Chapter 1: Introduction

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Planning and scheduling

- In simple language, planning is the way we organize and sequence the tasks needed to accomplish a goal
- For example: business plans, strategic plans, financial plans, etc.

- In construction, the planning required to construct an office building includes:
- Identifying the tasks needed to complete the building (i.e., excavations, footings, etc.)
- Sequencing the tasks in their logical order (i.e., columns before slabs, etc.)
- and much more ……

Schedule generation

- After the contractor decides to bid on a certain project, the contractor's team (project manager, estimator, scheduler, others) starts a careful review of contract documents

- **This review aims at:**

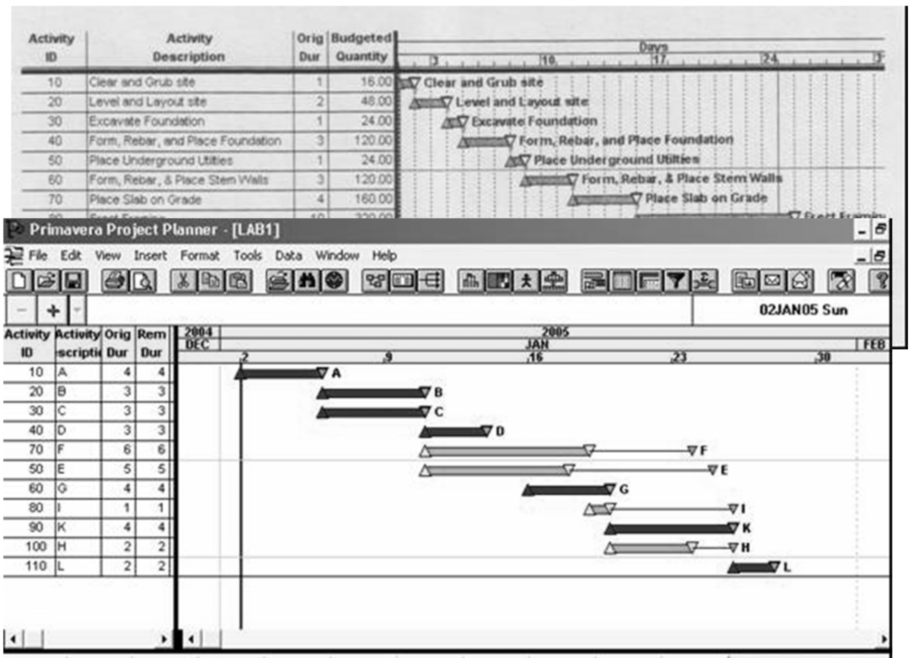
1. Visualizing the construction process
2. Visualizing work sequencing
3. Identifying tasks/activities needed to construct the project

4. Assigning durations to these activities based on productivity rates of work crews
5. Identifying the relationships between these activities and sequencing them in the right logic
6. Ensuring that project duration fits within the specified time frame

- <u>**The construction schedule is generated**</u>

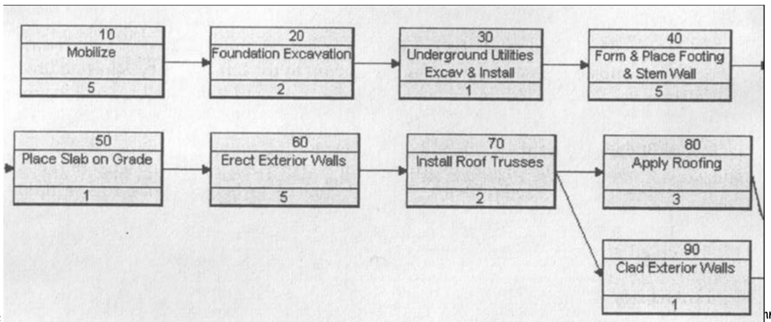
Displaying the schedule

- Several methods can be used to display the resulting network and its logic
- Bar charts: easily understood



- Network (logic) diagrams: show how activities are related

- Examples on network (logic) diagrams: Activity On Arrow (AOA), Activity On Node (AON)



History of scheduling

- Modern history of scheduling began in 1917 when Henry Gantt developed bar charts (or Gantt chart)

- He developed a method of relating a list of activities to a time scale in a very effective manner

- In the 1950s, two companies, Dupont and Remington developed the Critical Path Method (CPM) for the renovation, construction, and maintenance of chemical plants
- At almost the same time, the US Navy in collaboration with other companies developed Project Evaluation and Preview Technique (PERT) to help manage the multiple contractors of Polaris missile for use in submarines

- PERT assumes that an activity's duration can not be precisely determined and therefore uses a probabilistic approach (instead of CPM deterministic approach)
- In PERT, the planner specifies 3 separate durations
  - Most likely
  - Optimistic
  - Pessimistic

- The planner comes up with an "expected" duration based on these 3 durations

- PERT is used in research and development projects where historical data is not available and/or due to insufficient experience

Advantages of construction schedules

- For construction projects, success is typically measured by achieving both budget and schedule projections

- **The use of scheduling tools enables the constructor to:**

1. Visualize the planned construction work
2. Use computerized what-if capabilities to analyze alternatives and make schedule adjustments
3. Effectively allocate and level resources

4. Compare budgeted and actual costs, productions, and durations
5. Justifying the effects of change orders
6. Making claims for payment based on time percent complete
7. Monitoring project success

Planning and Scheduling

Developing a Network Model
Chapter 2 (Weber)
Chapter 2 (Hinze)

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Steps in building a network model

1. Define activities

↓

2. Order activities

↓

3. Establish activity relationships and draw a network diagram

***Note the continuous iteration for steps 1-3**

4. Determine quantities and assign durations to activities

↓

5. Assign resources and costs

↓

6. Calculate early and late start/finish times

↓

7. Compute float values and locate the critical path

↓

8. Schedule activity start/finish times

***Continuous revision and update for network logic and calculations; this happens both before and after construction starts**

Source: Hinze (2012)

Building a network model

- Note that the previous 8 steps are always subject to continuous revision and update during both the planning phase and construction phase
- <u>During the planning phase</u>: to ensure that we have the best and most reliable plan to execute construction operations

- During construction: to ensure that the schedule closely depicts the progress in the field (updated)
- The 8 steps process should result in a network that is a reasonable representation of the actual project
- However, it is usual in construction for unanticipated incidents that are not modeled in the schedule to happen

- Examples include:
- Owner initiated changes
- Labor shortages
- Delays in material delivery
- Performance problems with a subcontractor
- Differing site conditions
- And many others……

1. Defining activities

- All activities needed to construct the project should be included in the network
- There are several types of activities:
  - Production/construction
  - Procurement
  - Management

Production/Construction activities

- Physical installation of work
- Consume resources: labor, material, time
- Production activities usually include an action verb in their description: <u>***excavate***</u> basement, <u>***pour***</u> concrete, <u>***erect***</u> steel, <u>***paint***</u> wall, etc.

- Production activities are the heart of the construction schedule

- These activities usually consume the diverse set of resources needed to construct the project

Procurement activities

- Purchase and delivery of long lead-time items

- Arranging for acquisition of materials, money, equipment, manpower

- Influence the timing of production activities

- Long lead items are usual procurement activities

- ***Fabrication, order,*** **and *delivery*** are words often associated with procurement activities

Management activities

- Examples include:
  - Approving shop drawings
  - Tracking submittals
  - Developing as-built drawings
  - Testing

Milestones

- Sometimes, contracts require the contractor to meet certain intermediate deadlines
- These events are frequently known as milestones

- These milestones have no duration and use no resources
- They, simply, represent a point in time
- Milestones can be:
  – Start milestone
  – End milestone

- Start milestone
  - Marks the beginning of a specific set of activities
  - Such as: notice to proceed, give the contractor right of access to the site
- End milestone
  - Marks the end of a specific set of activities
  - Such as: issue taking over certificate, issue performance certificate

Activities level of detail

- A related issue in defining activities is the fact that the planner needs to consider the level of control needed to:
  - Track progress
  - Identify problems quickly
  - Incorporate changes easily

- What does constitute an activity?
- “Build a house”?
- Or “install light fixture #63”?
- Which alternative is better than the other?

- “Build a house”
  - At this level of detail, there is no intermediate control of time or money
  - It is almost impossible to tell whether the project will finish on time and within budget
  - There are no intermediate benchmarks with which to measure outcomes

- “Install light fixture #....”
  - At this level of detail, there could be hundreds/thousands of activities
  - Tracking time and money at this level of detail will turn very challenging

- The best approach
  - Each project manager must determine the appropriate level of detail
  - The resulting activities are used to prepare the initial schedule
  - As the project progresses, management may determine that certain areas of the project require more/less detail
  - Changes should be made to schedule as needed throughout the life of the project

Activity descriptions

- Activity description for production activities should include action-related verbs
- Each activity should have a distinct description
  - "Place concrete slab"
  - or "Place concrete slab – Building 1, floor 2"
  - Which description is better? Why?

Activity identification

- In addition to descriptions, activities usually have identifications (I.D.'s):
  - Numbers only (140)
  - Numbers and characters (CON140)

- Which one is better to number activities?
  - 1, 2, 3
  - Or 10, 20, 30
  - Why?

- In large projects they use 12 alphanumeric numbers and characters to make the identification more specific

LLL	TTT	X	NN
L = Location	T = Trade	X = Wk Type	N = Number

Such that PH1ELE001 could indicate installing Powerhouse 1 (PH1), Electrical (ELE), and a sequential number scheme (001). The first number, X, may relate to different types of trade-related activities such as 1 = substation, 2 = equipment installation, and 3 = terminations. SB CON010 could be used to represent placing Service Bay concrete at a certain level or location.

Figure 2.1

Source: Weber (2005, p.13)

2. Ordering activities

- To put a certain activity in its logical order, 3 related questions must be answered:

1. Which activities must precede it?
2. Which activities must follow it?
3. Which activities can be concurrent with it?

- In addition to the above 3 questions, several constraints control the ordering of activities:
  - Physical, resource, safety, financial, environmental, management, contractual, and regulatory constraints

Constraints

- Physical constraints
  - Logical order of putting things on place
  - For example: forms, rebar, then pouring concrete
- Resource constraints
  - Due to insufficient availability of resources
  - For example: 2 activities that need a crane can not be scheduled at the same time

- Safety constraints
  - For example: drilling and blasting will postpone the execution of adjacent activities
- Financial constraints
  - Securing loans
  - Avoiding high cost activities during a certain stage in construction (especially at the beginning of the project)
- Environmental constraints
  - Not executing certain activities so that the nature at certain seasons is not disturbed
  - Dust or noise control

- Management constraints
  - Any constraint imposed by management
  - For example: no work or shorten workdays during the holy month of Ramadan, etc.

- Contractual constraints
  - Imposed by the owner
  - Completing certain part of the project before starting with another part

- Regulatory constraints
  - Imposed by government agencies, municipalities: issuing permits

Constraints impact

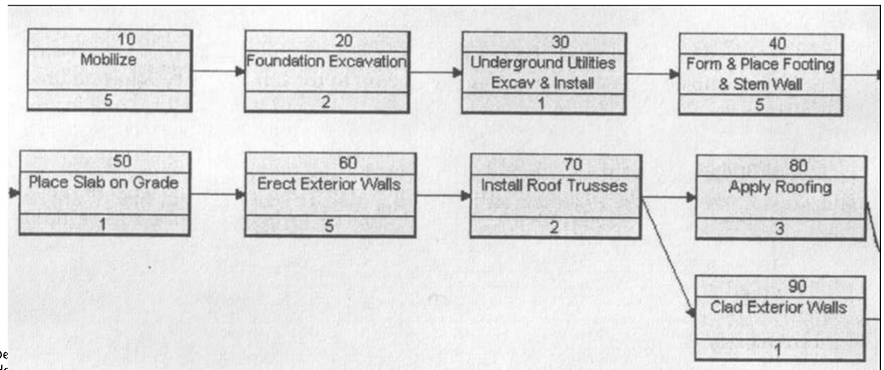
- Constraints have a negative impact on the schedule

- Sometimes, they confuse the logic of the schedule

- Scholars and practitioners recommend avoiding them as much as possible

3. Establish activity relationships and draw a network diagram

- Shows the network and relationships between activities



4. Assigning durations to activities

- The duration of an activity is the estimated time that will be required to complete it
- The usual unit of time: “days”
- Other units are possible depending on the nature and length of the project: hrs, wks, months, yrs, etc.

- Activity durations are calculated based on the resources used and their productivity (crew size, equipment, etc.)

- Productivity numbers are usually available per hour:
  - 50 m^3 /hr for an excavator
  - 10 m^2 /hr for a crew of painters (i.e., 1 skilled, 2 helpers)
  - 20 Linear-meter /hr of pipes for a crew of plumbers (1 skilled, 1 helper)
  - etc.

The duration of an activity is calculated as follows:

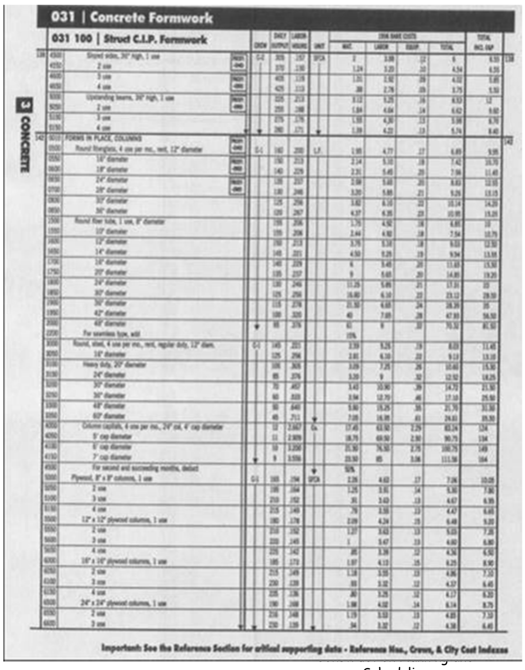
Duration (hours) = Quantity (m^3)/ Productivity (m^3 /hr)
= total_hrs

Duration (days) = total_ hrs / hours_worked_per_day

Productivity rates

- Are there any published productivity numbers (for construction) in Jordan?
- US productivity numbers:
  - Walker's building estimator reference book
  - Richardson's general construction estimating standards
  - R.S. Means cost data books

- Productivity numbers have to be reliable to depend on
- Firms depend on:
  - Historical data from previous projects executed by the firm
  - Experience of firm's personnel



031 | Concrete Formwork

031 100 | Struct C.I.P. Formwork

3 CONCRETE

Important: See the Reference Section for critical supporting data - Reference Nos., Crews, & City Cost Indexes

Source: RS Means (2000)

5. Assigning resources and costs

- Each activity in the network model has to be assigned resources and costs:
  - Labor hrs
  - Equipment hrs
  - Cost of labor, equipment, and material

- The major requirement for effective assignment of resources and costs to individual activities is a clear description of the relationship between the CPM activities and the units of work

Activity 300:

Pour concrete for slab of floor 1

Labor: to place and elevate concrete

How many labor hrs are needed?

How much is the cost for all these labor hrs?

Material: Concrete

How many cubic meters of concrete?

Cost of these cubic meters ?

Equipment

6. Calculating early and late start/finish times

- The early start time of an activity
  - Is the earliest time that an activity can start after the completion of its predecessors
- The late start time
  - Is the latest time an activity can be started without delaying the project

- The early finish time
  - Is the earliest time an activity can be finished if it is started at its early start time and is completed using its estimated duration
- The late finish time
  - Is the latest time an activity can be finished without delaying the completion of the project

Identify the critical path

- If the early and late start dates for an activity are the same:
  - The activity has no flexibility or "float"
  - If the activity starts later than the assigned date or if the activity takes longer to complete than the assigned duration, the project completion date will be extended by the same amount of time

- Those activities have "No Float" and are called "Critical Activities"

- The chain of "Critical Activities" from the beginning to the end of the project is called "Critical Path"

- From this feature came the name: "Critical Path Method – CPM"

8. Schedule activity start/finish times

- The network and the generated information are now used to best manage the execution of the project
- Management decisions can now be made regarding using the float available for some activities to schedule the start/finish of these activities

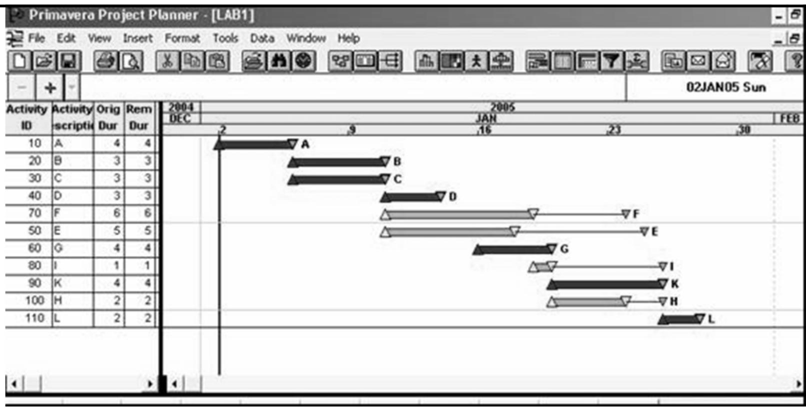
Bar Charts (Gantt Charts)

Chapter 3

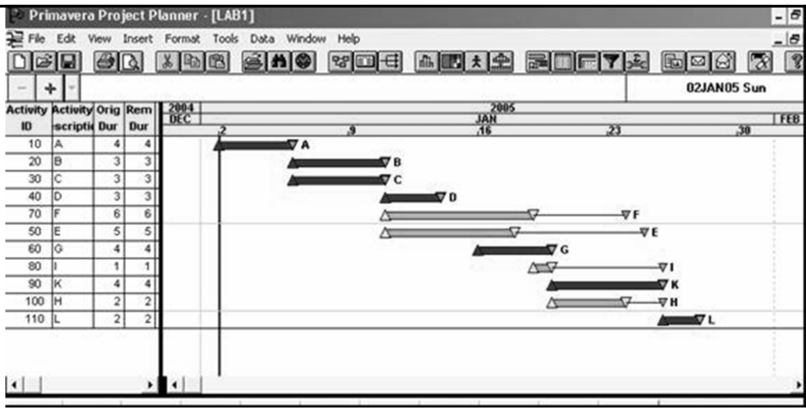
Dr. Mohammad S. El-Mashaleh

Bar charts

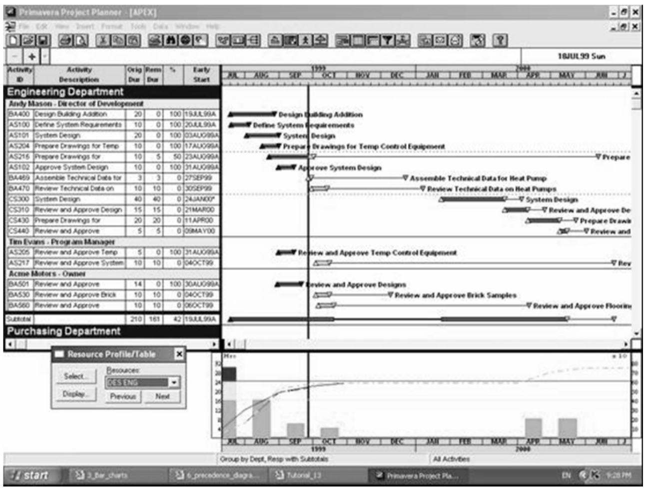
- Like we said before, bar charts are the oldest scheduling technique
- Found by Henry Gantt



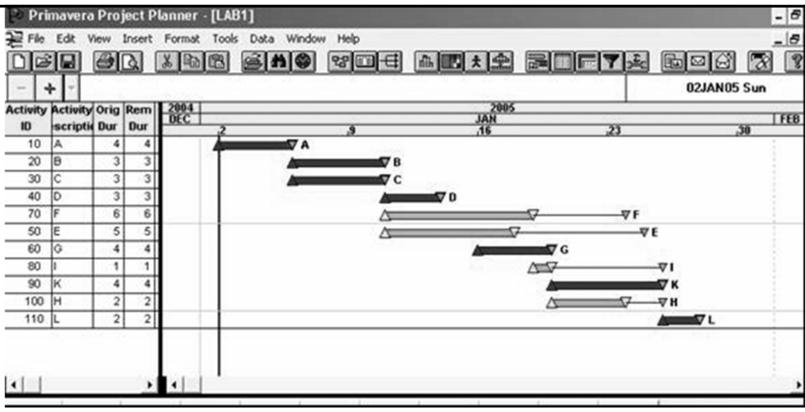
- Consists of horizontal bars and a time scale
- Each bar represents an activity, with the bar length represents its duration



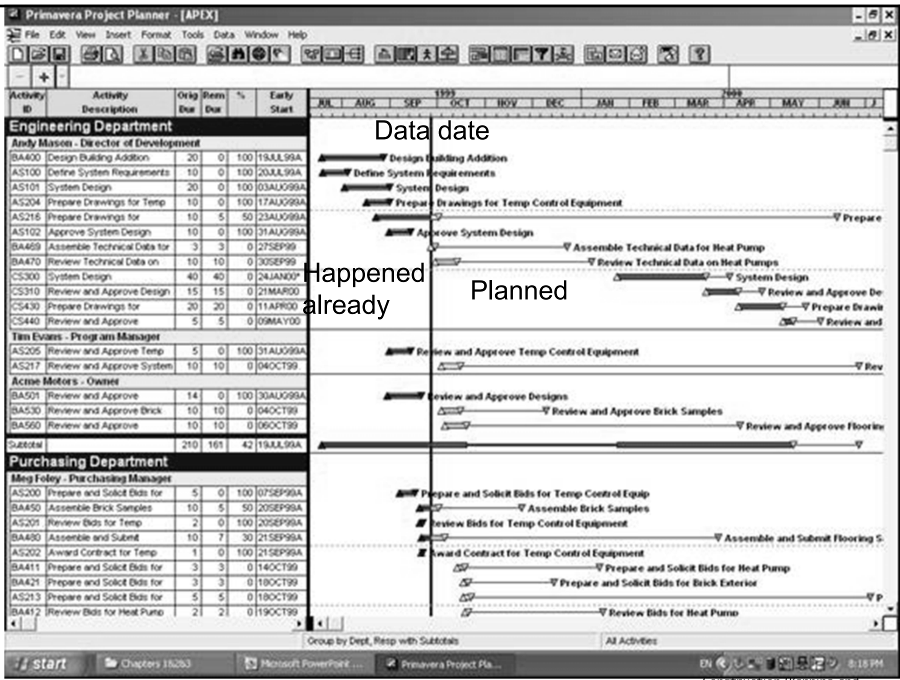
- In addition to the activity bars and the time scale, most bar charts contain data in columns
- Information may include: durations, resources, costs, other (customized)

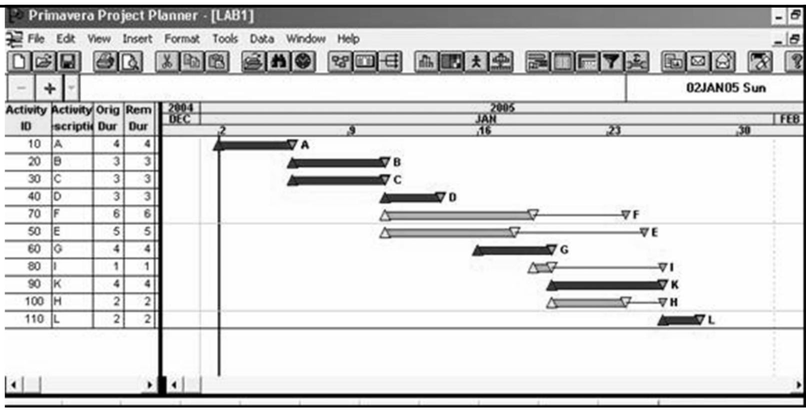


- Sometimes, bar charts are combined with resource graphics
- The resource related to each activity can be totaled to form histograms and s-curve (cumulative)



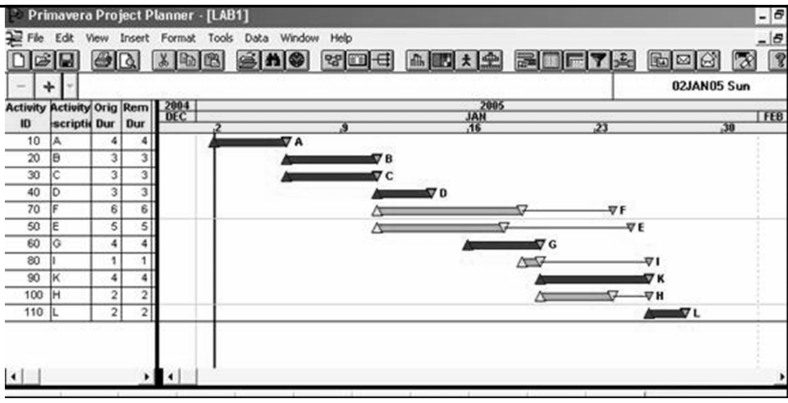
- In bar charts, activities are usually ordered by early start
- This means that the activity having the earliest start time is listed and plotted first at the top of the diagram
- It also means that the activity that happens last is the last on the list and diagram





- **Advantages**
- Ease with which it communicates project tasks, their durations, and anticipated start and finish times

- Easily constructed for small or simple projects
- Reviewers of the bar chart do not need any special knowledge to understand:
- The status of the project
- What is expected to be accomplished in the next few time periods
- When the project is expected to end



- **<u>Disadvantages:</u>**
- Do not typically show logic (logic is not obvious)
- For example, determine the dependency of F&E

- Since logic is not obvious, it is difficult to determine the downstream effect of changes to activities appearing early in the network

- Bar charts for long duration or complex projects are difficult to read when the entire project is shown on one diagram

Chapter 4: Precedence Networks

Part 1- Getting Started

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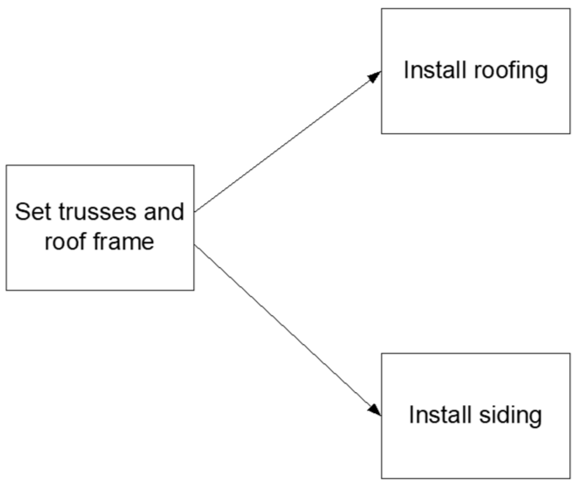
Precedence networks

- Precedence networks are the most common type of network schedule in use today
- Most scheduling software these days require the user to input the information in the form of precedence diagram

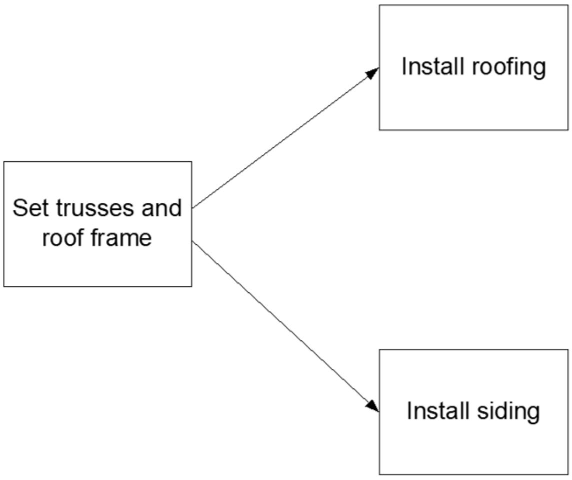
- Often called Precedence Diagramming Method (PDM)
- Also called Activity-On-Node (AON) because the node is used (rectangular box) to represent an activity
- As opposed to the arrow used with Activity-On-Arrow (AOA) networks

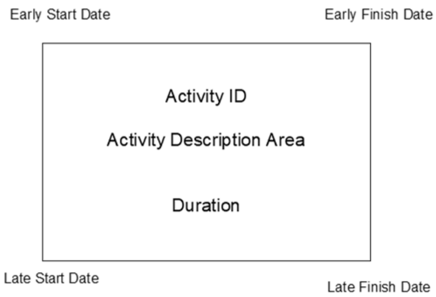
- In precedence diagrams, activities are represented as nodes
- Relationships are represented as arrows

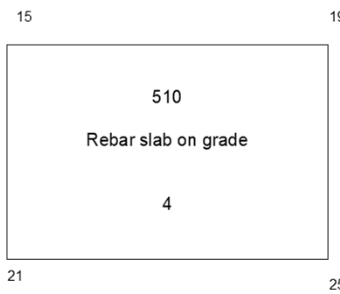


- Note that "install roofing" can not start until "set trusses and roof frame" has been completed

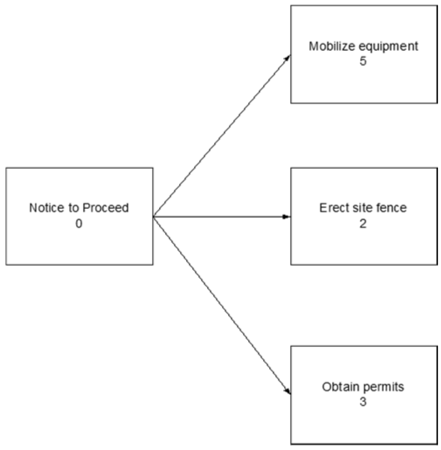
- An activity can not start also until all its predecessors have been completed



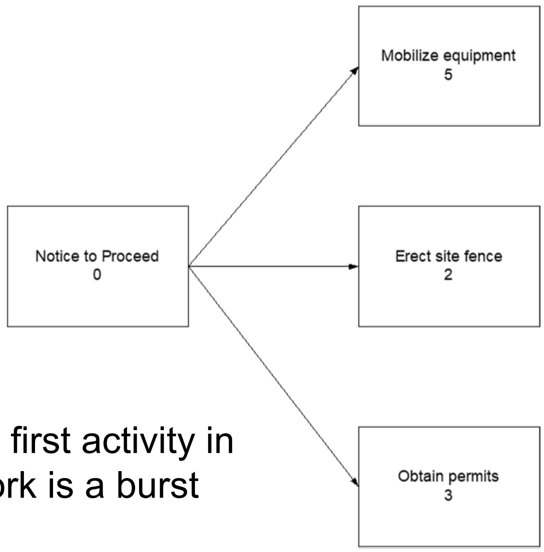




- Note that all activities except the first one in the network and the last one in the network have logical ties to activities before them and after them
- The first activity has no predecessors
- The last activity has no successors (followers)

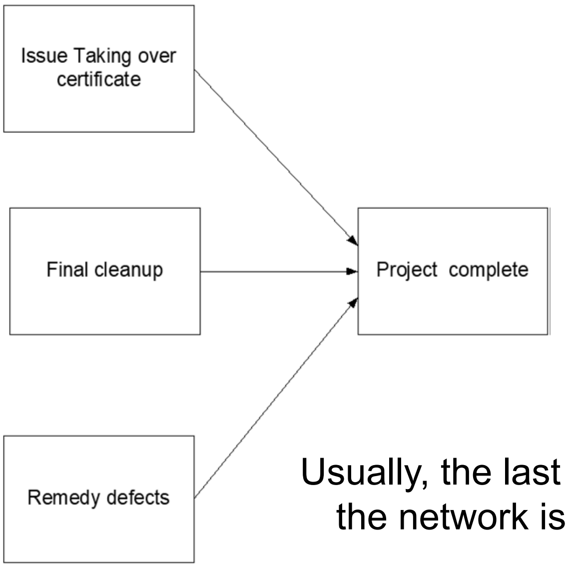


<u>Burst</u>



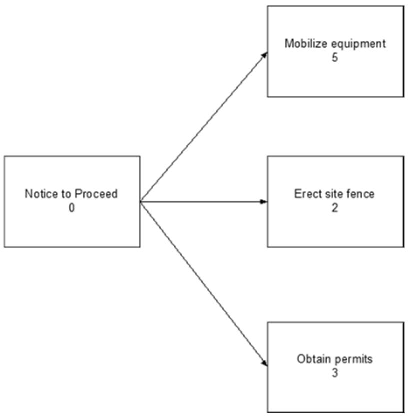
Usually, the first activity in the network is a burst

Merge

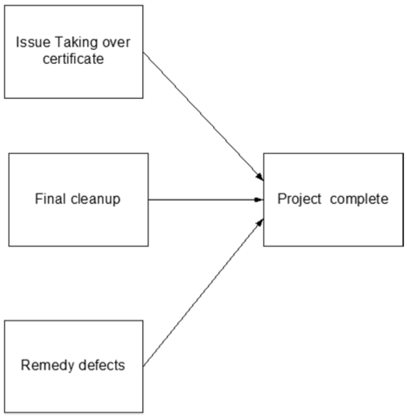


Usually, the last activity in the network is a merge

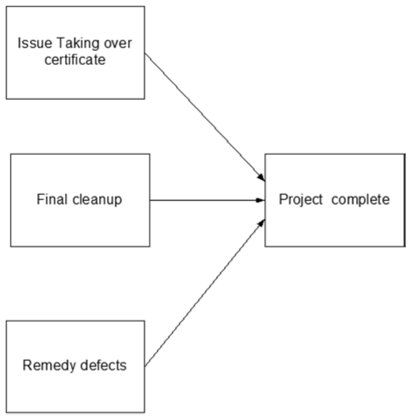
- When more than one activity starts or ends the network, a milestone must be added to the precedence network to adhere to the one activity start, one activity finish rule for CPM networks
- The milestone start may be "Notice to Proceed"



• The milestone finish may be "Project Complete"



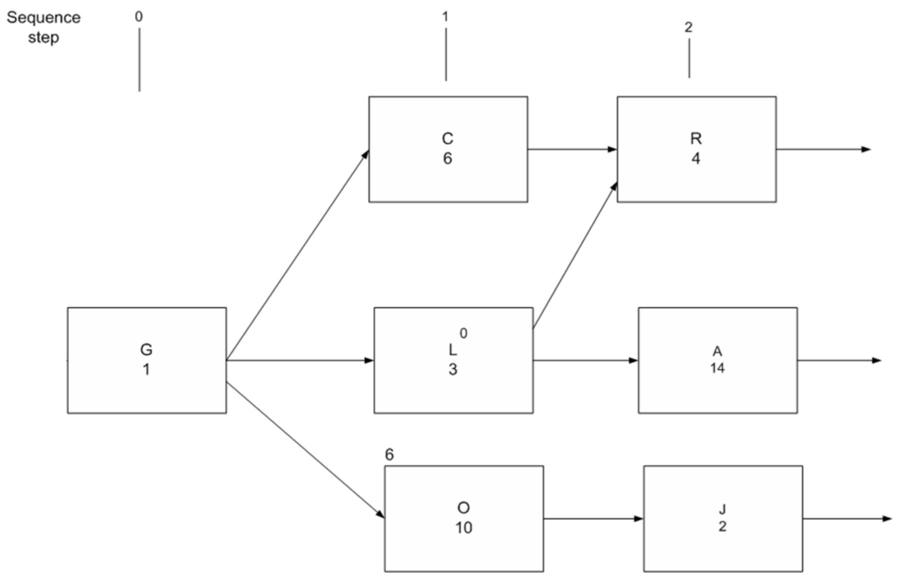
• Activities are always arranged from left to right without backward (right to left) connecting arrows



Creating precedence diagrams

- To ensure an orderly and structured presentation of the schedule logic, we can make use of sequence steps
- In sequence steps, activities in a chain are assigned to different sequence steps

- For example, all activities without predecessors are said to be on step 0
- Activities immediately following step 0 activities are on sequence step 1 and so on



Example 1

Example 2

Chapter 4: Precedence Networks

Part 2- Network Calculations

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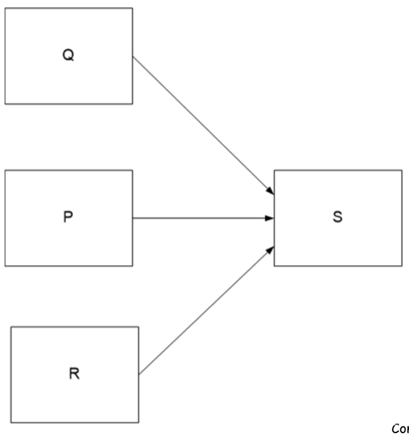
Project duration determination

- Forward and backward passes are used to:
  - Determine project duration
  - Determine early and late dates
  - Provide the information necessary to calculate floats

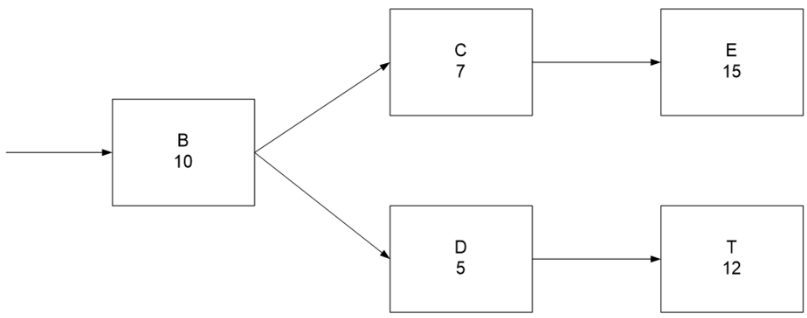
Forward pass

- To determine the project duration, a forward pass of calculations must be done
- The forward pass establishes the early start (ES) and early finish (EF) dates for each activity

- **<u>Early Start (ES)</u>**
  - The earliest time that an activity can start as determined by the latest of the early finish times of all immediately preceding activities



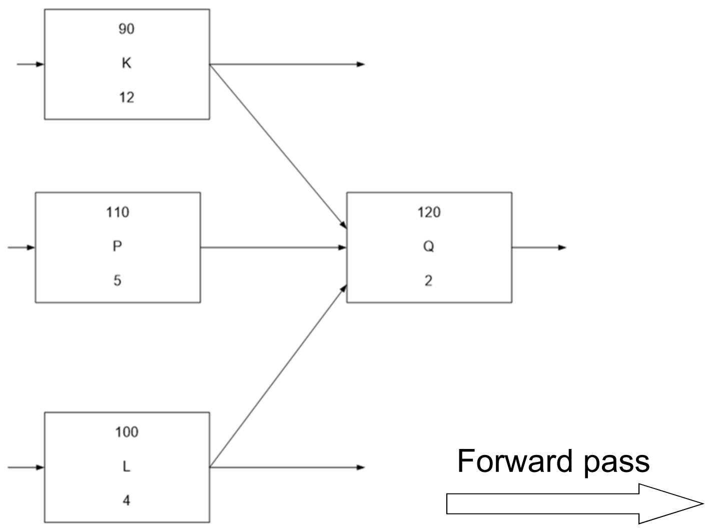
- **Early Finish (EF)**
  - The earliest time that an activity can finish
  - It is determined by adding the duration of the activity to the early start time of that activity



ES and EF calculations

$$\text{Early Start}_{\text{Follower}} = \text{Max}_{\text{all predecessor}} \left(\text{Early Finish}_{\text{Activity}}\right)$$

$$\text{Early Finish}_{\text{Activity}} = \text{Early Start}_{\text{Activity}} + \text{Duration}_{\text{Activity}}$$



- Note that ES and EF are calculated from the first activity in the network to the last activity
- The EF of the last activity in the network is the calculated project duration

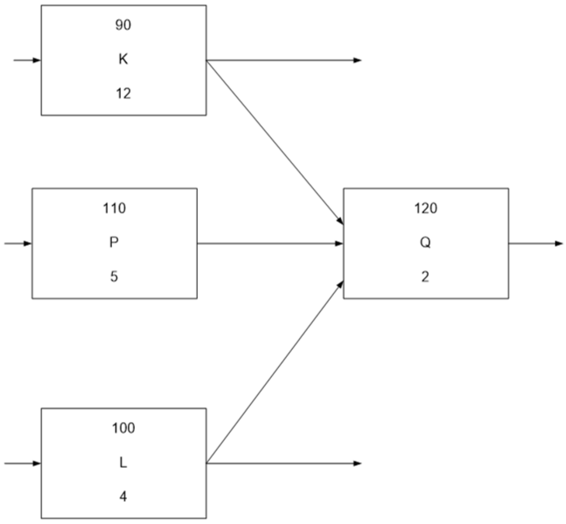
Backward pass

- The backward pass provides the late start (LS) and late finish (LF) for each activity

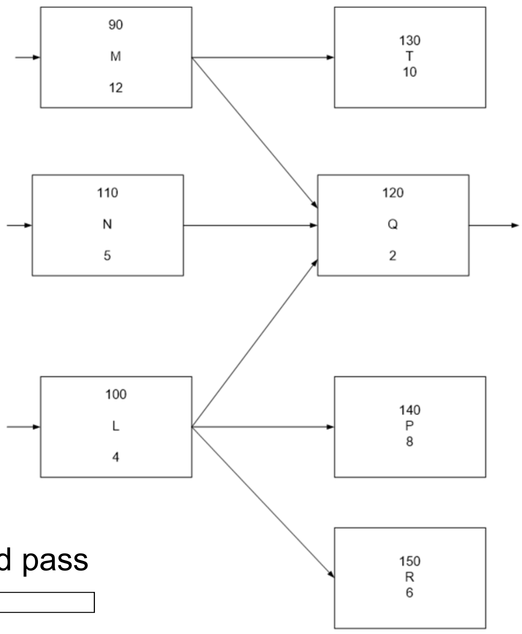
- These dates are shown below each box and are used to show the criticality of each activity and to identify any available float

- **<u>Late Start (LS)</u>**
  - The latest time that an activity can start without delaying the project completion

- **<u>Late Finish (LF)</u>**
  - The latest time that an activity can finish without delaying the project completion



Backward pass



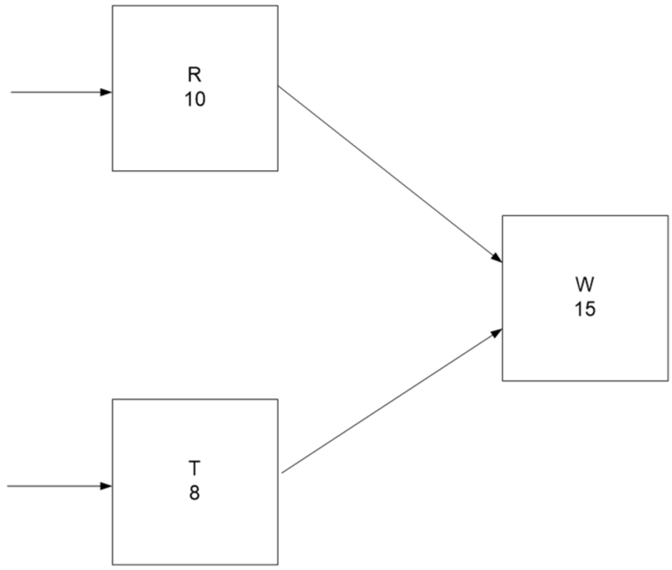
Backward pass

LS and LF calculations

$\text{Late Finish}_{\text{Activity}} = \text{Min}_{\text{all successors}} \ (\text{Late Start}_{\text{Successor}})$

$\text{Late Start}_{\text{Activity}} = \text{Late Finish}_{\text{Activity}} - \text{Duration}_{\text{Activity}}$

- Note that the backward pass begins at the last activity in the network and proceeds until the first activity in the network
- For the last activity in the network, we set
  - LF = EF
  - LS = ES
- The result of the backward pass should show that
  - LS = ES for the first activity in the network



Example 3

Example 4

Chapter 4: Precedence Networks

Part 3- Calculating Float and Locating the Critical Path

Dr. Mohammad S. El-Mashaleh

Float

- Total Float (TF)
  - The amount of time that an activity can be delayed before it delays the completion date of the project
- Free Float (FF)
  - The amount of time that an activity can be delayed before it delays the early start of any succeeding activity

Float calculations

$Total\ Float_{Activity} = Late\ Finish_{Activity} - Early\ Finish_{Activity}$

$TF_{Activity} = LF_{Activity} - EF_{Activity}$

$TF_{Activity} = LS_{Activity} - ES_{Activity}$

$Free\ Float_{Activity} = Min\ (Early\ Start_{Successor}) - Early\ Finish_{Activity}$

$FF = Min\ (ES_{Successor}) - Early\ Finish_{Activity}$

- Calculate TF and FF for the following partial network

Critical path

- The path(s) from the first activity to the last activity in the network that passes through only those activities that have a TF of ***<u>Zero</u>***

Examples 3 & 4

Chapter 4: Precedence Networks

Part 4 – Relationships Types

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Activity relationships

- The network calculations conducted so far are based on a Finish-To-Start (FS) relationship
- That is, an activity has to be completed before the succeeding activity can start

- Other types of relationships are utilized to prepare schedules that more accurately portray project execution

- There are four types of relationships:

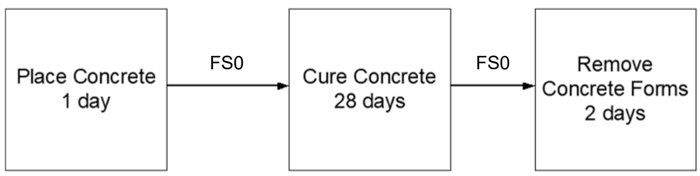
1. Finish-To-Start (FS)
2. Start-To-Start (SS)
3. Finish-To-Finish (FF)
4. Start-To-Finish (SF)

Lag

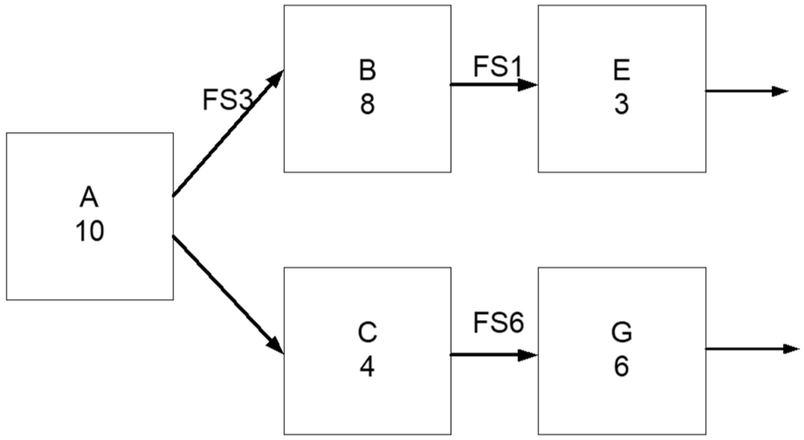
- Lag is the amount of time that exists between the EF of an activity and the ES of a specified succeeding activity (in the case of FS)

(1) Finish-To-Start (FS)

- All relationships types that we discussed in the past are FS with lag equals to Zero (FS0)
- FS with a lag value other than Zero are often used to account for resource constraints such as: concrete curing, crane movement, or equipment utilization



•Note that “Cure Concrete” consumes time only and uses no resources
•Basically, used to enforce a delay on the succeeding activity
•We can make use of FS28



$$ES_{Follower} = EF_{Act} + Lag$$

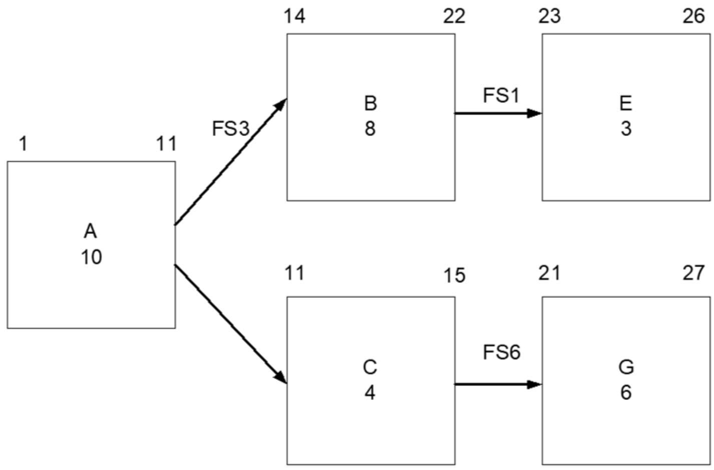
$$ES_{Follower} = Max_{all\ predecessors} (EF_{Act} + Lag)$$

$$TF = LF_{Act} - EF_{Act}$$

$$FF_{Act} = Min \{ ES_{Follower} - Lag – EF_{Act} \}$$

FF calculations

$FF_{Act} = \text{Min} \{ ES_{Follower} - Lag - EF_{Act} \}$



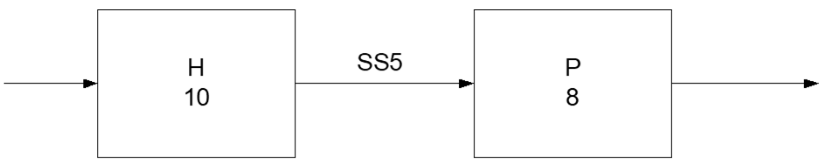
(2) Start-To-Start (SS)

- The SS relationship is used for activities whose starts are related
- SS relationships are used to relate activities that are done in parallel

- Example
- For a multi-story building, activities of "Build partition" and "Plastering" can be done in parallel with a SS relationship (SS4)

- 4 days after the start of building the partition, plastering can be started

$ES_{Follower} = ES_{Act} + Lag$



$TF = LF_{Act} - EF_{Act}$

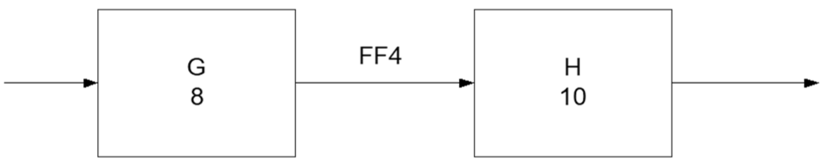
$FF_{Act} = Min \{ ES_{Follower} - Lag – ES_{Act} \}$

So, FF for H = ?

(3) Finish-To-Finish (FF)

- The FF relationship means that the finish of an activity controls the finish of another following activity
- FF relationships are similar to SS relationships in that they are frequently used with activities that are performed in parallel

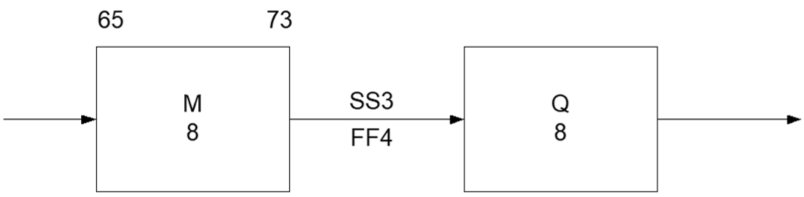
$EF_{Follower} = EF_{Act} + Lag$



$TF = LF_{Act} - EF_{Act}$

$FF_{Act} = Min \{ EF_{Follower} - Lag – EF_{Act} \}$

So, FF for G=?

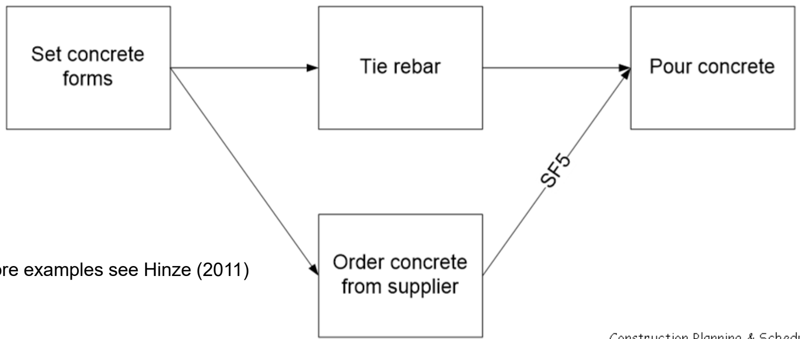


Therefore, which relationship controls?

FF4 controls

(4) Start-To-Finish

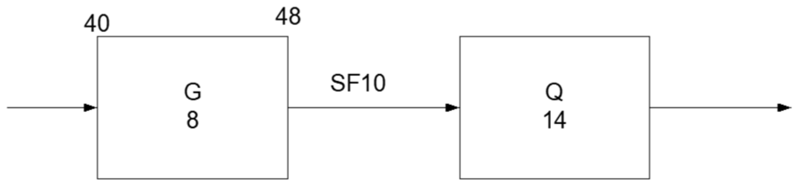
- Used to identify activities whose starts are related to the follower's finish



For more examples see Hinze (2011)

- In this example, order of ready-mix concrete has to be placed 5 days prior to pouring the concrete
- To finish “Pouring concrete,” “Order concrete from supplier” has to start before 5 days

$EF_{Follower} = ES_{Act} + Lag$



$TF = LF_{Act} - EF_{Act}$

$FF_{Act} = \text{Min} \{ EF_{Follower} - Lag – ES_{Act} \}$

Therefore, FF of G=?

Example

Examples 5 – 8

Chapter 16: Program Evaluation and Review Technique (PERT)

Part (1)

Dr. Mohammad S. El-Mashaleh

PERT

- PERT is a method for determining the length of a construction project and the probability of project completion by a specified date
- PERT is based on probabilistic activity durations

- Recall that AON diagrams are based on deterministic activity durations

- When we assume that the duration of activity “rebar columns” is 10 days, what does that really mean?

  – will “rebar columns” take exactly 10 days to complete?
  – or will the actual duration vary from the estimated duration?

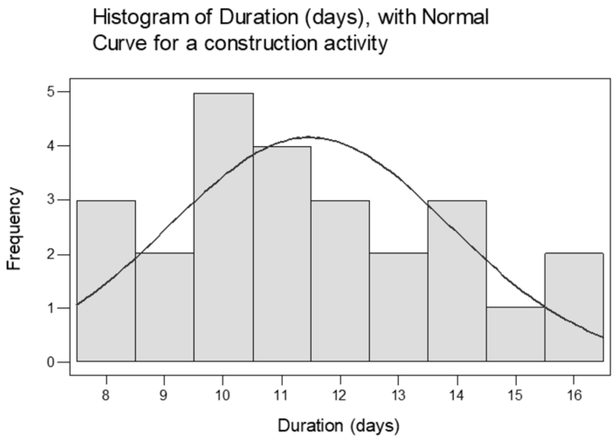
- It could mean that, on average, the duration is 10 days

- To accommodate the uncertainty associated with activity duration estimates, PERT is based on probabilistic activity durations

- Since construction companies engage in work that they have done in the past, this results in multiple occurrences of the same activity and a historical record of durations or productivities

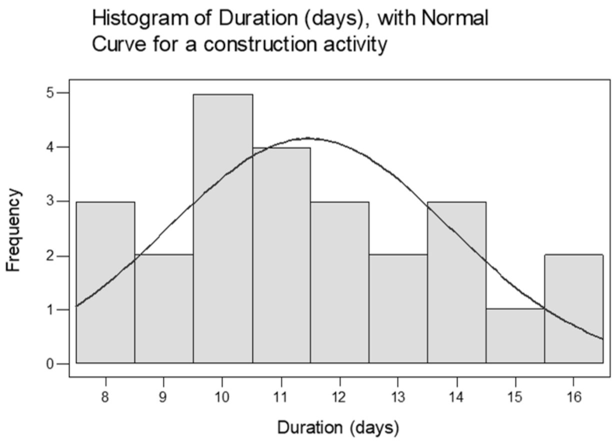
- PERT relies on activity durations that are established either by an analysis of historical data or through estimates of the range of probable activity durations

- Such data can be shown as a frequency histogram like the one shown below

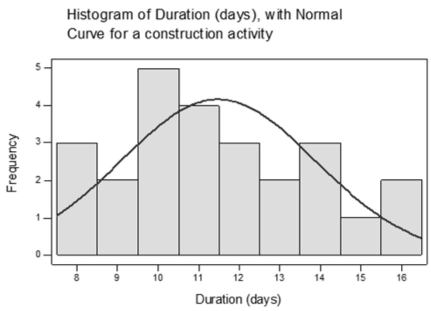


Source: Weber (2005, p.226)

- No matter of the actual distribution, there are three measures of central tendency: mean, mode, and median



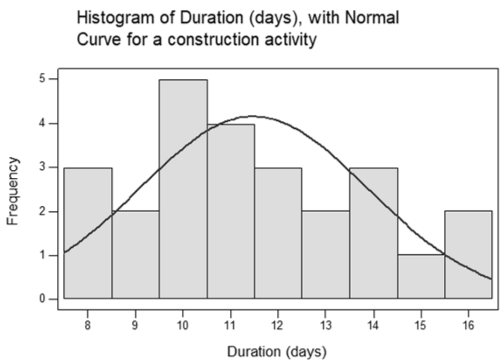
Source: Weber (2005, p.226)



- Mean = 11.48
- Mode = 10 (most frequent occurrence)
- Median = 11 (equal number of observations above it and equal number of observations below it)
- Note also that the range of observations = 16 – 8 = 8

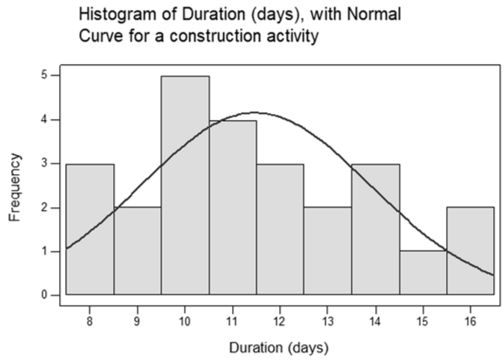
- If all activities have been performed multiple times in the past enough times to generate a frequency histogram, a sample can be taken from each distribution that will give a duration for each activity

- Activity durations in PERT are based on three time estimates:
  - Optimistic duration
  - Most likely duration
  - Pessimistic duration



- Optimistic duration: assumes maximum productivity
  - How many days in this example?

- Pessimistic duration: assumes the worst productivity
  - How many days in this example?



- Most likely: occurring most frequently based on historical performance
  - How many days in this example?

Calculating the mean estimate of duration

- The mean estimate of the activity duration is computed as follows

$$t_e = \frac{t_o + 4t_m + t_p}{6}$$

$$t_e = \frac{t_o + 4t_m + t_p}{6}$$

t_e = mean or expected activity duration

t_o :optimistic activity duration

t_m : most likely activity duration

t_p : pessimistic activity duration

Network calculations

- In PERT, project duration is called "project mean duration" ($\mathbf{T_e}$)
- $\mathbf{T_e}$ is calculated based on the regular forward pass using the activity mean durations $\mathbf{t_e}$ for every activity

Slack

- In PERT, what we used to know as "float" is called "slack"

- Activity Total Slack = ATS
- Activity Free Slack = AFS

Examples 1 & 2

Chapter 16: Program Evaluation and Review Technique (PERT)

Part (2)

Dr. Mohammad S. El-Mashaleh

Activity mean duration (t_e)

- As we already know, t_e is calculated based on 3 estimates: t_o, t_m, and t_p
- However note that t_e does not convey any information about the degree of uncertainty
- It would be helpful to have a measure to describe the extent to which the duration is expected to vary from the derived mean value

- Such a measure is known as the **Standard deviation (S)**
- We can use **S** to describe the extent to which the duration is expected to vary from the derived mean

$$\text{Standard deviation (S)} = \frac{\text{Range of activity durations}}{6}$$

$$S = \frac{t_p - t_o}{6}$$

The Variance

$$Variance(V) = S^2 = \left(\frac{t_p - t_o}{6}\right)^2$$

$$S = \sqrt{V}$$

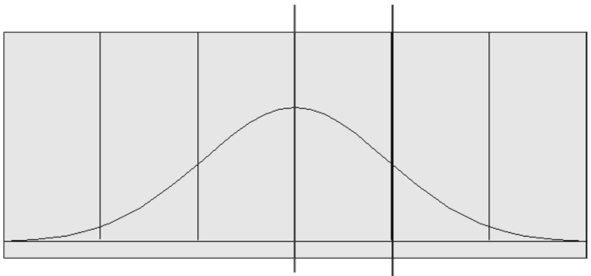
- Note that $S_{Project} = S_{CP} = \sqrt{\sum V_{CP}}$

Back to example 1

Calculating the probability of completing the project on certain dates

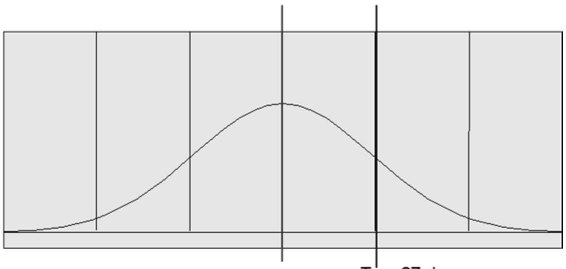
- Based on the normal distribution, we can calculate the probability of project completion within certain duration
- The probabilities of occurrence of a specific duration can be determined by simply knowing the number of standard deviations that the value in question is away from the mean

- The “standard normal curve areas” table is set up to give information of the probability that a particular duration will be less than some specified value that is given in terms of the number of standard deviations that the value extends beyond the mean



This is the normal distribution

The probability to complete the project in 24 days (mean duration) or less = 50%, which is the area under the curve



Now to find the probability of completing the project in 27 days, we need to find out the number of standard deviations that T_s (specified date) is away from T_e

$$Z = \frac{T_s - T_e}{S_{CP}}$$

Examples 3-6

TABLE 1

Standard normal curve areas

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5398	0.5398	0.5398	0.5398	0.5398	0.5398	0.5398	0.5398	0.5398
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.1	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.2	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.3	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.4	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

z	Area
3.50	0.99976737
4.00	0.99996833
4.50	0.99999660
5.00	0.99999971

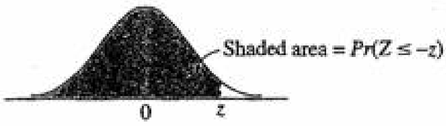


TABLE 1
Standard normal curve areas

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
−3.4	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002
−3.3	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003
−3.2	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005
−3.1	0.0010	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007
−3.0	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0011	0.0011	0.0010	0.0010
−2.9	0.0019	0.0018	0.0018	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014
−2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019
−2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
−2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
−2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
−2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
−2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
−2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
−2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
−2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
−1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
−1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
−1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
−1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
−1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
−1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
−1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
−1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
−1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
−1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
−0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
−0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
−0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
−0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
−0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
−0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
−0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
−0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
−0.1	0.4602	0.4602	0.4602	0.4602	0.4602	0.4602	0.4602	0.4602	0.4602	0.4602
−0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641

z	Area
−3.50	0.00023263
−4.00	0.00003167
−4.50	0.00000340
−5.00	0.00000029

Source: Computed by M. Longnecker using Splus.

Chapter 5: Time-Cost Tradeoff

Part (1)

Dr. Mohammad S. El-Mashaleh

Time-cost tradeoff

- What is meant by time-cost trade-off?
- Trading "one thing" for "another"?
- Trading "time" for "cost"?

- There are certain situations where we are asked to "**shorten**", "**expedite**", or "**accelerate**" a project

- Usually, we refer to that as "**crashing**" a project

- Why would an owner (or a contractor) be interested in crashing a project?

- To owners, acceleration may be advantageous in the following circumstances:

(1) Achieving earlier completion for commercial reasons

(2) Making substantial savings because of potential escalation in costs

(3) Actual loss for late completion is greater than acceleration costs

- What options are available to us to crash or shorten a project?
  - Extended work days
  - Multiple shifts
  - Utilize more/larger resources

- To crash/shorten a project, which activities do we target? Why?

Activity cost theory

- Each activity has a cost and duration and these attributes are not deterministic

- In reality, cost and duration are statistical distributions that describe the variability inherent in the construction process

- If the same task is performed on several projects, the productivity and duration of the same quantity of work would vary from project to project

- Even though there is variability that can be statistically viewed, constructors usually use deterministic durations based on average productivities and expected quantities

- Figure 5.4 shows a typical **direct cost-duration** chart

- What we see here is a hyperbolic curve that relates an activity's duration to its cost

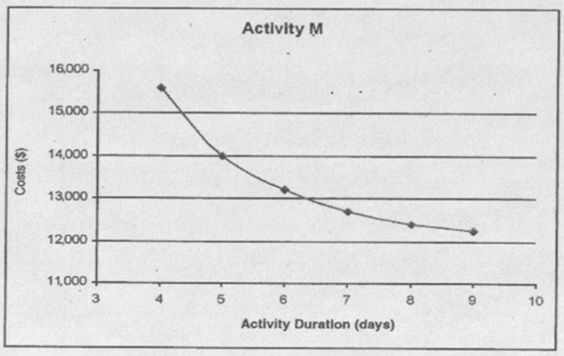


Figure 5.4
Activity cost-duration curve.

Source: Weber (2005, p.69)

- Note that for every duration, there is a cost associated with it
- For example, for a duration of 9 days, the cost is a little higher than $12,000

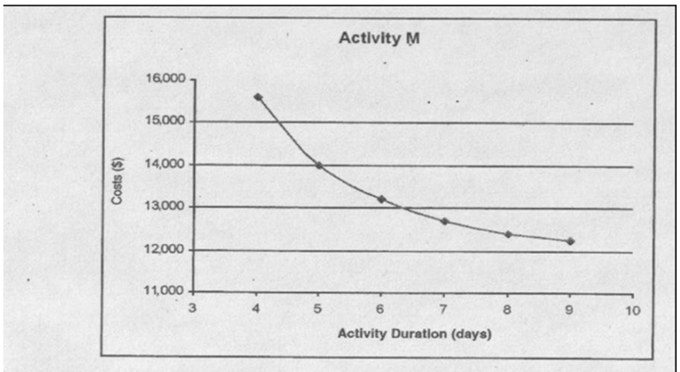


Figure 5.4
Activity cost-duration curve.

Source: Weber (2005, p.69)

- Time/cost graphs for activities take into account the variability resulting from factors related to the physical characteristics of the project, human factors, environmental variables, and resource efficiencies

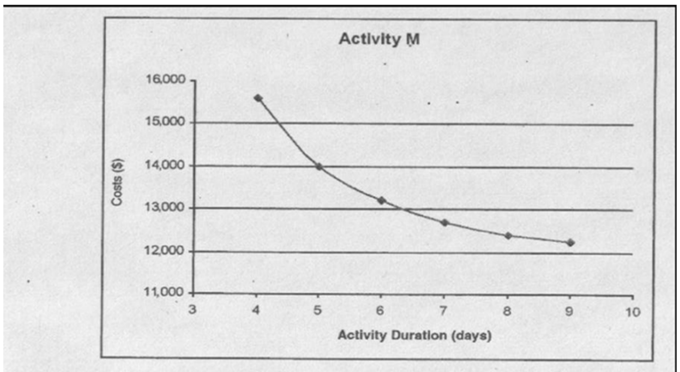


Figure 5.4
Activity cost-duration curve.

- For example, the highest cost-shortest duration end of the curve for the activity results when increases in crew size have no effect on duration

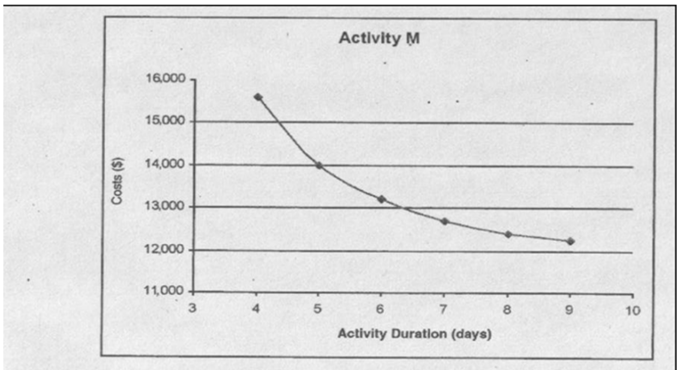


Figure 5.4
Activity cost-duration curve.

Source: Weber (2005, p.69)

- Minimum and maximum durations can be obtained from historical records

- To use the activity data properly, it may be necessary to convert the curve to a piecewise linear representation that mimic the smooth curve

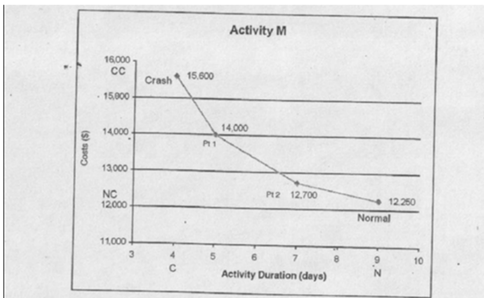


Figure 5.5
Piecewise linear resource representation.

Source: Weber (2005, p.70)

- Note that each resulting line segment has a slope equivalent to cost per unit time

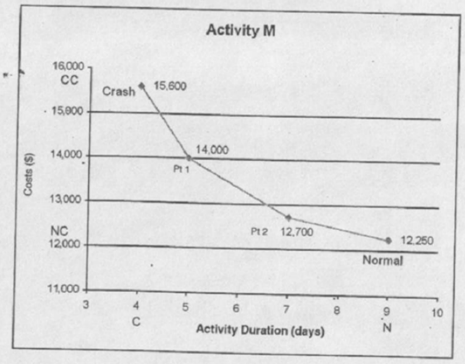


Figure 5.5
Piecewise linear resource representation.

Source: Weber (2005, p.70)

- These slopes, or change in cost per unit change in time ($\Delta C/\Delta T$), provide a convenient method of making least-cost comparisons when activities must be shortened or crashed

$$Slope = \frac{\Delta C}{\Delta T}$$

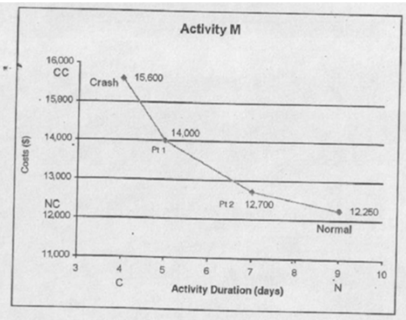


Figure 5.5
Piecewise linear resource representation.

Source: Weber (2005, p.70)

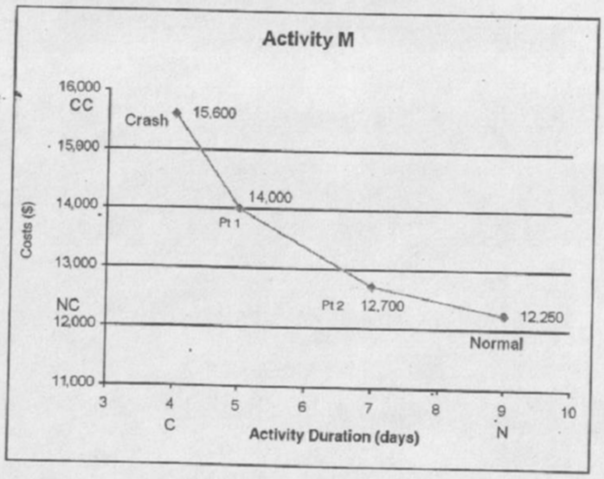


Figure 5.5
Piecewise linear resource representation.

- Most companies attempt to assign activity durations at their minimum or normal cost (NC)
- This point relates to the maximum duration on the graph, or the normal duration (ND)

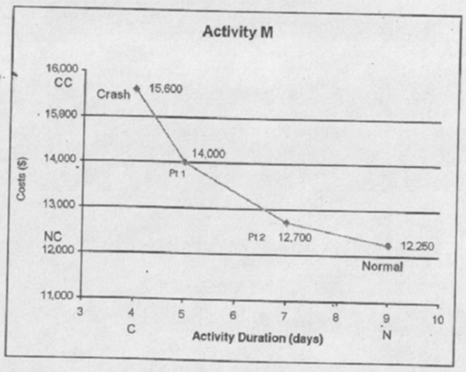


Figure 5.5
Piecewise linear resource representation.

- Points at line-segment junctions, not at the normal or crash points, are intermediate points and labeled as such (e.g., Pt1, Pt2)

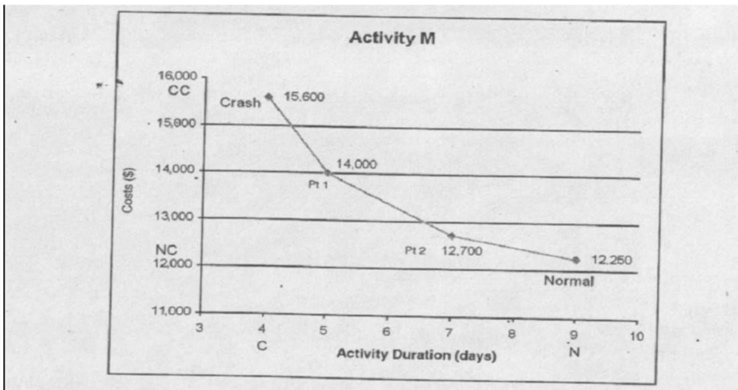


Figure 5.5
Piecewise linear resource representation.

- Based on the cost-duration curve, we can develop a cost/slope matrix

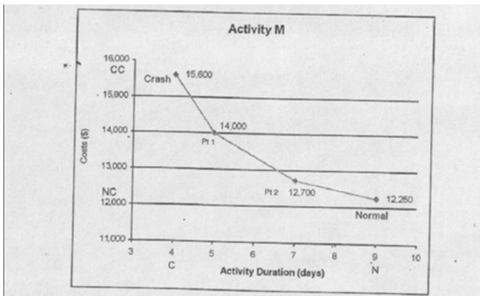


Figure 5.5
Piecewise linear resource representation.

To / From	C 4	Pt1 5	Pt2 7	N 9
C 4				
Pt1 5				
Pt2 7				
N 9				

- The matrix is constructed using the slope ΔC/ΔT of each segment such that the cells contain a daily rate of change in cost when moving from point to point on the graph

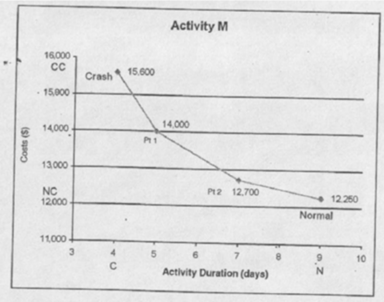


Figure 5.5
Piecewise linear resource representation.

To / From	C 4	Pt1 5	Pt2 7	N 9
C 4				
Pt1 5				
Pt2 7				
N 9				

Example 1

Example 3 Solution

Iteration	Crashing possibilities / Cost	Project duration	Incremental cost	Cumulative cost
1	C / $3,750 **X** F / $4,250 **X** (b/c "SS") H / $2,700 **√**	23 to 22	2,700	2,700
2	**CP1:** C / $3,750 **X** F / $4,250 **X** (b/c "SS") **CP2:** B /$4,500 **X** D /$4,250 **√** **Joint CP1 & CP2:** H/$2,700 **√**	22 to 21	4,250 2,700	9,650
3	**CP1:** C / $3,750 **X** F / $4,250 **X** (b/c "SS") **CP2:** B /$4,500 **X** D /$4,250 **√** **Joint CP1 & CP2:** H/$2,700 **√**	21 to 20	4,250 2,700	16,600

Chapter 5: Time-Cost Tradeoff

Part (2)

Dr. Mohammad S. El-Mashaleh

Day-at-a-time crashing

- When we crash a network, we conduct that one-day-at-a-time by using the following steps:

1. Calculate the network and identify the critical path and all floats

2. Identify the paths that may become critical – those with TF < # of days to be crashed

3. Determine which of the activities identified can be crashed based on normal and crash cost

4. Determine which activity on the critical path should be crashed based on least cost to reduce the duration. Ties can be broken if more than one activity has the least cost by selecting the activity with the most available days for reduction

5. Check the relationships to ensure that crashing an activity's duration will have the desired effect on the project duration

6. Reduce the project duration one day at a time, noting all changes in duration and float

7. Continue to crash the critical path until the desired duration is reached by starting again at step 4. When there is more than one path, activities on all critical paths must be crashed until the desired duration is reached

8. When the desired project duration is achieved, stop

Examples 2 & 3

Chapter 6: Resource Leveling and Resource Constraining (Allocation)

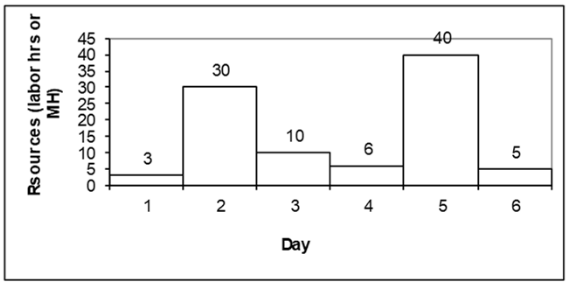
Part (1) – Introduction

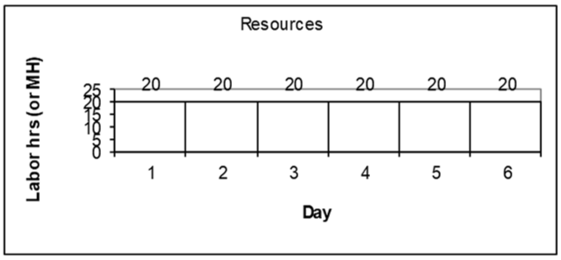
Dr. Mohammad S. El-Mashaleh

Introduction

- Leveling and constraining (allocation) are used to investigate resource distributions in light of resource limits
- The purpose is to achieve a uniform resource distribution

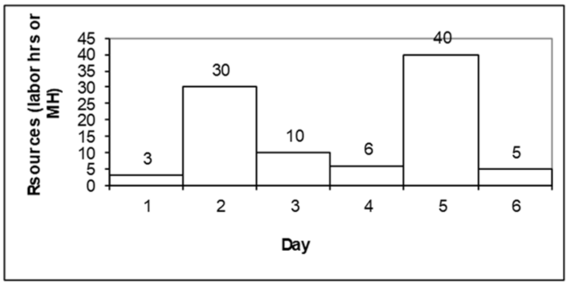
- For example, lets consider the following 2 resource profiles of resource hours



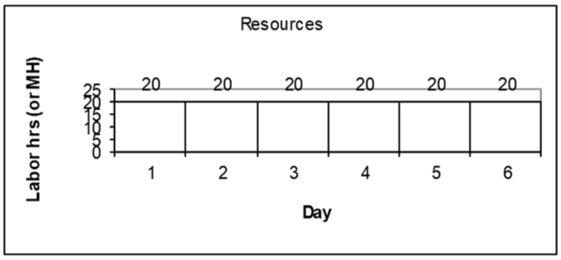


Which one is better than the other one?

Peaks and valleys?



Rectangular?

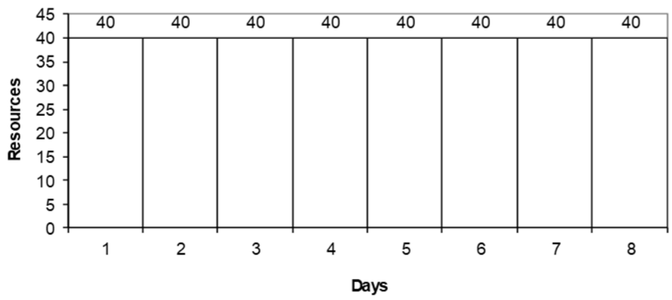


- If the average resource use (resource/day) could be applied on each day, how do you expect the resource histogram to look like?

- Rectangle of resources

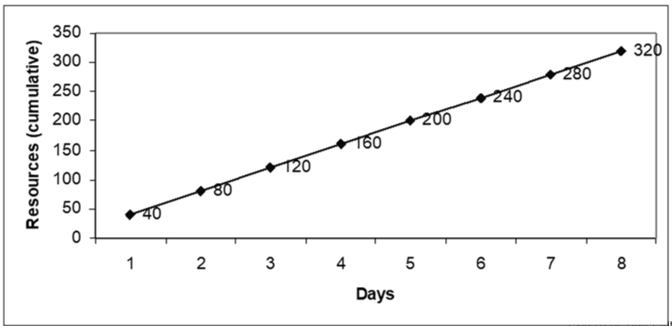
- Meaning, that we will have a uniform distribution of resources

- This uniform distribution will have the same value on day 1 as on the last day of the project



- Would the resulting cumulative curve maintain its “S” shape?

- No, it will actually look like a line that increases linearly as the project progresses



When do we “**level**” and when do we “**constrain**”?

- Resource leveling and resource constraining are based on making use of available float to move activities in order to smooth the resource profile

- So what is the difference between the two?

- **Resource leveling**
- The assumption of "**unlimited**" resources
- Project duration **can not be extended**

- **Resource constraining (allocation)**
- The assumption of "**limited**" resources
- Project duration **is extended**

Chapter 6: Resource Leveling and Resource Constraining (Allocation)

Part (2) – Resource Leveling Using the Minimum Moment Algorithm Approach

Dr. Mohammad S. El-Mashaleh

Resource leveling

- Leveling suggests that resources can be better allocated than the peaks and valleys, while staying within the limits of each activity's total float
- Therefore, no extension of project duration is expected with leveling

- To accommodate resource leveling, activities make use of their FF
- As a result, activities move to dates that range between their ES and LS

Resource leveling methods

- There are several methods
- We will discuss the Minimum Moment Algorithm approach

Minimum moment algorithm

- Resource requirements on a project are smoothed or leveled by making use of the available free float
- The activities are first arranged by an early start schedule

- With resource leveling, one can systematically evaluate the impact of using any float associated with each activity
- The minimum moment algorithm approach assumes that once an activity has been started, it can not be interrupted
- Another assumption is that resource consumption is constant over the duration of an activity

- The approach will focus on the merits of shifting any non-critical activities by reducing their float
- The leveling decision is based on calculating an **Improvement Factor (IF)**

$$\text{IF (Activity, \# of FF days consumed)}$$

$$= R \times \left(R_V - R_O - R \times N_r\right)$$

$$\text{IF (Activity, \# of FF days consumed)}$$

$$= R \times \left(R_V - R_O - R \times N_r\right)$$

R: *# of resources used by the activity per day*

R_V: *# of resource days currently assigned to those days that will be vacated when the activity start date is changed*

R_O: *# of resource days currently assigned to those days that will be occupied when the activity start date is changed*

N_r: *the smaller value of the # of days of FF consumed and the duration of the activity*

- Like we just said, the leveling decision is based on calculating **IF**

- In case: **IF ≥ 0,**
- Then, moving the start date of the activity will result in a better resource histogram

Rules to go by after calculating **IF**

(1) When **IF** is calculated for several activities, the governing activity is the one with the largest **IF** value

(2) If two activities are tied with the same **IF**, priority is given to the activity with the most resources per day

3) If a tie still exists, the activity that will use up the largest number of free float days is selected

4) If still tied, the activity with the latest start date is selected

Examples 1 & 2

Chapter 7

Constraints

Dr. Mohammad S. El-Mashaleh

Objectives

- Understand the concept behind the use of constraints
- Know and distinguish between 3 main types of constraints
- Realize the computational problems associated with the use of constraints

Reasons behind the use of constraints

- Generally, the purpose of a constraint is to limit when an activity can start or finish

- The use of constraints helps the planner to include:
  - Owner-imposed schedule dates
  - Limits imposed by material suppliers
  - Subcontractor availability
  - Other ………..

Types of constraints

- Three types:
  - Conditional constraints
  - Mandatory constraints
  - Zero float constraints

- Types 1&2 can be applied to:
  - Start/finish of an activity
  - Also to the early/late times

Start Constraint

Scheduled Early Start (SES) – *Start No Earlier Than*

- When the contractor receives information that the delivery of materials, the ability of subcontractors, or other resources will not be available until a certain date, the SES constraint (start no earlier than) is often used to delay earlier calculated start times

- When the early start constraint is earlier than the calculated date, then the calculated date is used in calculating the schedule

- When the early start constraint is later than the calculated date, the constraint is used in calculating the schedule

- In short, we can conclude that:

$ES_{\text{SES Constrained Activity}} = \text{Max}_{\text{(calculated ES or SES)}}$

Impact on float

- Note that even though activities G and K are sequential, their TF are different
- Also FF of G ≠ 0
- Why?

- Bear in mind that the rules about float no longer apply when constraints are used

Finish Constraints

Scheduled Late Finish (SLF) – *Finish No Later Than*

Therefore:

$$LF_{\text{SLF Constrained Activity}} = \text{Min}_{\text{(calculated LF or SLF)}}$$

What happened to float?

Mandatory Constraints

Must Start On (MSO)

or

Schedule Must Start (SMS)

- When an activity must start or finish on a specific date, the mandatory constraint is used
- Mandatory constraints operate differently than early start/finish or late start/finish constraints

- No matter what the calculated date is, the mandatory constraint is recognized and used in both the forward and backward pass calculations

•ES_K = --------   , though calculated ES_K = ---------

•Since an SMS constraint, we set both ES and LS of K = -----------------

•We also set EF and LF of K = ------ (-------- + ------)

•Reason: No matter what the calculated date is, the mandatory constraint is recognized and used in both the forward and backward pass calculations

•TF_K = ---------- < FF_K = ------------

•Any issue with this?

•Regular rule: $TF \geq FF$

•What about negative float?

•Where is the sense in that?

- Because scheduled dates (starts, finishes, or mandatory) are the only way of creating negative float, special attention should be given to the application of constraints and to the network analysis when constraints are used

- Mandatory constraints do not allow float to pass them

Creation of zero TF and zero FF

- There are times when activities need to be linked together by a zero TF or zero FF

- Available scheduling software allow us to enforce these zero floats

Zero FF

- Consider the network in the next slide

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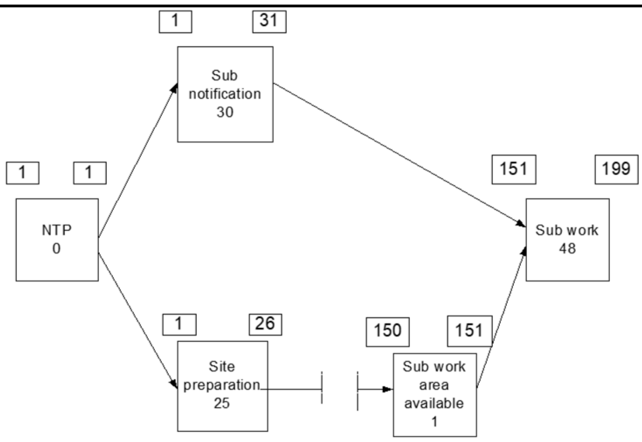

- **Note that there are more activities between "Site preparation" and "Sub work area available"**
- **A forward pass shows the numbers that we see**

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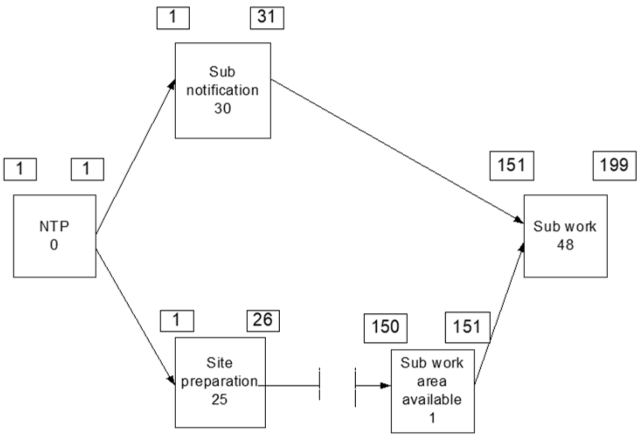
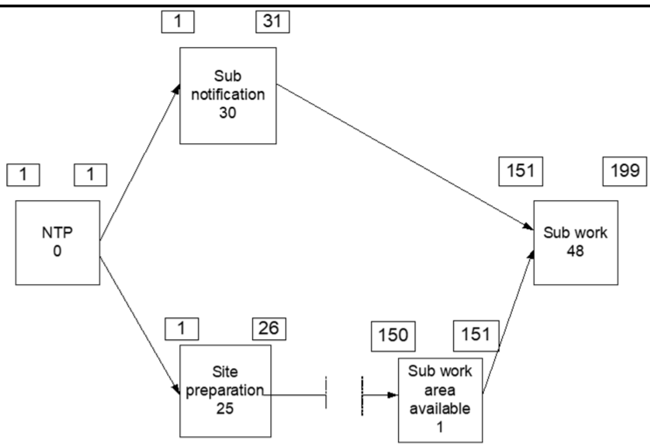
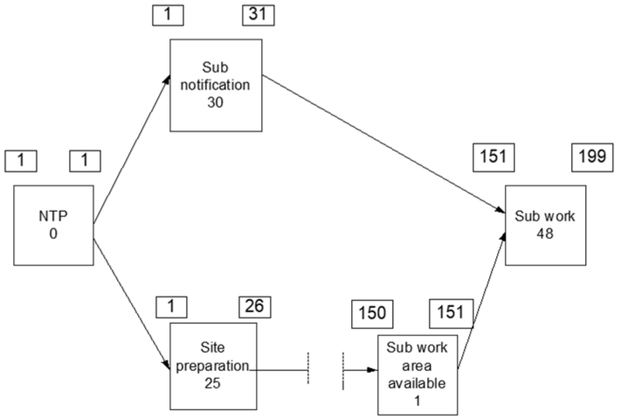


- **If we calculate the FF of "Sub notification":**
- **FF =**



- **We want to force "Sub notification" to start 30 days prior to "Sub work"**
- **How can we do that?**



- **Creating a zero FF constraint between activities “Sub notification” and “Sub work”**

Zero TF

- Making an activity to look critical when traditional calculation logic does not create this condition
- We can enforce that in scheduling software

Exercise caution with the use of constraints

- Sometimes, extraordinary network manipulations with regard to constraints can create more problems than they fix
- Exercise care when using zero float constraints and mandatory constraints because they may create unexpected float conditions on linked activities

- The effect of using constraints is that the relationships that we know between TF and FF no longer apply
- Also, the definition of the critical path can be changed when constraints are imposed on a network
- With a constraint in the network, there may be more than one critical path that does not start from the first activity and terminate at the last activity
- Instead, paths without TF or with –ve TF may begin and end anywhere within the network, based on the type and location of the applied constraints

Examples

- For the following examples, conduct forward and backward passes
- Determine project duration
- Calculate floats
- Locate the critical paths

Earned Value

Chapter 9

Dr. Mohammad S. El-Mashaleh

Project status

- In construction projects, it is usual to raise the following questions:

(1) What is the stage of completion of the project?

- Is the project 30% complete, 60% complete, etc.?

(2) Where do we stand in relation to project schedule?

- Are we **ahead** or **behind** schedule?

(3) Where do we stand in relation to project cost?

- Are we **under** or **over** budget?

Earned Value (EV)

- To address the previous questions, the **Earned Value (EV)** was developed
- First introduced by the U.S. Department of Defense (DoD) to improve the performance of their projects
- **EV** is used to monitor the progress of work and compare accomplished work with planned work

- The idea is that the contractor has "**Earned**" the work that has actually been completed
- This value becomes a measure against which other cost and schedule data can be compared in order to determine actual cost and schedule status
- Therefore, **EV** can be used to determine:
- Percent complete of the project (%comp)
- Cost performance (i.e., CV, CPI)
- Schedule performance (i.e., SV, SPI)

- **EV** compares several measures to obtain an overall picture of project status:
  - **BCWS:** Budgeted Cost of Work Scheduled (Planned)
  - **BCWP:** Budgeted Cost of Work Performed (Earned)
  - **ACWP:** Actual Cost of Work Performed (Actual)
  - **BAC:** Budgeted Cost At Completion
  - **EAC:** Estimated Cost At Completion

Planned

BCWS = Budgeted Cost of Work Scheduled

- This one is based on project plan
- The BCWS is the amount of money (or work-hours) that was planned, or budgeted, at each time period in the project

- To explain BCWS calculations, note the following **baseline bar chart**. Data date is day 6
- What information does it convey to us?

Activity info				**Workdays**													
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14
10	A	4	32	8	8	8	8										
20	B	3	6			2	2	2									
30	C	7	28			4	4	4	4	4	4	4					
40	D	2	14										7	7			
50	E	5	25										5	5	5	5	5
60	F	3	9														
Total			114											3	3	3	
Period sum				8	8	14	14	6	4	4	4	4	12	15	8	8	5
Cumulative sum				8	16	30	44	50	54	58	62	66	78	93	101	109	114

Source: Weber (2005)

- How much should it have cost us to execute the work that was“ planned” in our baseline schedule?
- Simply, the “cost” of the activities that were supposed to be completed by day 6

Activity info				Workdays													
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14
10	A	4	32	8	8	8	8										
20	B	3	6			2	2	2									
30	C	7	28			4	4	4	4	4	4	4					
40	D	2	14										7	7			
50	E	5	25										5	5	5	5	5
60	F	3	9														
Total			114											3	3	3	
Period sum				8	8	14	14	6	4	4	4	4	12	15	8	8	5
Cumulative sum				8	16	30	44	50	54	58	62	66	78	93	101	109	114

- By day 6, we planned to execute all of A, all of B, and 4/7 of C

Activity info				Workdays													
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14
10	A	4	32	8	8	8	8										
20	B	3	6			2	2	2									
30	C	7	28			4	4	4	4	4	4	4					
40	D	2	14										7	7			
50	E	5	25										5	5	5	5	5
60	F	3	9														
Total			114											3	3	3	
Period sum				8	8	14	14	6	4	4	4	4	12	15	8	8	5
Cumulative sum				8	16	30	44	50	54	58	62	66	78	93	101	109	114

Actual

ACWP = Actual Cost of Work Performed

- The ACWP is the actual amount of money (or work-hours) that has been spent at any point in time during the project

- Represent what has been paid

- The following shows **actual updated cost bar chart**
- Meaning the actual costs to date (incurred)

Activity information				**Workdays**														
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
10	A	4	35	7	9	9	10											
20	B	3	8					3	3	2								
30	C	7	34				5	5	5	5	6	4	4					
40	D	2	14											7	7			
50	E	5	25											5	5	5	5	5
60	F	3	9															
Total			125													3	3	3
Period sum				7	9	9	15	8	8	7	6	4	4	12	12	8	8	8
Cumulative sum				7	16	25	40	48	56	63	69	73	77	89	101	109	117	125

- Note that we did all of A, 2/3 of B, 3/7 of C
- However, we "incurred" different costs than we "planned" in their execution

Activity information				Workdays														
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
10	A	4	35	7	9	9	10											
20	B	3	8					3	3	2								
30	C	7	34				5	5	5	5	6	4	4					
40	D	2	14											7	7			
50	E	5	25											5	5	5	5	5
60	F	3	9															
Total			125													3	3	3
Period sum				7	9	9	15	8	8	7	6	4	4	12	12	8	8	8
Cumulative sum				7	16	25	40	48	56	63	69	73	77	89	101	109	117	125

Activity information				Workdays														
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
10	A	4	35	7	9	9	10											
20	B	3	8					3	3	2								
30	C	7	34				5	5	5	5	6	4	4					
40	D	2	14											7	7			
50	E	5	25											5	5	5	5	5
60	F	3	9															
Total			125													3	3	3
Period sum				7	9	9	15	8	8	7	6	4	4	12	12	8	8	8
Cumulative sum				7	16	25	40	48	56	63	69	73	77	89	101	109	117	125

Earned

BCWP = Budgeted Cost of Work Performed

- This is the **E**arned **V**alue
- The BCWP is the amount of money (or work-hours) **<u>“earned”</u>** based on the work that has been completed

- The question is:
- For the activities that we “actually” executed,
- how much should it have cost us to execute these activities?

Actual bar chart (Activity information / Workdays)

ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9
10	A	4	35	7	9	9	10					
20	B	3	8					3	3	2		
30	C	7	34				5	5	5	5	6	4
40	D	2	14									
50	E	5	25									

Baseline bar chart (Activity info / Workdays)

ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8
10	A	4	32	8	8	8	8				
20	B	3	6			2	2	2			
30	C	7	28			4	4	4	4	4	4
40	D	2	14								
50	E	5	25								

- A should off have cost us
- 2/3 of B, should off have cost us
- 3/7 of C, should of have cost us

BCWP

Activity information			Actual bar chart									Workdays
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8	9
10	A	4	35	7	9	9	10					
20	B	3	8					3	3	2		
30	C	7	34				5	5	5	5	6	4
40	D	2	14									
50	E	5	25									

Activity info			Baseline bar chart							Workdays	
ID	Act	Dur	Total Res	1	2	3	4	5	6	7	8
10	A	4	32	8	8	8	8				
20	B	3	6			2	2	2			
30	C	7	28			4	4	4	4	4	4
40	D	2	14								
50	E	5	25								

Measures of performance

(1) Cost performance

– Cost Variance (CV)

– Cost Performance Index (CPI)

(2) Schedule Performance

– Schedule Variance (SV)

– Schedule Performance Index (SPI)

Cost Variance (CV) and Cost Performance Index (CPI)

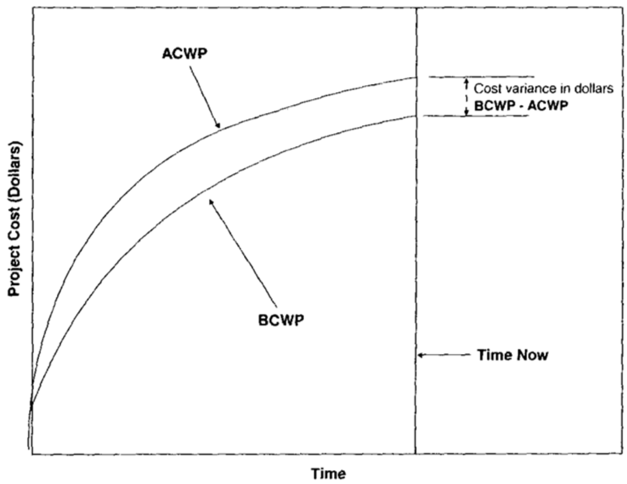
Comparison of
what was **Done** against what was **Paid**

CV = BCWP – ACWP (Earned - Actual)

$$CPI = \frac{BCWP}{ACWP} \qquad \frac{Earned}{Actual}$$

- A +ve variance and an index ≥ 1.0 indicates a favorable performance

- Is this project under/over budget?



Source: Hinze (2008)

Schedule Variance (SV) and Schedule Performance Index (SPI)

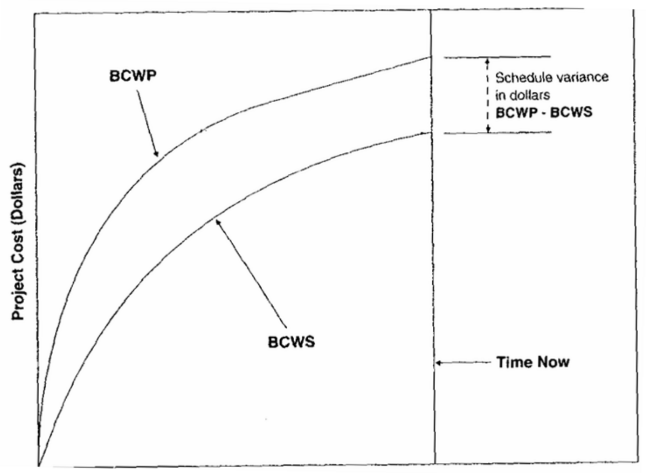
Comparison of
what was **Done** against what was **Planned**

SV = BCWP – BCWS (Earned - Planned)

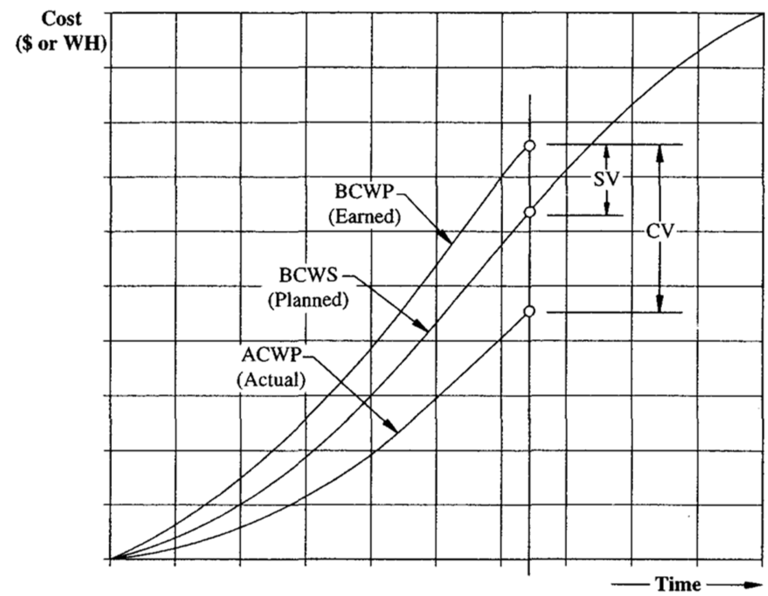
$$SPI = \frac{BCWP}{BCWS} \qquad \frac{Earned}{Planned}$$

- A +ve variance and an index ≥ 1.0 indicates a favorable performance

- Is this project ahead/behind of schedule?



Source: Hinze (2008)



Source: Oberlender (2014)

Calculating %complete

%complete = [BCWP/BAC] X 100%

Forecasting

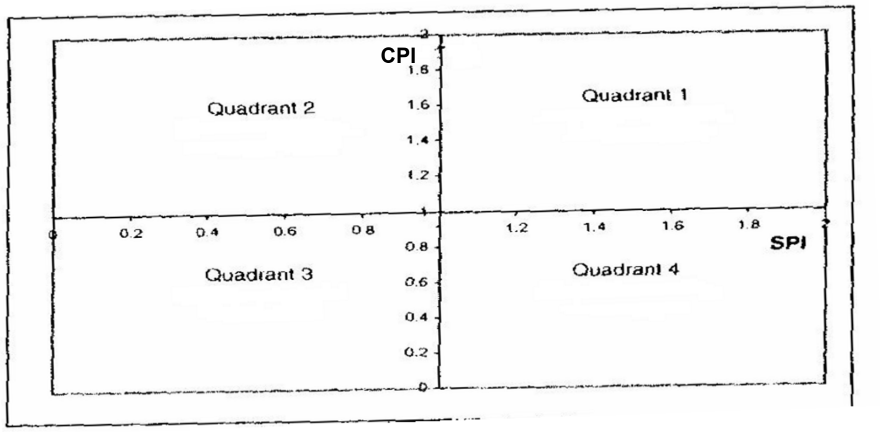
- **EV** can also be utilized for forecasting

EAC = ACWP + (BAC – BCWP)

- **BAC = Budgeted cost At Completion**
- This is the original cost estimate of the total cost of construction

- **EAC = Estimated cost At Completion**
- This is the forecast of the total actual costs required to complete a project based on performance to date and estimates of future conditions

Plotting SPI against CPI



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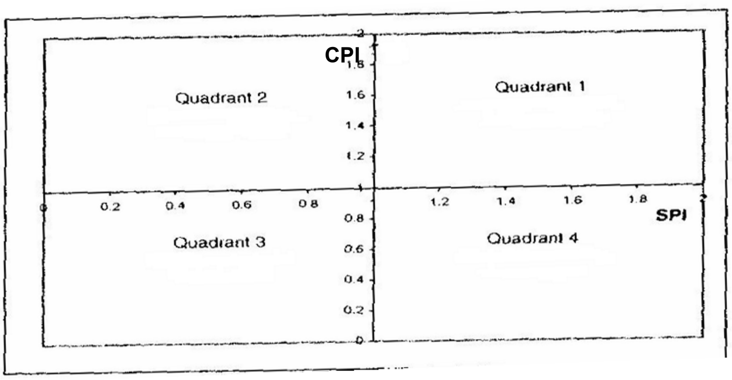
- So, what does each quadrant refer to?
- Each quadrant relates to a composite of the project's performance



Source: Weber (2005)

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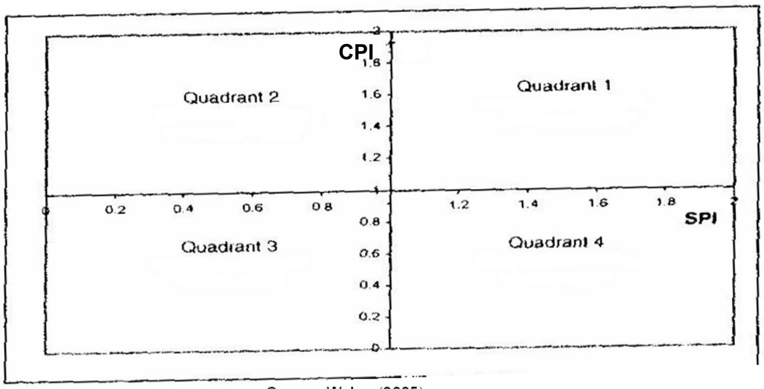
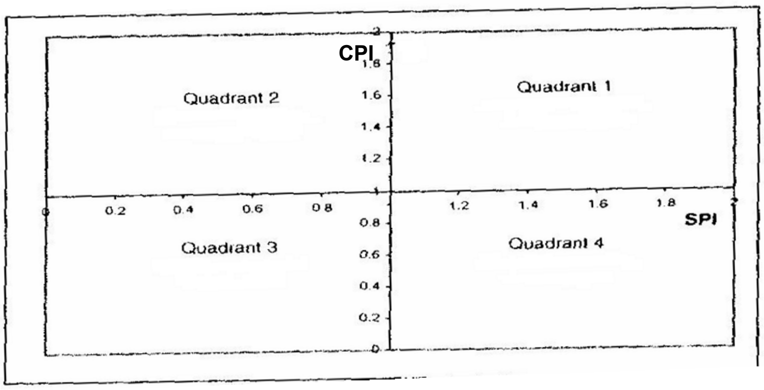
• Which quadrant is the most favorable?



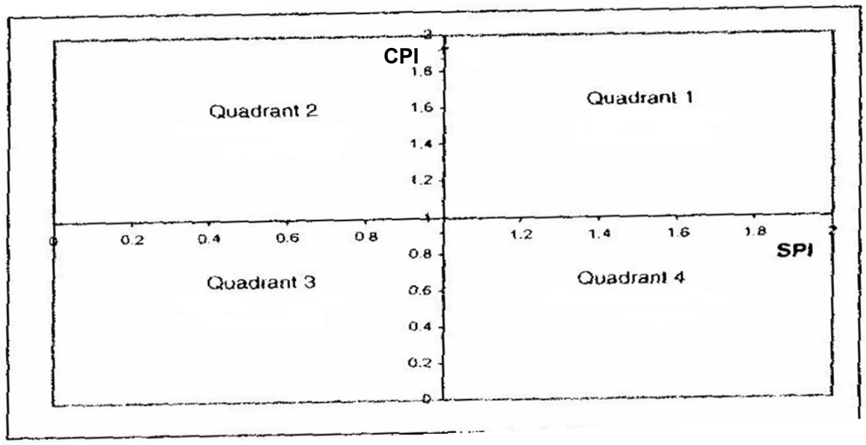
Source: Weber (2005)

• Which quadrant is the least favorable?



Source: Weber (2005)

- What about the other quadrants?



Examples

Linear Scheduling Method (LSM)

Chapter 14

Dr. Mohammad S. El-Mashaleh

Introduction

- For some construction projects, the same activities are performed several times by the same crew through out the duration of the project
- For example, highway construction involves several repeated activities by the same crew from one station to the next:
- Clearing, grubbing, grading, sub-base, base coarse, and paving

- Often, the only distinguishing feature for these linear-type activities is their rate of progress

- Some examples of projects that have activities of repetitious nature:

(1) Pipeline installation where every 100 feet is considered a repeat

(2) On high-rise structures, the repetition might be on a floor-by-floor basis

(3) A housing project of 50 homes, where every home is considered a repeat

- Precedence networks can be used to schedule repetitious activities

- However, the resulting schedules are:

(1) Either very small (if durations of activities are large) – there are only few activities in the schedule

(2) Or boringly repetitious:

- Plaster flr 1, plaster flr 2, plaster flr3, …..., plaster flr 10
- Paint flr 1, ……………, paint flr 10

- When projects have repetitive activities, linear scheduling may be the most appropriate way to communicate how the work is to be done

- Linear schedules are also known as:

- Time-space scheduling, velocity diagrams, vertical production method, repetitive-unit construction

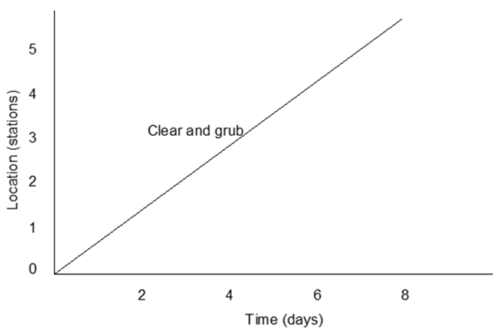
- Weber (2005) indicates that LSM is an outgrowth of the industrial engineering technique known as the line of balance (LOB) used by Goodyear Tire and Rubber Company to monitor production in 1941

The linear schedule

- The linear schedule is a graphical representation of activities in 2 axes

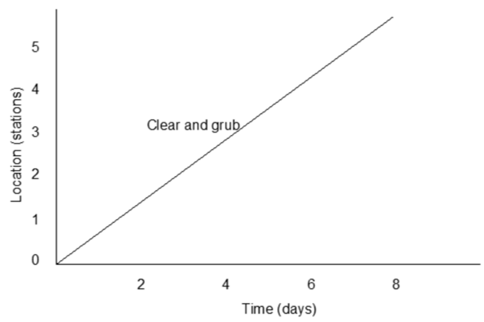
- Time on X-axis
- Location on Y-axis

- Note that some textbooks put time on the Y-axis and location on the X-axis



Time (X-axis)

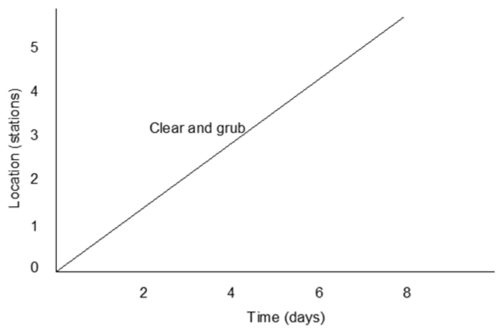
- Depending on the project's overall duration, time could be measured in days, weeks, or months



Location (Y-axis)

- In horizontal construction, the location is usually a measure of distance, such as a station, mile, etc.

- In vertical construction, the location is often a discrete measure, such as the floor or an apartment of a building



Activities

- Activities are represented as lines
- The slope of the line shows the activity's productivity

- Productivity is measured by its change in location divided by the change in time

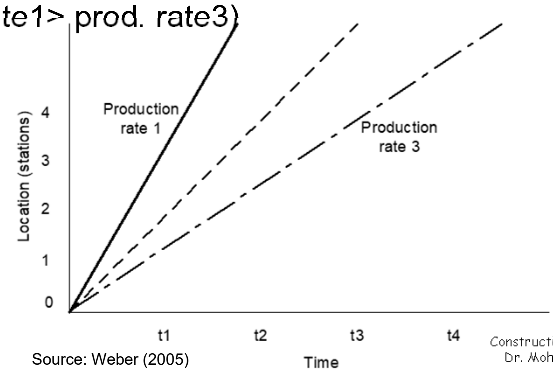
- The line of the activity shows:
- The location of the activity on any day

- Its total duration

- And its completion date

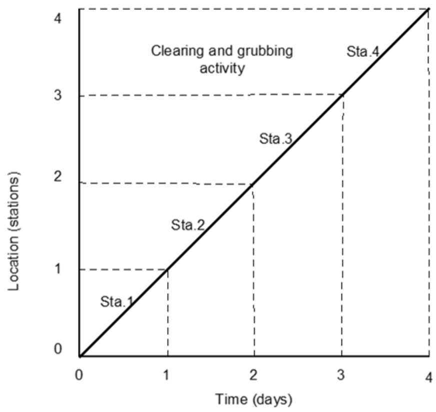
- Here its clear that clearing and grubbing has a duration of 8 days

- Different activities have different productivities, and consequently different slopes
- Since the horizontal axis is time, the slope of the activities represents the rate of production (distance/time)
- So, steeper slopes mean higher production rates (i.e., prod. rate1> prod. rate3)

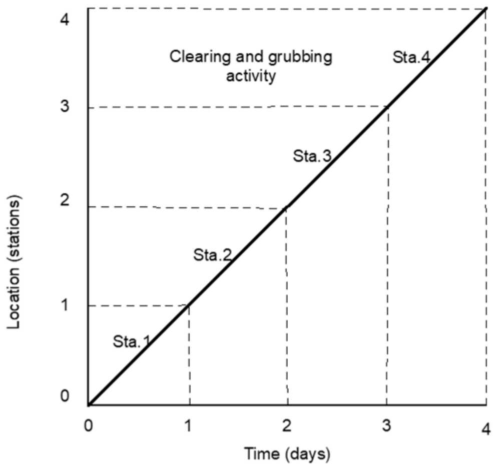


Source: Weber (2005)

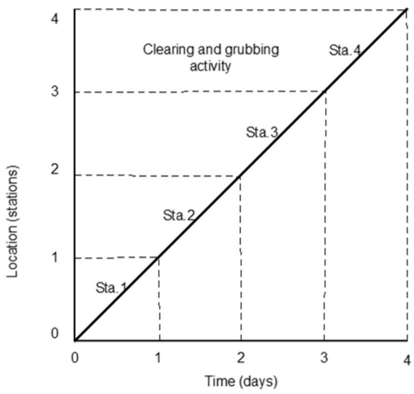
- The productivity of each activity is derived during the estimating process
- The slope of the line designating an activity in the linear schedule is a function of its productivity, generally measured in **working days**



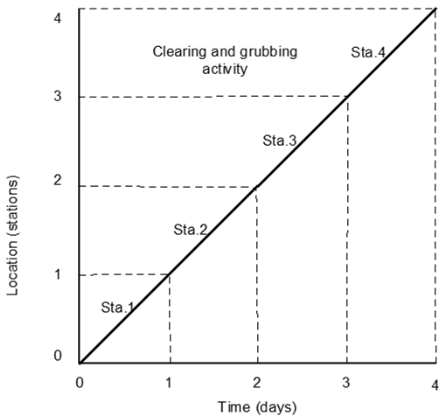
- For example, "clearing and grubbing" is progressing as follows:
- Day1: finished Sta.1
- Day 2: did Sta.2
- And so on



- What does that mean?
- It means that we are progressing at the same rate (i.e., constant rate)
- Productivity rate is the same for this activity from Sta.1-Sta.4

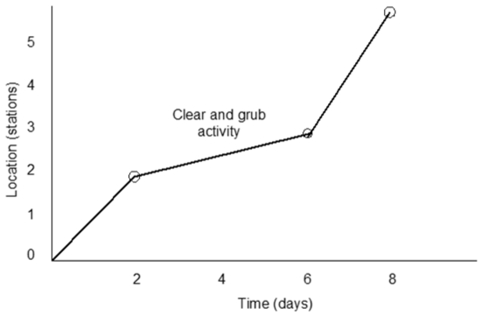


- Is that always the case? Constant rates?
- Why?
- For example, changes in productivity might be attributed to:
- Planned changes in crew composition
- Anticipated weather delays
- Work of greater scope or complexity
- Resource constraints
- Managerial decisions



- In case we have different productions rates for different stations (or different time periods), then how do we express that on the diagram?

- Consider the following clearing and grubbing activity

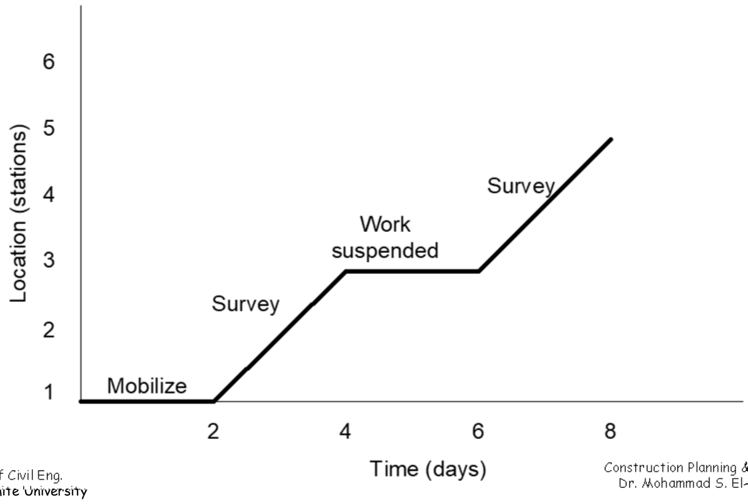


- Production is slower between stations 2&3 compared to other stations
- Clearing and grubbing is more difficult and time consuming between these 2 stations
- Or may be, we have fewer resources during the time periods of 2-6

Activities found in one location

- Some activities such as mobilization, demobilization, the construction of a bridge or a box culvert are accomplished at only one location
- These activities are depicted as horizontal lines at their location

• Examples: mobilize, work suspended

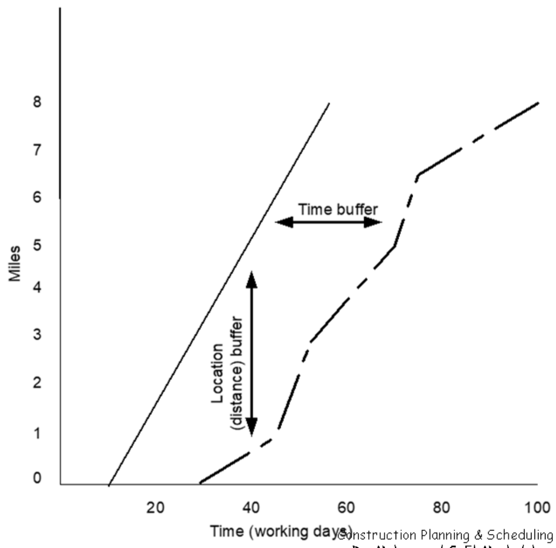


Buffers

- Linear schedules use 2 types of buffers:

(1) Time buffer

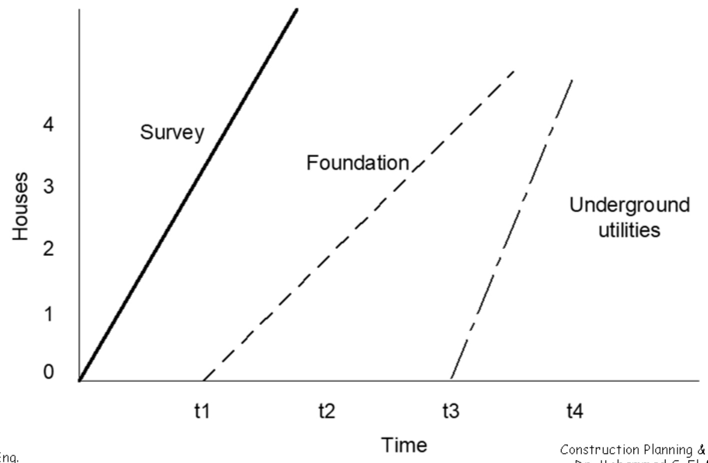
(2) Location (space) buffer



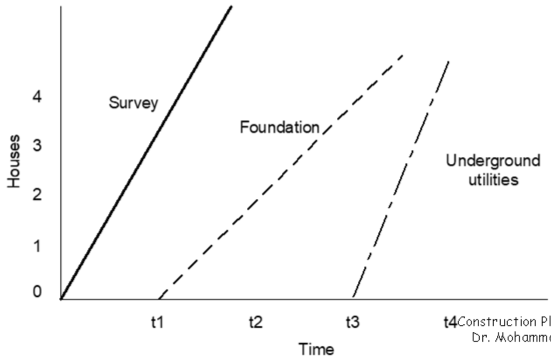
(1) Time buffers

- Formed by a horizontal offset from one activity to its follower

- Here, we notice 3 activities that progress as follows: Survey; Foundation; Underground utilities



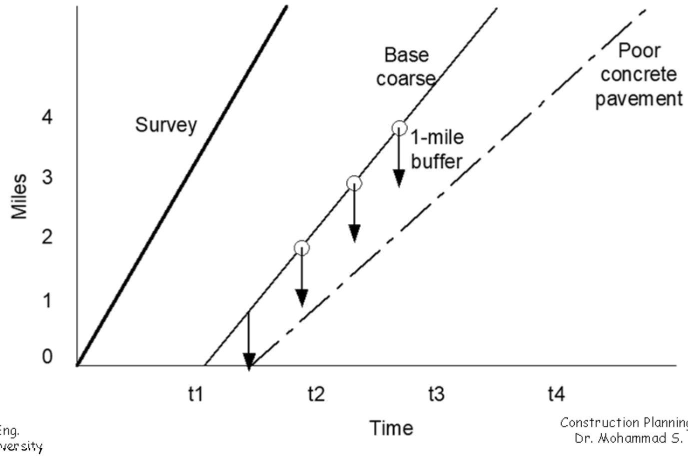
- However, note that the production rate of “Underground utilities” is higher than its predecessor “Foundation”
- To make sure that the logic is maintained, we need to impose “**<u>time buffer</u>**” between these 2 activities



Location buffers

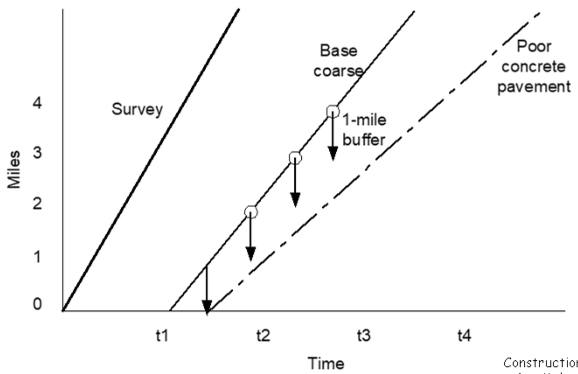
- Used to keep a distance between 2 activities

- For example, “Base coarse” must stay 1 mile in front of the paving machine



- The vertical arrows represent 1mile buffer that must be maintained

- This provides ample room for the concrete to be delivered to the paver



Development of a linear schedule

- The development of a linear schedule for a project is similar to any other scheduling process

- The first 3 steps are:
- Identify activities
- Estimate activity production rates
- Develop activity sequence

Float and critical path

- Neither TF nor FF of activities in a linear schedule can be calculated as they can when using other networking techniques

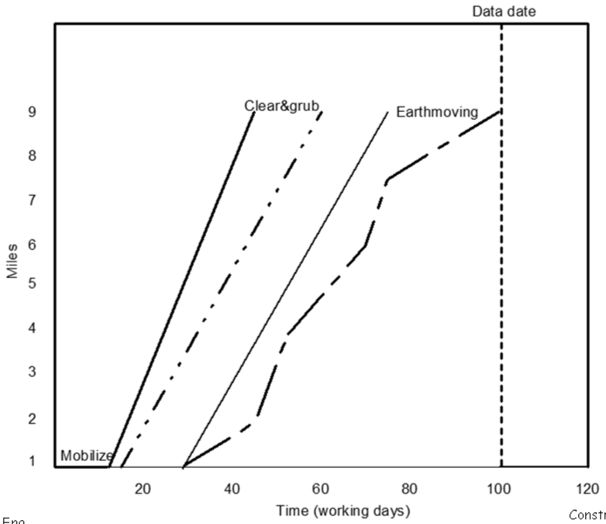
- It is also more difficult to find the critical path in LSM compared to other scheduling methods

- Weber (2005) recommends using PDM to identify the critical path
- Callahan et al. indicate that buffers are used in LSM to identify critical activities
- A critical activity in LSM schedule has a minimum buffer at both the start and completion of the activity

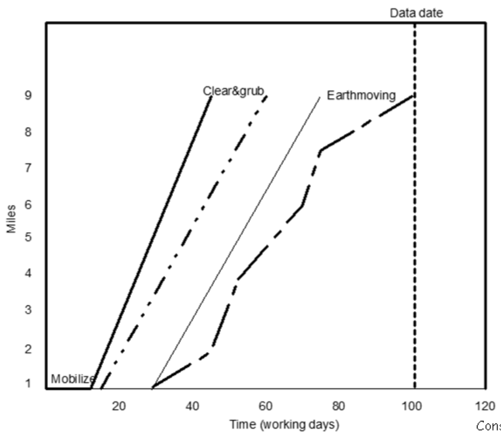
Updating

- Activities in LSM can be updated by indicating actual progress with lines of different color, texture, or dimension
- The updated schedule quickly shows differences between the productivity that was expected and what was achieved

- Updates are shown as dotted lines
- Data date is working day 100



- Clear and grub proceeded at a slower rate than was anticipated. However, the rate was constant
- On the other hand, earthmoving had different productivity rates through out its execution



Main advantages of LSM schedules

- Easily developed and understood by management and field staff
- Show rate of progress for the different activities
- Allow the use of different production rates between different time periods and different locations (i.e., stations, floors, etc.)

Examples