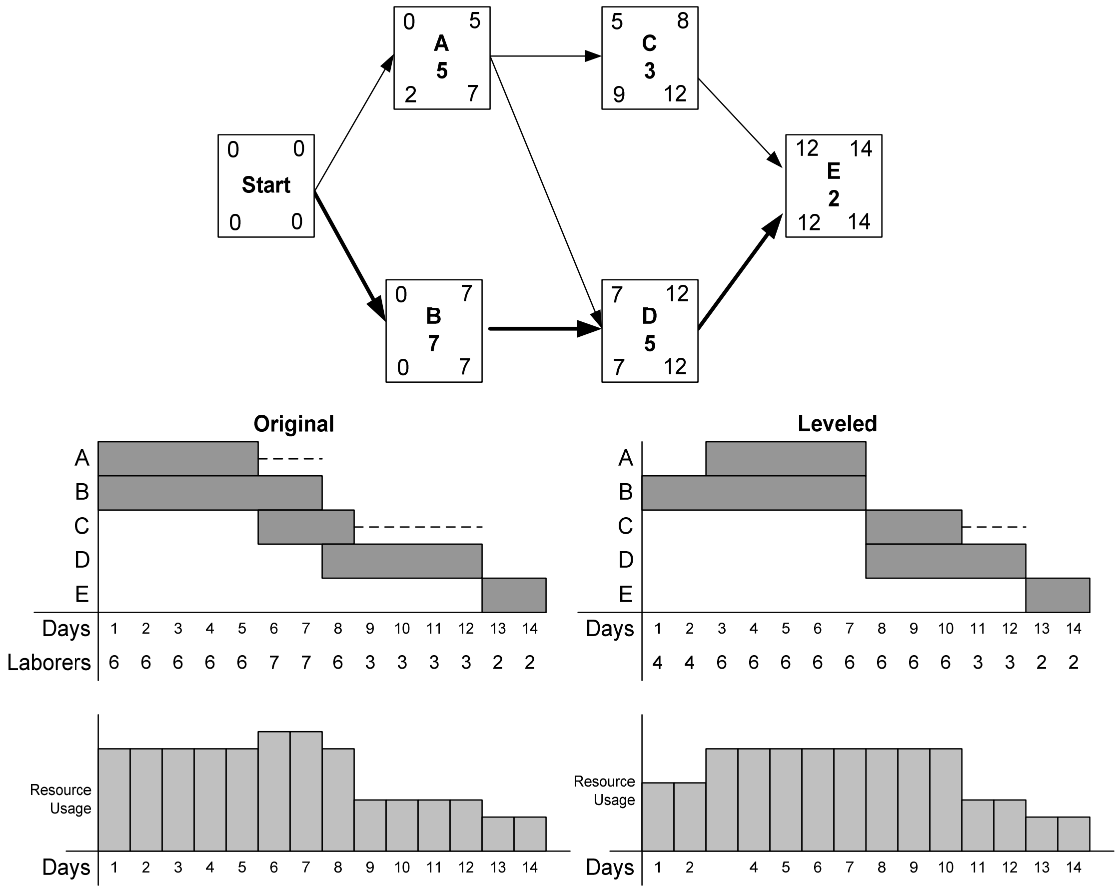



**Figure 9: Resource leveling without constraints (within original project duration)**

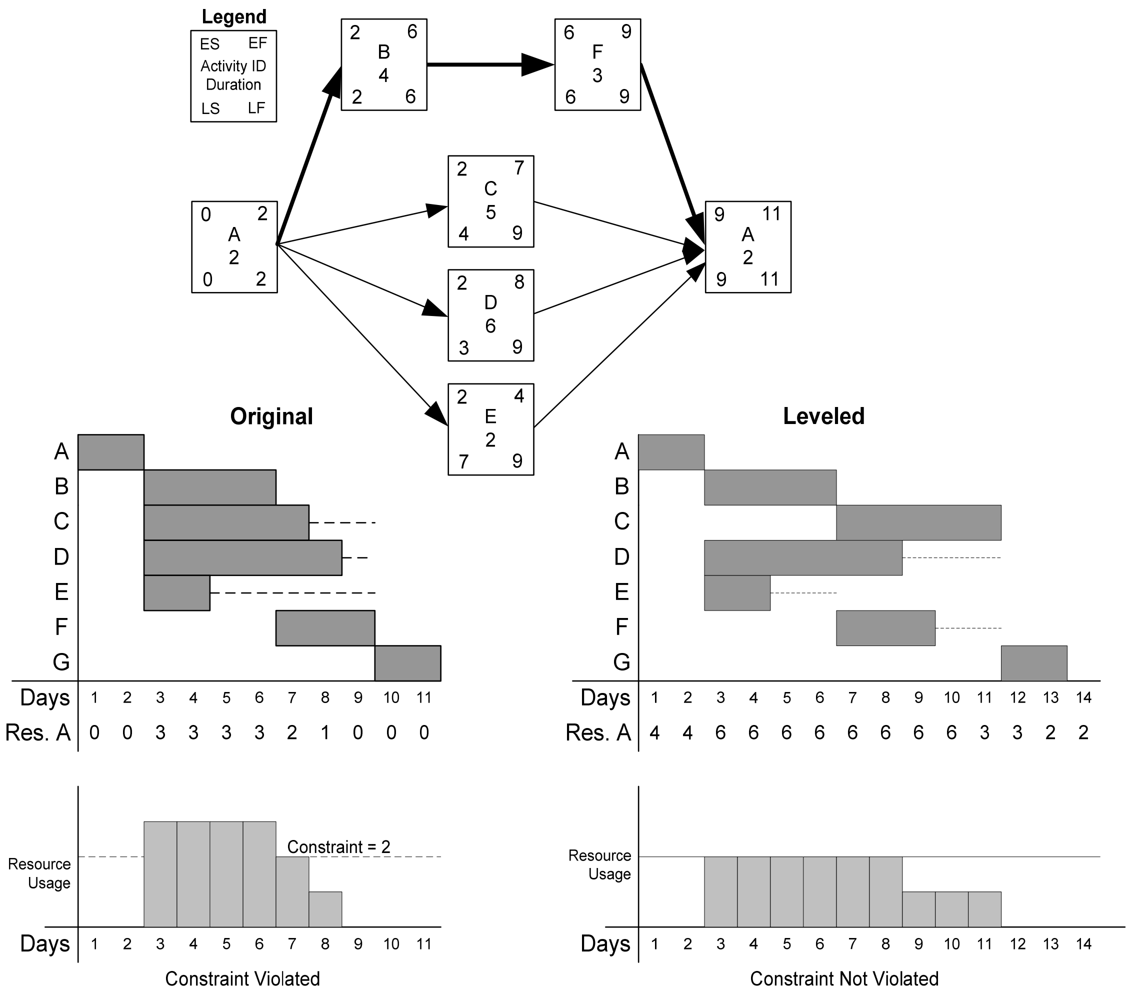



**Figure 10: Resource leveling with constraints (project duration extended 2 days)**

# 5 The Outputs

The outputs of the scheduling process are essentially *what we get* from the calculations based on *what we provided* as inputs because of *what we wanted* in order to improve construction project management—time monitoring and insurance. We get a substantial amount of data which is organized, visually represented, and used in offensive and defensive ways, as listed in the introduction. Historically, the construction industry has been data rich, but information poor. The process directly provides data such as activity time windows, the available total and free float, the critical path, and the overall baseline or target schedule. The data becomes useful information when visualized as the output of the planning and estimating assumptions, represented as bar charts, logic diagrams, and time-scaled logic diagrams. Moreover, the data is used to create tools that aid time-monitoring and progress measurement, such as resource histograms and profiles, commodity curves, and earned value curves.

## 5.1 Time Windows

Scheduling specifically answers the question, *when will* and *when could* an activity occur? The forward and backward passes provide this information, defining the early times and the late times. The early times are the absolute earliest an activity can start and finish without violating the job logic. Similarly, the late times are the absolute latest an activity can start and finish without extending the project duration. Thus, the schedule indicates the available time window for each activity.

## 5.2 Total Float

When the early and late times of an activity are different, i.e. when the available time window is longer than the activity's duration, total float exists. In other words, total float is the maximum amount of time an activity can be delayed from its original early start without delaying the duration of the entire project. Numerically, to obtain total float, subtract the ES from the LS or the EF from the LF (the same result is generated by each). If the result is zero, then no total float exists and the activity is called critical. An important thing to understand about total float is that it is *shared.* The calculated float does not belong to any one activity, but it is shared among all the activities. Total float used on one activity affects the entire schedule, which periodic updates should reflect.

## 5.3 Critical Path

The critical path is the network path with the longest duration; any delay will cause an equal total project delay. As its name suggests, the most important part of CPM is the critical path. Although these activities may not necessarily be the most difficult or most important, any delays along the path will delay the entire project. Thus, the critical path denotes job areas that project managers should closely monitor in order to remain on schedule.

## 5.4 Free Float

Free float is another indication of extra time; but unlike total float, free float is unique to an activity—it is not shared by the entire network. Formally, the free float of an activity is the amount of time the start of an activity can be delayed or its duration extend without affecting the start of any successor [Buttelworth 2005]. Therefore, delaying the start of a succeeding activity will extend the project duration. To calculate, free float is found by subtracting the earliest finish time of an activity from the earliest start of any succeeding activity. However, it should not be confused with a lag. Free float is naturally occurring extra time that is a direct product of the calculations on the inputs to the scheduling process; a lag is a purposeful placement of extra time defined as an input to the process. Clearly, the differences between total float and free float are significant. The two terms should not be used interchangeably or even mistakenly.

## 5.5 Baseline Schedule

A direct end result of the scheduling process is the baseline schedule. Also called the target or the construction schedule, the baseline is a prediction based on the quality of the inputs and previous experiences.

It represents the contractor's original understanding of the project and the intended schedule for completing the project. Therefore, the baseline must be reasonable and realistic and account for the following considerations:

- work and weather conditions
- size and complexity of the project
- local codes and regulations
- location and access, labor market
- materials and equipment availability
- prices
- procurement time [Mubarak 2005]

These considerations should appropriately influence the inputs and then are suitably reflected in the contractor's baseline schedule. Traditionally, the schedule is prepared prior to the start of the project but used throughout the project to detect any deviations and to compare performance. Ideally, the construction schedule should be used daily to build the project and updated frequently in order to accurately measure progress. The baseline is normally visualized in three main forms: the bar chart, the precedence network, and the time-scaled logic diagram.

## *5.6 Bar Charts*

Developed in 1917 by Henry Gantt, bar charts are depictions of when activities are scheduled. Within the industry, they are the most often used scheduling visualization tools because of their simplicity and unsurpassed visual clarity; anyone can read and prepare them. Therein lies the greatest asset of the bar chart and its greatest weakness—it is too simple. A bar chart does not show logical dependency among activities and does not support manual project progress measurement. Although the status of an activity is easily determined, the status of a project is very unclear. Thus, the bar chart only gives fuzzy projections, a false sense of security, and is completely ineffective for project shortening, resource management, and most other project management methods. However, the advent of CPM and the evolution of powerful computers have reinvigorated the importance of and reliance on bar charts. No longer a stand-alone tool, modern bar charts usually have a CPM calculated schedule or update supporting them even if it not reflected on the chart. But, the major flaw, to reiterate, is that intent is not explicit because a bar chart inherently lacks viewable job logic. Nonetheless, bar charts are still used because of their ease of creation and understanding. Figure 11 illustrates a traditional bar chart schedule.

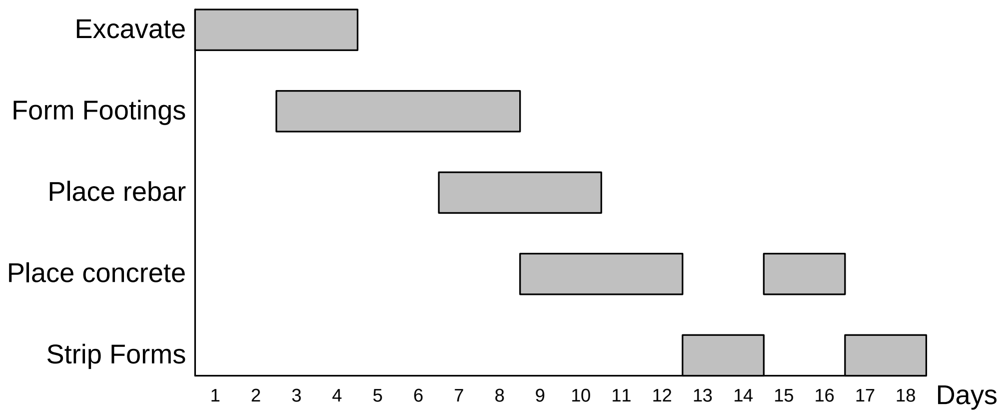



**Figure 11: Example bar chart for placing a simple slab on a grade**

## *5.7 Precedence Network*

After performing the forward and backward passes, calculating the float, and determining the critical activities, the precedence diagram created in the plan becomes a network of scheduled activities. Unlike the bar chart, the strengths and weaknesses of the precedence network are more or less reversed—the precedence network explicitly depicts the logic that connects activities but does not show time. Consequently, precedence diagramming is a technique that is used less in schedule visualization and more in planning a project. Figure 12 illustrates a simple precedence network.

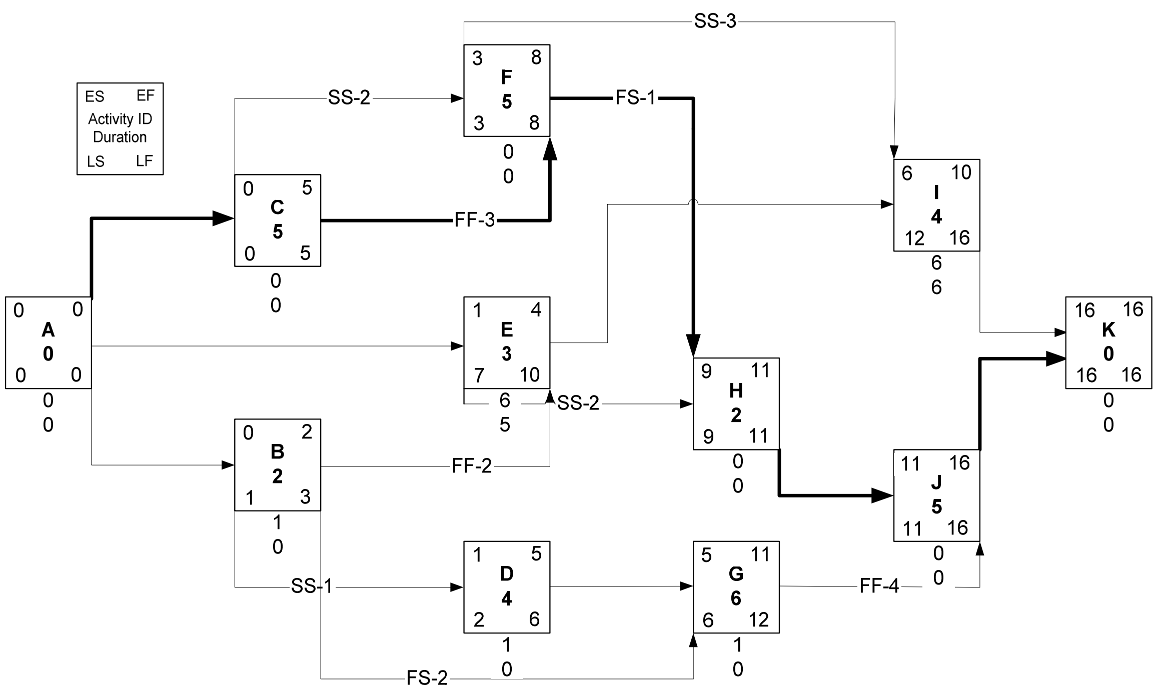



**Figure 12: Scheduled Precedence Network**

## 5.8 Time-scaled Logic Diagram

To integrate the strengths of the precedence network and the bar chart, the time-scaled logic diagram intends to clearly depict both time and logic, successfully answering *what*, *when*, and *in what order*. The diagrams are effective tools for checking daily project labor and equipment needs and for the advanced recognition of conflicting resource demands. Hence, project managers find more use from time-scaled logic diagrams. However, depicting sophisticated relationships makes the logic markedly less clear than in networks and much more cluttered than in bar charts. For smaller, less complicated schedules, the diagram provides a good and acceptable visualization solution [Mubarak 2005]. Figure 13 illustrates a normal time-scale logic diagram.

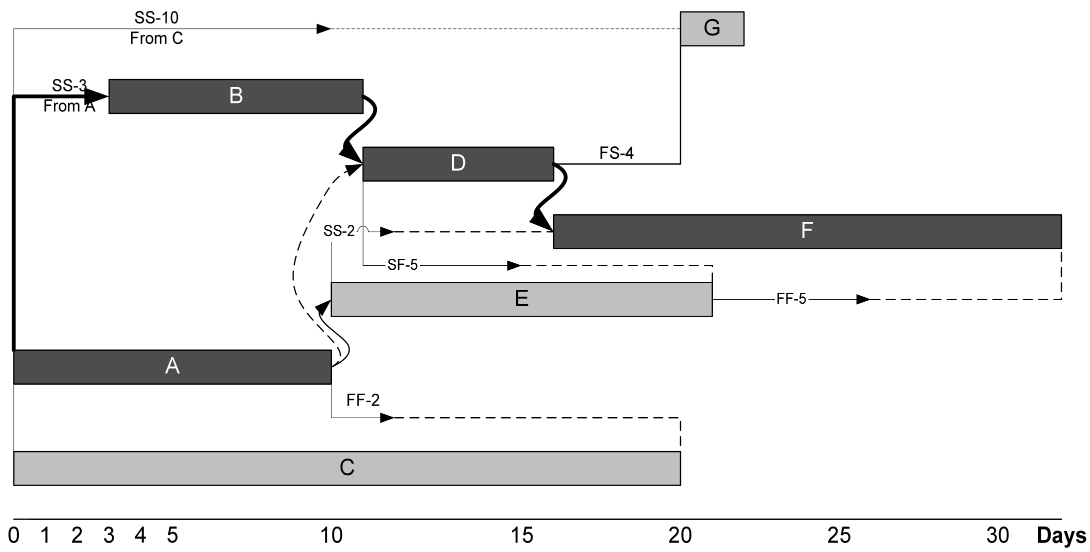



**Figure 13: Time-scaled Logic Diagram**

## 5.9 Commodity Curves

Once resources have been added to the activities and the schedule has been leveled, commodity curves are generated to graphically represent resource utilization and project progress. Curves are created for three main types of commodities: input resources such as labor, output commodities such as cubic meters of regular excavation, and contract value—the ultimate commodity. For input commodities, the appropriate resources are pulled directly from the resource-loaded schedule to generate a planned utilization. As the project proceeds, actual utilization is recorded, inputted, and the progress measured against the plan. Figure 14 illustrates the tracking of labor hours daily as a histogram and cumulatively as early and late curves.

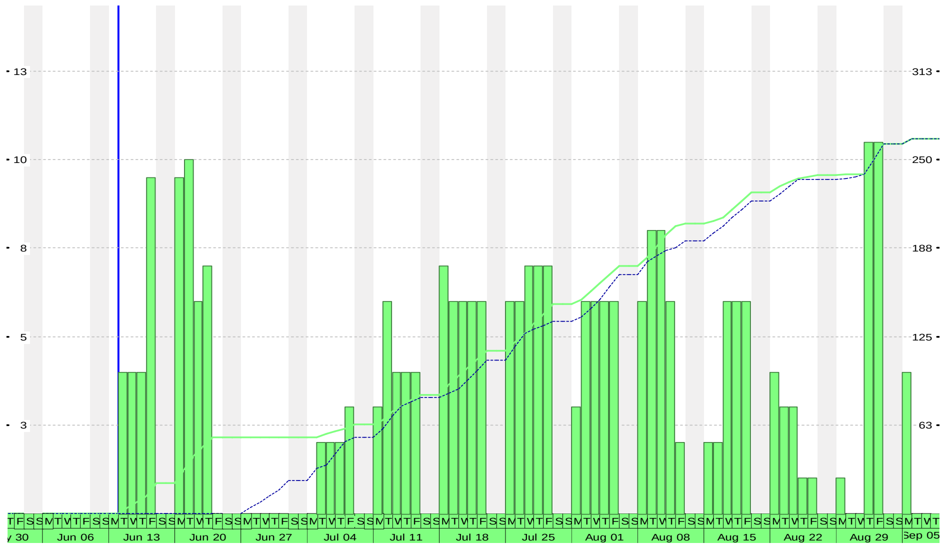



**Figure 14: Resource Profile for Input (Labor) Commodity**

Measuring the progress of output commodities provides the most reliable depiction of project progress; the actual quantities are directly compared to the planned amounts. From the schedule, a planned quantity versus time curve is developed. Then, critical outputs, like cubic meters of regular excavation or linear feet of pipe laid, are monitored and their actual quantities recorded. Using the actual data, a comparison is made between actual and planned quantities, which is a direct measure of progress. Figure 15 illustrates a typical output commodity curve that shows the daily and cumulative progress of placing superstructure steel on an example bridge.

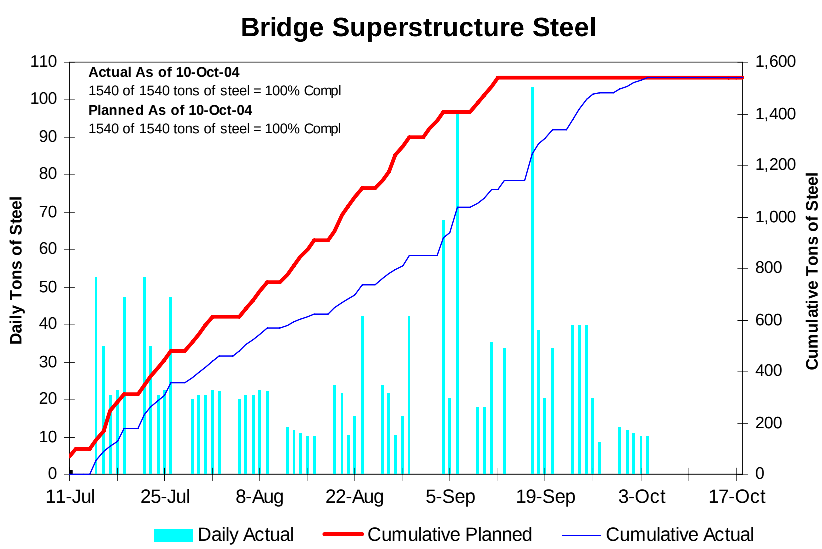



**Figure 15: Superstructure Steel Commodity Curve**

Money is the ultimate concern. Thus, the ultimate commodity curve applies contract value to activities and measures the progress of activities to give an accurate picture of the flow of money. This *earned value* analysis is an integrated cost-schedule technique used to monitor and analyze the progress of a project. Specifically, it provides a monetary baseline, the budgeted cost of work scheduled (BCWS), against which the actual data, the actual cost of work performed (ACWP) and budget cost of work performed (BCWP), are compared. Analyzing the three specific pieces with the data date provides the cost and schedule variance, how much the project is ahead or behind schedule and over or under budget. Specifically, the difference between the BCWS and BCWP gives the schedule variance in either dollars or days. And the difference between the ACWP and the BCWP gives the cost variance. The curve created of the three measures clearly indicates whether or not the project is meeting the schedule and budget. Simply stated, if the BCWS curve is above the BCWP curve, the planned project schedule is more complete than the actual progress; therefore, the project is behind schedule. If the BCWS is below the BCWP, then the project is ahead of schedule. Moreover, if the ACWP curve is above the BCWP curve, then the project is paying more for what was thought to cost much less; therefore, the project is over budget. If the ACWP is below the BCWP, then the project is under budget. Figure 16 illustrates a typical earned value curve and the variances that may be drawn from it.

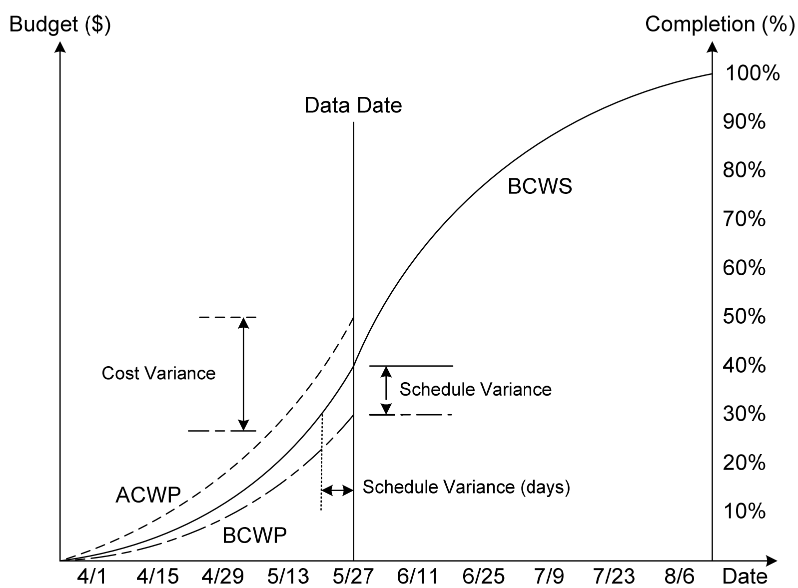



**Figure 16: Earned Value Curve**

## *5.10 Schedule Narrative*

The schedule narrative is another important output of the scheduling process; it summarizes and describes the Contractor's plan for construction and general flow of work. Specifically, the Contractor will report to the Owner the planned utilization of labor and equipment so that the interim milestones and final completion date are met. In addition, the schedule narrative should identify and explain the assumptions, sequencing, and restraints for major work categories. Moreover, relationships between similar activities shall reflect crew restraints based on the assumed number of crews for a given type of work. The narrative should list:

- anticipated workdays per week
- holidays
- number of shifts per day
- number of hours per shift
- anticipated delays lost due to weather per month.

Of particular importance, some contracts require that the schedule narrative include a "resource analysis" report and an earnings schedule of cash flow projection. Therefore, the histograms, profiles, and curves generated have an additional use, to satisfy the requirements of schedule narrative requirements. Engineering is as much a science of assumptions as of anything else. Accordingly, without a detailed description and explanation of the assumptions on which the schedule is based, it bears little relevance to an Owner or other interested parties.

# 6 Summary

The level of scheduling understanding by managers and executives who supervise schedulers has declined. As a result, the proper use of scheduling language and an appreciation of the importance and complexity of the scheduling process have also decayed. Herein, we emphasized the key management aspects of scheduling: the language, the inputs to the process, and the outputs. In general, scheduling answers *who* and *when*, determining the sequence and timing of construction operations. The schedule is the end result of planning which conveys *what* must be done, *how* and *where* it will be performed, and in what general sequential order it will be completed. Essentially, the inputs to the scheduling process are direct results of the planning efforts. Therefore, an inability to schedule stems from a reluctance or incapacity to plan. The underlying principle of the entire process is to make abstraction fit real project conditions, to narrow the gap between the model and the construction project. Our focus was on the data that the project plan provides as inputs to the scheduling process, how time is applied using CPM, and the information outputted from the process.

## *6.1 The Inputs*

The inputs are what we need to provide to the scheduling process in order to get what we want from it. The importance of the planning process is that nothing is achieved by planning to a greater level of detail than that required for control and we cannot control to any greater level of detail than that to which we have planned. Therefore, the inputs are the most important part of scheduling. The Grand Plan gives a framework for the scheduling and construction of the project. Milestones identify significant intermediate reference points. The WBS is a task-oriented breakdown of activities that organizes, defines, and graphically displays the project work. Clearly, the WBS is one of the most important outputs of the planning process because it uniquely guides the scheduling process by defining and grouping work tasks. The definition of calendars is another important input to the schedule that significantly affects the construction schedule. Scheduling with multiple calendars, notwithstanding the added complexity, is practical, and prominent project management software provides the necessary functions to do so with relative ease. The planning phase defines the necessary activities and the scheduling phase determines their sequence and timing. Activities usually consume time and resources, they are assignable and measurable, they have a definable scope of work, and an identifiable start and finish. In general, the determination of activity durations is a critical part of the planning process, resulting in a vital input to the schedule. Without well defined activity durations, putting the activity time-windows together in the schedule is relatively meaningless.

Success on construction projects depends on the efficient utilization of limited and costly resources—labor, materials, and equipment. Furthermore, the project resources should be leveled with resource constraints in order to improve work efficiency and minimize cost. These resource limitations may drive the schedule, changing the critical path. Because activities consume time, resources, and money, they must be assigned and measured. A cost-loaded plan is the assignment of contract dollar values to work activities. Essentially, assigning contract value to activities which compose the schedule enables the effective integration of cost and time.

Job logic is simply the connections between activities, what activities precede and succeed each activity. Appropriately, the construction schedule hinges on reputable job logic, which uniquely depends on the know-how of the planner. Thus, the validity of the construction schedule relies heavily on the experience of the planner(s) and the care put into establishing the job logic. Relationships are applied to define how activities are connected. Easy finish-to-start relationships cannot accurately represent the actual flow of work of a construction project alone. To realistically model the construction process, “smart” relationships are used in project schedules. Once activities are defined and appropriately sequenced, the network diagram is drawn to easily and visually demonstrate how a project will be completed. A network diagram is the graphical representation of a detailed project plan; it illustrates the job logic and basic activity sequencing. In general, a network diagram shows the ‘big picture,’ what is going to happen and in what order. Undoubtedly, the inputs are the most important part of scheduling.

## *6.2 The Process*

Modern calculations are performed by intelligent computer-based scheduling software. Inside the “black box,” the software performs all the tedious calculations and iterations instantaneously. However, schedules produced by software are only as relevant as the inputs are reflective of the actual construction plan and only as accurate as the software correctly applies the rules of CPM and resource leveling. Thus, to gain a general understanding of CPM, resource leveling, and to develop an appreciation for the scheduler and scheduling software, we took a brief look at the process. The forward pass is the calculation of early start and finish times for each activity and the minimum total project duration. The backward pass yields the late start and late finish of each activity and further helps identify the critical path and floats. The use of multiple calendars adds another layer of complexity to even the simplest of CPM calculations, making them very difficult and tedious. A resource-loaded schedule demonstrates the interdependencies between activities and resources. Resource leveling minimizes the fluctuation in daily resource usage throughout the life of the project by shifting non-critical activities within their available float. Scheduling is not an easy process, but with the aid of computer-based software, the tedious and repetitive parts of scheduling are performed instantly.

## *6.3 The Outputs*

The outputs of the scheduling process are essentially *what we get* from the calculations based on *what we provided* as inputs because of *what we wanted* in order to improve construction project management. The inputs are processed and used to create tools that aid time-monitoring and progress measurement, resource histograms and profiles, commodity curves, and earned value curves. The process directly provides data such as activity time windows, the available total and free float, the critical path, and the overall baseline or target schedule. Total float is the maximum amount of time an activity can be delayed from its original early start without delaying the duration of the entire project. The calculated float does not belong to any one activity, but it is shared among all the activities. The critical path is the network path with the longest duration and any delay along this path will cause an equal total project delay. The collection of these activities is called the critical path, which denotes job areas that project managers should closely monitor in order to remain on schedule. Free float is unique to an activity—it is not shared by the entire network. Formally, the free float of an activity is the amount of time an activity's start or duration can extend without affecting the start of any successor. Clearly, the differences between total float and free float are significant. The two terms should not be used interchangeably or even mistakenly.

The baseline schedule represents the Contractor's original understanding of the project and the intended schedule for completing the project and is normally visualized in three main forms: the bar chart, the precedence network, and the time-scaled logic diagram. Bar charts are simple and clear depictions of when activities are scheduled. A bar chart does not show logical dependency among activities and does not support manual project progress measurement. The major flaw is that intent is not explicit because a bar chart inherently lacks viewable job logic. Nonetheless, bar charts are still used because of their ease of creation and understanding. The precedence network explicitly depicts the logic that connects activities but does not show time. Consequently, precedence diagramming is a technique that is used less in schedule visualization and more in planning a project. To integrate the strengths of the precedence network and the bar chart, the time-scaled logic diagram intends to clearly depict both time and logic.

Commodity curves are generated to graphically represent resource utilization and project progress. Curves are created for three main types of commodities: input resources such as labor, output commodities such as cubic meters of regular excavation, and contract value—the ultimate commodity. Actual utilization and performance are recorded, inputted, and the progress measured against the plan. Measuring the progress of output commodities provides the most reliable depiction of project progress. But, the ultimate commodity curve applies contract value to activities and measures the progress of activities to give an accurate picture of the flow of money. This *earned value* analysis is an integrated cost-schedule technique used to monitor and analyze the progress of a project. Lastly, once all inputs are generated and the schedule calculated, a narrative is developed which puts the planning and scheduling processes in words. A scheduling narrative describes the Contractor's plan for construction and general flow of work. Accordingly, without a detailed description and explanation of the assumptions on which the schedule is based, it bears little relevance to an Owner or other interested parties.

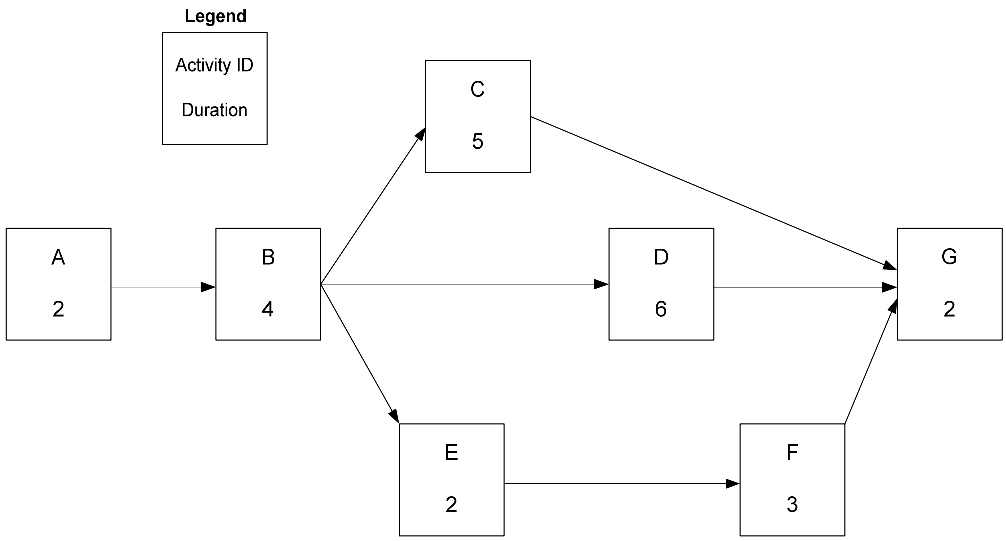
## 6.4 Conclusion

The outputs of the planning process are the inputs to the scheduling process. Therefore, an inability to schedule stems directly from a reluctance or incapacity to plan. Planning to reduce risk is money well spent. Moreover, meaningful monitoring depends on a good schedule derived from solid plans; inadequate planning can ruin opportunities for time-impact analysis. Planning, therefore, is uniquely bound to scheduling. Because the scheduling process, the calculations and outputs derived therefrom, is performed by powerful software, the focus or emphasis should be on the detailed development of realistic inputs and on the manipulation of useful outputs. As it becomes more complex and more valuable, management must increase their understanding of and appreciation for scheduling

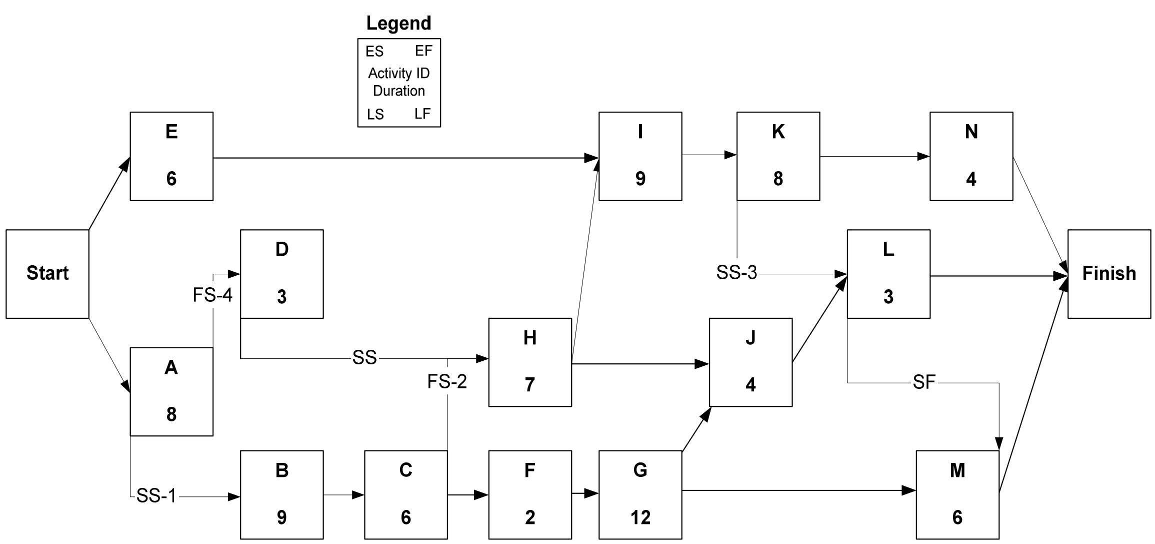
# 7 Demonstration Exercises:

## *7.1 Forward and Backward Passes*

Perform a forward and backward pass on the following networks. Specifically, find the ES, LS, EF, and LF for each activity, label according to the legend and identify the critical path.




**Example Figure 1: Network with Simple Logic**

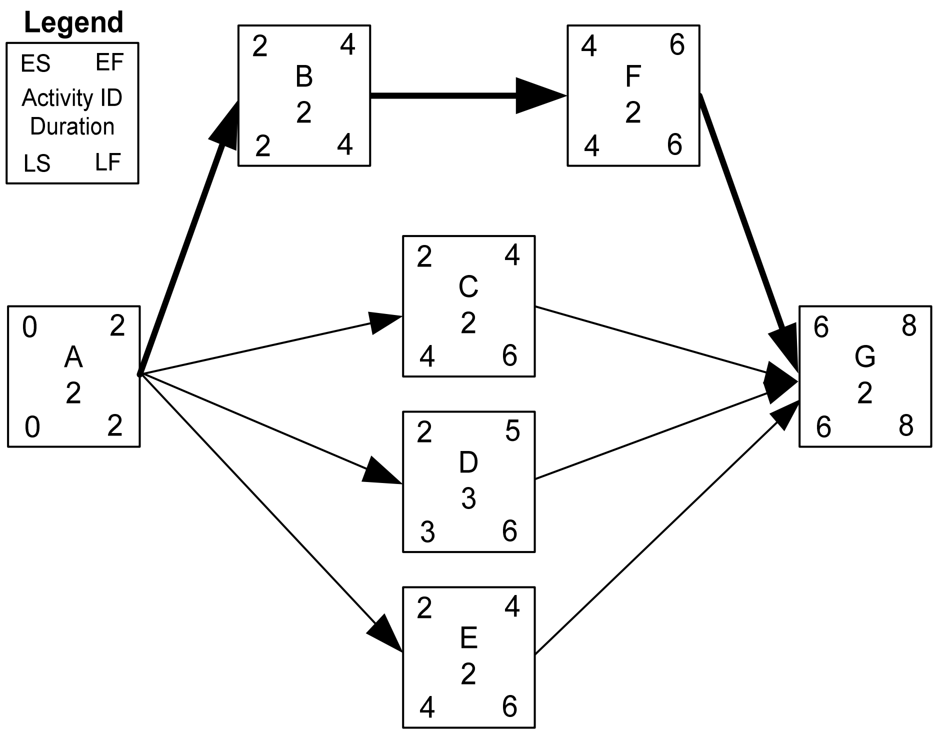



**Example Figure 2: Network with Smart Logic**

Hint: Collect all possible ES for the forward pass and choose the latest; and, collect all possible LF for the backward pass and choose the earliest.

### 7.2 *Resource Leveling*

Imagine that all of the activities below require concrete everyday of their duration. However, due to concrete batch plant restrictions, only one of the scheduled activities can receive concrete on any given day. Using this information and the diagram below, level the resources appropriately and answer the question: Is the total duration extended?

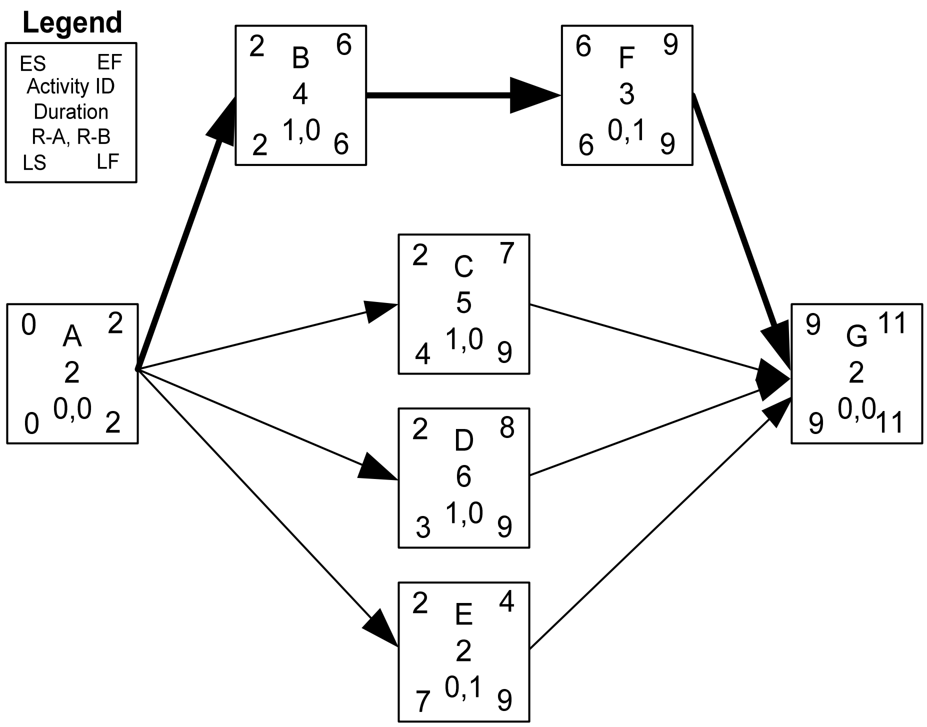



**Example Figure 3: Resource Leveling Network**

*Hint*: Since only one activity can receive concrete each day, the activities with the least total float get concrete first and then those with the greatest remaining duration.

### *7.3 Resource Profiles*

Given the network below and the listed resources for each activity (the third line in each bubble is "Resource A, Resource B"), provide a daily utilization histogram and a cumulative profile for each resource.




**Example Figure 4: Multiple Resource Leveling Network**

### *7.4 Output Commodity Curves and Contract Value*

Superstructure concrete for the piers is scheduled to be placed according to the timing of the planned quantities given below. To monitor the progress by physical quantities and by dollars, create an output commodity curve and an earned value curve. Is the project ahead of or behind schedule and over or under budget?

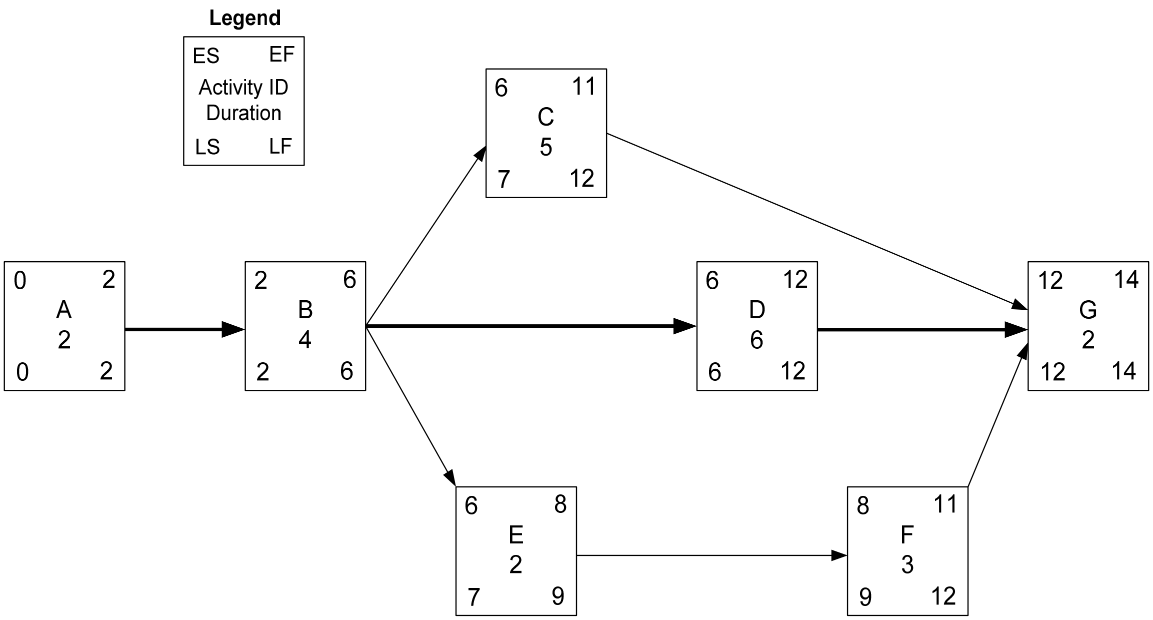
**Example Table 1: Quantities and Costs for Concrete Bridge Superstructure**

**Bridge Superstructure Concrete**

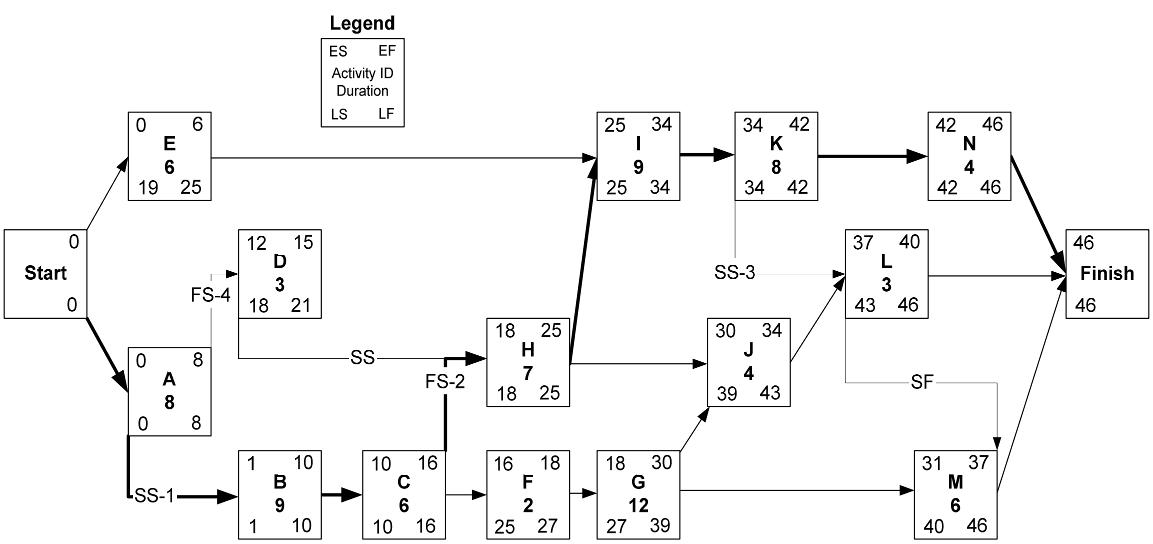
| Week of | Concrete Placement (cy) | | Concrete Contract Value ($) | | Actual Cost | |
|---|---|---|---|---|---|---|
| | Actual | Planned | Actual | Planned | | |
| 2-May | 0 | 0 | $ - | $ - | $ - | |
| 9-May | 0 | 150 | $ - | $ 63,750 | $ - | |
| 16-May | 125 | 250 | $ 53,125 | $ 106,250 | $ 65,000 | |
| 23-May | 200 | 300 | $ 85,000 | $ 127,500 | $ 100,000 | |
| 30-May | 250 | 200 | $ 106,250 | $ 85,000 | $ 125,000 | Data date |
| 6-Jun | | 450 | | $ 191,250 | | |
| 13-Jun | | 450 | | $ 191,250 | | |
| 20-Jun | | 0 | | $ - | | |
| 27-Jun | | 0 | | $ - | | |
| 4-Jul | | 0 | | $ - | | |
| 11-Jul | | 0 | | $ - | | |

# 8 Exercise Solutions

## 8.1 Forward and Backward Pass



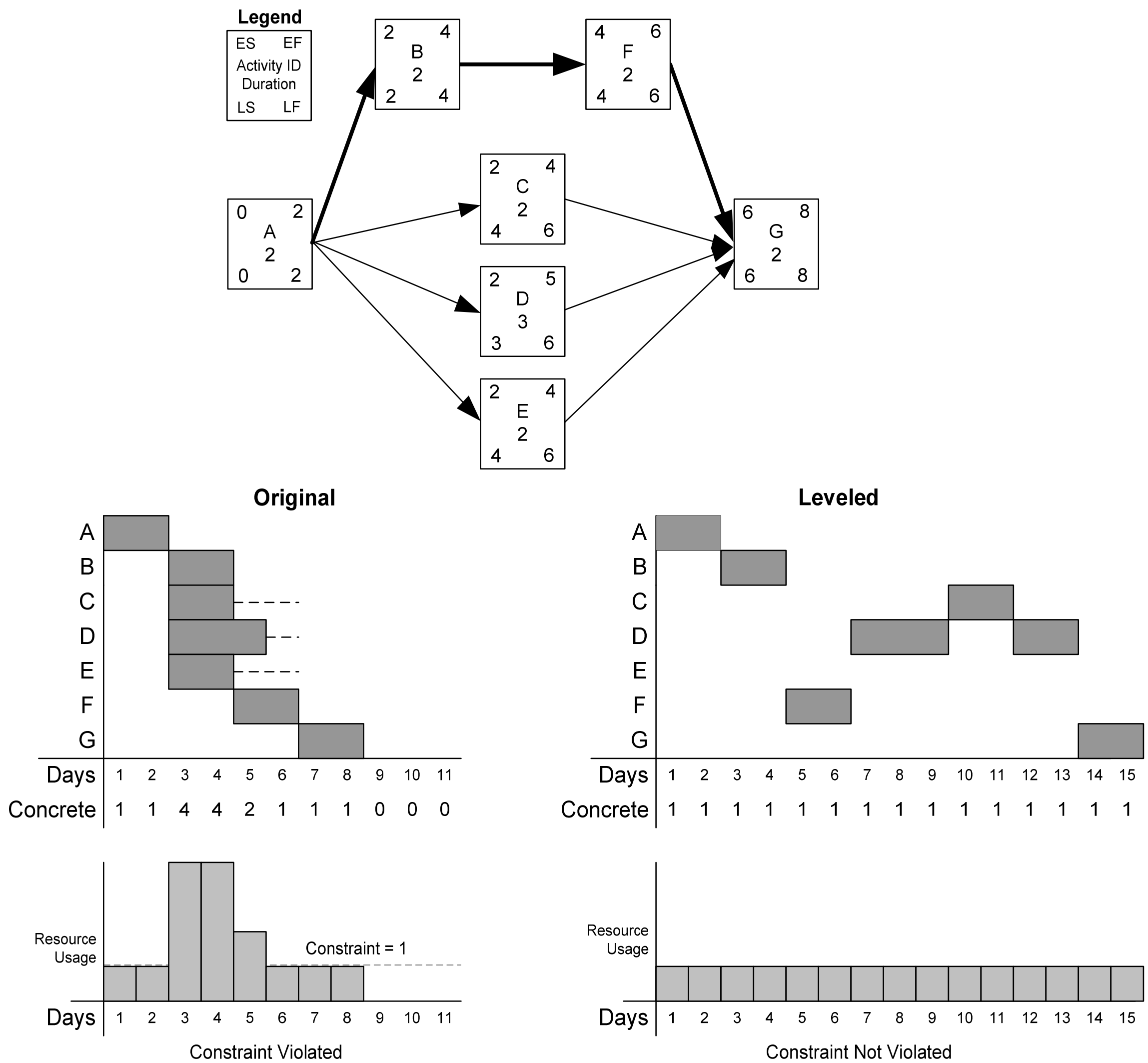

**Solution Figure 1: Network with Simple Logic**




**Solution Figure 2: Network with Smart Logic**

***Commentary***: The first exercise is easily solved by employing the basic rules of the forward and backward pass. However, few projects have such simple precedence networks; most diagrams encompass hundreds or thousands of activities. Even with simple, strictly finish-to-start activity networks, performing a forward and backward pass would be extremely tedious. The second exercise incorporated smart relationships, increasing the level of difficulty of finding the activity early and late times and the total project duration. Imagine performing these calculations on a large set of data which employs smart relationships and leads and lags. Thankfully, scheduling software perform the same processes instantaneously.

## *8.2 Resource Leveling*

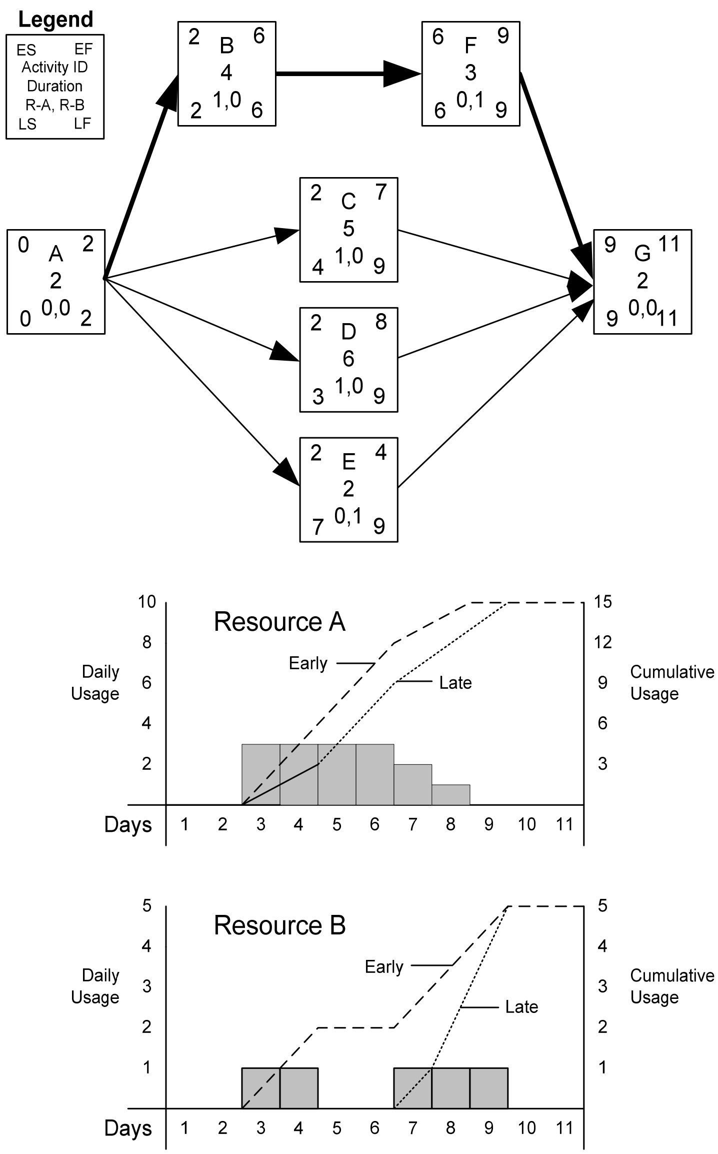



**Solution Figure 3: Resource Leveling Network**

***Commentary***: The early start schedule grossly violates the imposed constraints. To meet the constraints, the schedule proceeds one activity at a time in the order specified. Because they have less total float, in fact none, activities B and F take precedence over activities C, D, and E. Between C, D, and E, D precedes the other two because it has a greater remaining duration. C and E are essentially interchangeable, so C was arbitrarily chosen to precede E. Because of the constraints imposed on concrete availability, the total duration is extended by seven days. Even this very simple exercise takes considerable thought and time;

luckily, scheduling software can perform the same calculations on many more activities and with many more resources instantly.

## 8.3 Resource Profiles




**Solution Figure 4: Multiple Resource Leveling Network**

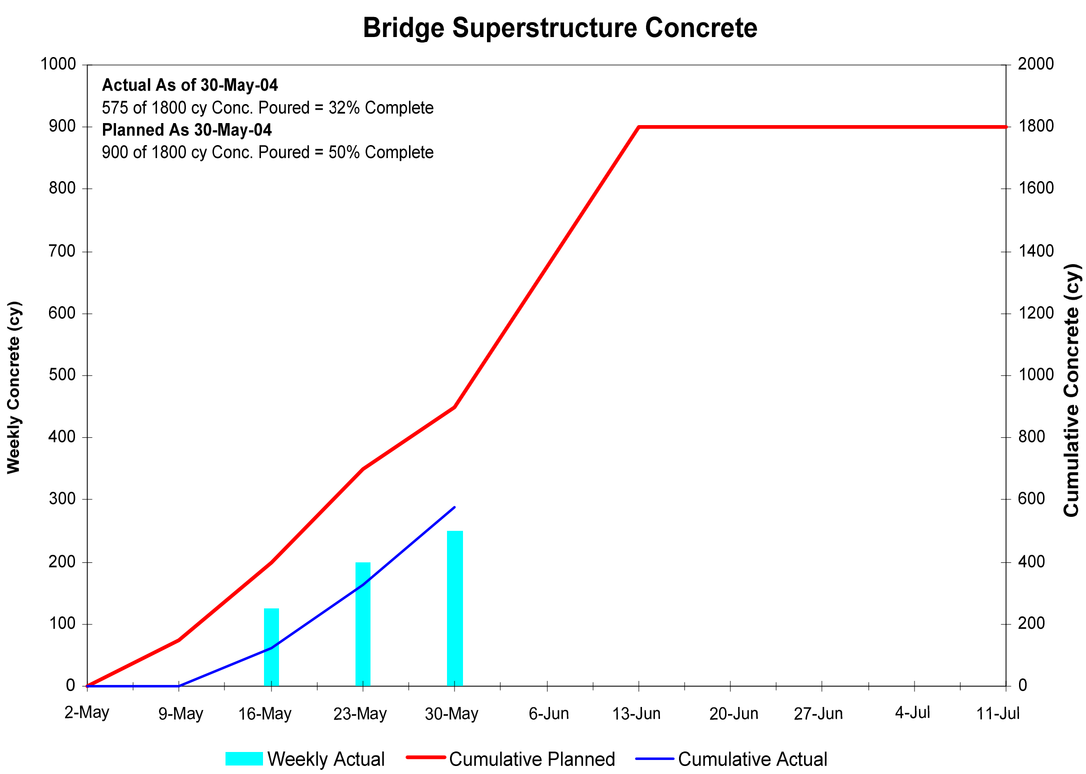
***Commentary***: This straightforward exercise illustrates that early and late times should be strongly considered. The resource utilization of the two activities is easily plotted because of the simplicity of the network and minimal resources. However, most construction projects have many more activities and employ many more resources that should be tracked. For short term schedules with minimal critical resources, these methods may be used; but, the power of scheduling software should be otherwise utilized in order to quickly and accurately generate the histograms and profiles.

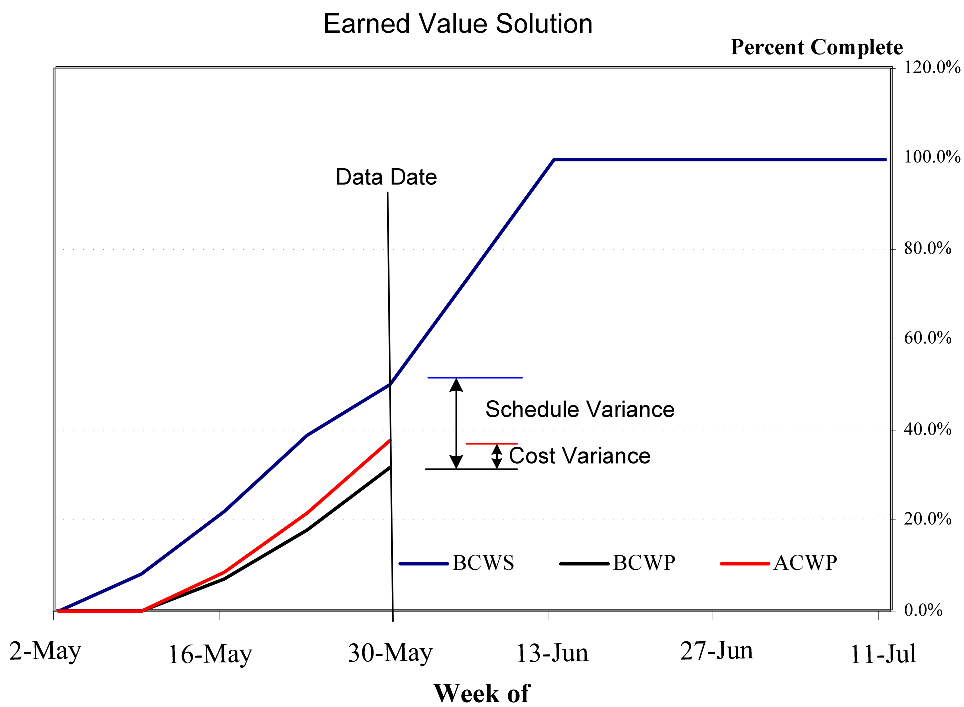
## 8.4 *Output Commodity Curves and Earned Value*

**Solution Table 1: Output Commodity Curves and Earned Value**

**Bridge Superstructure Concrete**

| Week of | Cumulative (cy) | | Cumulative | | | Earned Value | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Actual | Planned | Actual | Planned | Act. Cost | BCWS | BCWP | ACWP | |
| 2-May | 0 | 0 | $ - | $ - | $ - | 0.0% | 0.0% | 0.0% | |
| 9-May | 0 | 150 | $ - | $ 63,750 | $ - | 8.3% | 0.0% | 0.0% | |
| 16-May | 125 | 400 | $ 53,125 | $ 170,000 | $ 65,000 | 22.2% | 6.9% | 8.5% | |
| 23-May | 325 | 700 | $ 138,125 | $ 297,500 | $ 165,000 | 38.9% | 18.1% | 21.6% | |
| 30-May | 575 | 900 | $ 244,375 | $ 382,500 | $ 290,000 | 50.0% | 31.9% | 37.9% | Data Date |
| 6-Jun | 575 | 1350 | $ 244,375 | $ 573,750 | $ 290,000 | 75.0% | 31.9% | 37.9% | |
| 13-Jun | 575 | 1800 | $ 244,375 | $ 765,000 | $ 290,000 | 100.0% | 31.9% | 37.9% | |
| 20-Jun | 575 | 1800 | $ 244,375 | $ 765,000 | $ 290,000 | 100.0% | 31.9% | 37.9% | |
| 27-Jun | 575 | 1800 | $ 244,375 | $ 765,000 | $ 290,000 | 100.0% | 31.9% | 37.9% | |
| 11-Jul | 575 | 1800 | $ 244,375 | $ 765,000 | $ 290,000 | 100.0% | 31.9% | 37.9% | |






***Commentary:*** Using the data given, cumulative quantities and costs were calculated and graphed using Microsoft Excel. The output commodity curve for concrete, illustrated on the previous page, shows that progress is behind schedule. From the graph, we can find that concrete placement started late, but comparing the slopes of the cumulative planned and actual lines shows that since the delay, placement has reflected the expected production. Along with the cumulative data, the earned value (BCWS, BCWP, ACWP) was calculated in order to make the graph above, which reiterates that the project is behind schedule and also shows that it is over budget. Specifically, the BCWS is greater than the BCWP; therefore, at this point, the schedule was expected to be more complete, i.e. the project is behind schedule. The ACWP is greater than the BCWP; therefore what has been placed has cost more than it was originally thought to cost, i.e. the project is over budget. Clearly, both output commodity curves and earned value curves are immediate and useful tools for monitoring project progress.

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