Course Outline

- Introduction to project management
- Project Work breakdown
- Time Planning & Scheduling Techniques
- Critical Path Method (CPM)
- Resources Management & Planning
- Cost Planning
- Cash Flow Analysis
- Time Cost Trade-Off
- Crashing a schedule
- Project Monitoring & Control
- Earned Value Management
- Computer Applications in CM
Grading System

- 1st exam 25%
- 2nd exam 25%
- Final exam 50%

Hope You Success

Text Book & References

Text Book:

References:
Communication & Contact

- You can use the Zagel system to post your comments and enquiries in the discussion forum.
- Frequently check the Zagel system to find my assignments.

Before we start

- Attend the class on time.
- Switch off your mobile.
- Stop the side talks.
- Be a smart listener.
- Use your analytical skills.
- Question every piece of information you acquire.
What is a Project?

A project is defined as a temporary endeavor (effort) undertaken to create a unique product or service. Has a definite beginning and a definite end.

Project Characteristics

- Temporary
- Unique
- definite beginning and a definite end
- Consumes resources
Examples of projects include:

- Developing a new product or service.
- Designing a new transportation vehicle.
- Constructing a building or facility.
- Running a campaign for political office.
- Implementing a new business procedure or process.

What is Project Management?

- **Project management** is the application of knowledge, skills, tools and techniques to project activities in order to meet or exceed stakeholder needs and expectations from a project.

- **Project management** is the planning, organizing, directing, and controlling of company resources for a relatively short-term objective that has been established to complete specific goals and objectives.
Management Functions

- Planning
- Organizing
- Staffing
- Directing
- Controlling

What are the stakeholder needs?

competing demands among:
- time, cost, and quality.
- Identified requirements (needs) and unidentified requirements (expectations).
In construction

Project Management is the sum of all activities such as Planning, organising, implementing and controlling a project in order to meet the client’s expectation from start to finish within the planned period, budget and quality.
Project Constraints

- Constraints triangle:
  - Time
  - Cost
  - Quality

Why a Project Fails???

- Unclear project objectives
- Unrealistic expectations
- Risk not identified
- Inadequate planning & co-ordination
- Resources are not available
- Low productivity
- Weak project & technical management
Why a Project Fails???

- Ineffective project organization
- Inadequate quality systems
- Inappropriate management control system
- Poor team co-ordination

CONSTRUCTION PROJECTS
Project life cycle ï Owner Perspective

1) Pre construction/Design
2) Procurement
3) Construction
4) Close-out

1) Pre construction

This stage includes the following phases:

1) conceptual planning
2) schematic design
3) design development
4) contract documents
2) Procurement

- Also known as award or biding phase
- The project formally transits from design into construction
- This stage begins with a public advertisement for all interested bidders or an invitation for specific bidders
- In fast-track projects, this phase overlaps with the design phase
- It is very important stage to select highly qualified contractors.
- It is not wise to select the under-bid contractors

3) Construction/Execution

- The actual physical construction of the project
- This stage takes the project from procurement through the final completion
- It is the time where the bulk of the owner's funds will be spent
- It is the outcome of all previous stages (i.e., good preparation means smooth construction)
- Changes during construction may hinder the progress of the project
4) Close-out

- Transition from design and construction to the actual use of the constructed facility
- In this stage, the management team must provide documentation, shop drawings, as-built drawings, and operation manuals to the owner organization (as-built drawings are the original contract drawings adjusted to reflect all the changes that occurred)
- Assessment of the project team’s performance is crucial in this stage for avoiding mistakes in the future.
- Actual activity costs and durations should be recorded and compared with that was planned. This will serve as the basis for the estimating and scheduling of future projects

Ref.
Planning

- The road to project failure is paved with poor plans

**PLANNING: Influencing the future by making decisions today based on missions, needs and objectives.**

- It is an art not science.

Planning is NOT a one time activity
Categories of planning:

- Time
- Cost
- Resources
- Quality
- Contingency

Time Planning

- When to start
- when to finish
- Time plans will be transformed to schedule (time scale)
Time planning steps

1) Divide project into component parts
2) Sequencing component parts in order of accomplishment
3) Assign durations to each component part

Cost Planning

- Allocating direct and indirect costs to the project components
- Expenditure/revenue
- (cost / schedule integration)
Resources Planning

- **Construction Resources includes:**
  - money
  - Material
  - Human resources
  - Equipments and tools

- Check if the needed resources are available or NOT.
- Eliminate idle time.
- Resources should be planned considering the budget.
- Attention to critical resources for project success

Quality Planning

- what is the minimum accepted quality?
- Should I exceed the required quality?
- How can I achieve this quality?
Contingency (Risk) Planning

- Planning for variability and uncertainty
- “What if” planning to include items subject to variability which are significantly impact project cost and time

Control

- The heart of the project management system is controlling the execution of the works.
- The purpose of this control is to determine and predict deviations in a project so corrective actions can be taken.
- The milestones of the control process are as follows:
  - To determine the aim
  - To evaluate the actual results and to compare to the planned
Control

A defining the quality of the management

Construction scheduling
Construction scheduling

To be able to build up a successful schedule. You need to:
1) Define activities
2) Establish activities relationships
3) assign durations to activities
4) resources and costs allocation
5) calculate early and late start/finish times
6) calculate float values and identify the critical path

Construction activity

Anything that must be accomplished in order to complete the project may be considered as activity.

Consumes time and resources.

Activity duration: is the estimated time required to complete an activity.
Project Breakdown

Work Breakdown Structure

Integrating Planning

- Integration of time, cost and resource planning against the same basic structure (WBS)
- Resource budgeting against time
- Cost budgets plotted against time
Thousands of tasks

- The psychologists say our brains can normally comprehend around 7-9 items simultaneously.

- So, divide and subdivide the project.

The WBS (Work Breakdown Structure)

- It is used to break down the project from one main and relatively big entity into smaller, defined, manageable and controllable units, usually called work groups (packages) or tasks, or, at the finest level of detail (which is undesirable) activities.
Take care!!!

- The deeper you go into the lower levels of the WBS, the more detailed knowledge you will need to know.

- See next slide.
The WBS (Work Breakdown Structure)

1.0 house

1.1 structure
  1.1.1 sub Çstructure
    1.1.1.1 earth work
      E10 excavation
      E20 backfilling
      E30 leveling
    1.1.1.2 foundation
      F10 blinding
      F20 footings
      F30 tie beams
      F40 ground slab
  1.1.2 super structure
    1.1.2.1 structural elements
      CS10 columns
      CS20 beams
      CS30 roof slab
    1.1.2.2 finishing
      C10 plaster
      C20 tile
      C30 painting
      C40 doors & windows

1.2 mechanical
  1.2.1 HVAC

---

The WBS

- it is a major task to undo.

Why???

- Because cost collections begins at a WBS element,
Conclusion

- The work breakdown structure defines the product elements (work packages).
- And their interrelations to each other and to the product.
- The WBS mostly ends with project tasks.
- Using the tasks you can extract project activities.

Construction scheduling
Construction scheduling

To be able to build up a successful schedule, you need to:
1) Define activities
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3) Assign durations to activities
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5) Calculate early and late start/finish times
6) Calculate float values and identify the critical path

Construction activities

Anything that must be accomplished in order to complete the project may be considered as activity.
Activities Duration

- **Activity duration**: is the estimated time required to complete an activity.

- Activity duration mainly calculated based on:
  1) the quantities take off.
  2) labor or machines productivity rates.

Activities Duration

- Durations could be estimated by experience. (previous similar jobs)

- If experience not available, others experience could be utilized.

- If not, handbooks of productivity rates are available provide the required information.
Activities Duration

Activity duration can be calculated as follows:

\[
\frac{\text{quantity of the work}}{\text{qty / crew hour}} = \text{crew hours}
\]

- \text{qty / crew hour} is the productivity rate.
- Time unit is hours could be changed to working days.

Example: assume that you have a floor tile area of 600 M\(^2\), and the productivity rate of a tile mason and one helper is 1.5 M\(^2\) / hour.

By applying the previous equation:

\[
\frac{600 \text{ M}^2}{1.5 \text{ M}^2 / \text{h}} = 400 \text{ hours}
\]

If the time unit is working day (8 hours):

\[
\frac{400 \text{ hours}}{8 \text{ hours}} = 50 \text{ days}
\]
Activities Duration

By using two tile masons and two helpers:

\[
\frac{600 \text{ M}^2}{2 \times 1.5 \text{ M}^2/\text{h}} = 200 \text{ hours}
\]

If the time unit is working day (8 hours):

\[
\frac{200 \text{ hours}}{8 \text{ hours}} = 25 \text{ days}
\]

Activities Duration

By using 3 tile masons and 3 helpers:

\[
\frac{600 \text{ M}^2}{3 \times 1.5 \text{ M}^2/\text{h}} = 133.3 \text{ hours} = 134 \text{ hours}
\]

If the time unit is working day (8 hours):

\[
\frac{134 \text{ hours}}{8 \text{ hours}} = 16.75 \text{ days} = 17 \text{ days}
\]

Time preferably should be rounded up:
Activities Duration

By using 4 tile masons and 4 helpers:

\[
\frac{600 \text{ M}^2}{4 \times 1.5 \text{ M}^2 / \text{h}} = 100 \text{ hours}
\]

If the time unit is working day (8 hours):

\[
\frac{100 \text{ hours}}{8 \text{ hours}} = 12.5 \text{ days} = 13 \text{ days}
\]

Assume in the previous example that this activity is critical and should be finished within 5 days:

If the working day is 8 hours:

5 days \times 8 \text{ hours} = 40 \text{ hours}

Apply the equation:

\[
\frac{600 \text{ M}^2}{X} = 40 \text{ hours}
\]

\[X = 15 \text{ M}^2 / \text{h}\] is the productivity rate

The crew number should be \[
\frac{15}{1.5} = 10 \text{ gangs}
\]
Activities Duration Vs. Direct Cost

- Having defined an activity duration, it means that the planner have already defined the number of resources that will be employed in a particular activity.

- Knowing activity duration and resources employed, it is simple to estimate the activity direct cost.

Example

- If the daily production rate for a crew that works in an activity is 175 units/day and the total crew cost per day is 100 $. The material unit cost is 1 $.

  a. Calculate the time and cost it takes the crew to finish 1400 units
  b. Calculate the total unit cost.
Solution

- Activity duration = Qty / crew output
  = 1400 / 175 = 8 days

- Crew cost = 8 days * 100 $/day = 800 $
- Material cost = 1400 unit * 1 $ = 1400 $

- Total direct cost = Labor cost + Material Cost
  = 800 $ + 1400 $ = 2200 $
- Total Unit cost = total cost / quantity
  = 2200 $ / 1400 unit = 1.57 $/unit

Some Factors that affects Duration

1) Weather.
2) Availability and training of Labor.
3) Required quality
4) Familiarity with the work.
5) Quality of workmanship specified.
6) Quality of management/supervision.
7) Size and completion date of project.
8) Length and incidence of holidays.
9) Physical constraints of the site. Such as access, size, storage space and etc.
Types of Construction activities

1) production/construction activity.
2) Procurement activity.
3) Management activity.

production/construction.

- **production/ construction activities**: activities that relate directly to the physical efforts of creating the project.

- E.g. Concrete work, plaster, tile and etc.
- Usually use traditional resources, labor, material and equipments.
Procurement.

- **Procurement activities**: These activities include arranging for the acquisition of materials, money, equipment and manpower.

- Influence the start of production activities.

- Should be incorporated in the Schedule if they are long or special orders.

Management.

- **Management activities**: support and administrative tasks.

- Such as, preparing inspection reports, obtain shop drawing approvals. Tracking submittal approval and tests.
Construction Scheduling methods

Construction scheduling

- What is the difference between a schedule and a Plan?
- The schedule: putting the plan on time scale.
- Schedule: what would be done in a certain time and who will be working.
Most Common Scheduling methods

- common scheduling methodologies:
  - Bar Chart (Gantt Chart)
  - Critical Path Method (CPM)
  - PERT (program Evaluation & Review Technique)
  - Linear Scheduling Method (LSM)

Bar Chart or Gantt chart

- Bar chart is a collection of activities listed vertically, and the horizontal scale represents the time.

- First applied by HENRY GANTT in 1917
Bar Chart or Gantt chart

Advantages of Bar / Gantt Chart

1) Plan, schedule and progress are all depicted graphically on a single chart

2) Easily read

3) Provides simple way to schedule small projects

4) Provides summary display of more detailed plans and schedules.

5) Best used for management briefings
Bar Chart or Gantt chart

Disadvantages of Bar / Gantt Chart

1) Activity dependencies cannot adequately be shown.
2) Difficult to determine how activity progress delays affect project completion.
3) Difficult to establish and maintain for large projects
Critical Path Method (CPM)

- Two basic methods of analysis:

1) ADM -- Arrow Diagramming Method or Activity On Arrow (AOA) or I-J Method
2) PDM -- Precedence Diagramming Method Activity On Node (AON) Method

1) ADM -- Arrow Diagramming Method

- Activity on Arrow (AoA) or noun as i ð j method
- In the ADM the activity represented by an arrow.
- The arrow head represents the relation with other activities (interdependency).
- It looks like the following figure
The Excavation activity OR activity \(i - j\) with duration of 7 (time unit)

ADM -- Arrow Diagramming Method

- Linear sequencing
- Summation of all activities durations = total duration

Total Duration = 2 + 1 + 1 + 7 = 11 days
ADM -- Arrow Diagramming Method

1. Sitting out

2. Excavate foundation

3. Order timber

4. Make Formwork

5. Erect Formwork

6. (not connected)

--

10: Plumbing

11: Electrical conduit

12: Door frames

13: Windows frames

14: Walls plaster

15: (not connected)
Dummy activities

- Dummy activity has ZERO duration and Does NOT consume resources.

1) Dummies help in activities identification
Dummy activities

If activity R follows P and activity S follows T, does the above figure depict the statement???

What about this
**Dummy activities**

If the method statement changed that activity S is dependent on both activities P & T, and activity R dependent on P only.

2) Dummy activities help to maintain the logic of the network

---

**Exercise: draw arrow diagram for the following project.**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>Predecessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>--</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>A</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>B &amp; C</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>B</td>
</tr>
<tr>
<td>G</td>
<td>1</td>
<td>D</td>
</tr>
<tr>
<td>H</td>
<td>4</td>
<td>F &amp; E</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>F</td>
</tr>
<tr>
<td>J</td>
<td>4</td>
<td>G &amp; H</td>
</tr>
<tr>
<td>K</td>
<td>4</td>
<td>I &amp; H</td>
</tr>
<tr>
<td>L</td>
<td>1</td>
<td>K &amp; J</td>
</tr>
</tbody>
</table>
The Arrow Network will be:

Network calculations

- **Forward Pass**: deals with the early start and early finish
- **Backward Pass**: deals with the late start and late finish
An activity time values

- **ES**: the earliest time that an activity can start as determined by the latest of the early finish times of all immediately preceding activities.

- **EF**: the earliest time that an activity can finish, determined by \( EF = ES + D \)

- **LS**: the latest time that an activity can start without delaying the project completion. \( LS = LF - D \).

- **LF**: the latest time that an activity can be finished without delaying the project completion, as determined by the earliest of the late starts of the immediately succeeding activities.

Example

```
\begin{array}{c}
\text{1} & \text{2} & \text{3} & \text{4} & \text{5} \\
A & C & D & E & \text{8} \\
1 & 4 & 2 & 2 & \\
\end{array}
```

**EF = ES + Duration**

Forward Pass calculations to determine the early start and early finish dates

Beginning of the day convention
Example

Backward pass calculations to determine the late start and late finish dates

LS = LF – Duration

Example

Backward pass calculations to determine the late start and late finish dates

LS = LF – Duration
Tabular Schedule

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>ES</th>
<th>EF</th>
<th>LS</th>
<th>LF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
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<td>B</td>
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<td>1</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>6</td>
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<tr>
<td>D</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>6</td>
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<tr>
<td>E</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>

Total Float (TF)

TF = LS \_ ES \text{ OR } LF - EF

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>ES</th>
<th>EF</th>
<th>LS</th>
<th>LF</th>
<th>TF</th>
</tr>
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<tbody>
<tr>
<td>A</td>
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<td>2</td>
<td>0</td>
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<tr>
<td>B</td>
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<td>C</td>
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<td>6</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

TF: the amount of time that an activity can be delayed before it impacts the project completion.
ES \& EF Schedule

Early Times Schedule (ES Č EF)

LS \& LF Schedule

Late Times Schedule (LS Č LF)
Early / Late times schedule

Critical Path

The critical path: is the longest path in the network and the shortest possible duration.
Forward Pass calculations (ES, EF)

backward Pass calculations (LS, LF)
Determining the Critical Path

The Critical path passes through activities where TF = 0
Early Schedule

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>ES</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
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Bar / Gantt chart Early Start / Finish
EF = ES + D
### Early / Late Schedule

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<th>EF</th>
<th>LS</th>
<th>LF</th>
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**Bar / Gantt Chart Late Start / Finish**

$LS = LF - D$

<table>
<thead>
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<th>Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
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<td>B</td>
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<td>24</td>
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<tr>
<td>L</td>
<td>26</td>
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</table>
Total Float (TF): The amount of time an activity can be delayed without delaying the overall project completion.

\[ TF = LF - EF = LS - ES \]

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>ES</th>
<th>EF</th>
<th>LS</th>
<th>LF</th>
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<td>20</td>
<td>19</td>
<td>20</td>
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</tr>
</tbody>
</table>

Bar / Gantt of the previous network
2) PDM Precedence Diagramming Method

Activity On Node (AON) Method

- PDM is the primary method in use today.
- Used by most of the computer software.
  - MS Project
  - Primavera
  - Sure Track

PDM Precedence Diagramming Method

- The PDM depicts activities as NODES in the network linked with logic lines.
- The node representing the activity.
- Arrow representing relationship / dependency
- PDM should be read left to right
PDM Precedence Diagramming Method

- PDM looks like the following:

  Activity A  →  Activity B

- The shape of the node could be any shape

PDM vs. ADM

ADM  =  PDM

1 A  2 C  3

4 B  5 D  6

A  →  C

B  →  D
### Exercise

**A** Draw a PDM for the following activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Activity Description</th>
<th>Predecessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Lay out</td>
<td>--</td>
</tr>
<tr>
<td>B</td>
<td>Excavation</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>place formwork</td>
<td>B</td>
</tr>
<tr>
<td>E</td>
<td>purchase steel</td>
<td>--</td>
</tr>
<tr>
<td>F</td>
<td>bend steel</td>
<td>E</td>
</tr>
<tr>
<td>G</td>
<td>place steel</td>
<td>C,F</td>
</tr>
<tr>
<td>H</td>
<td>order concrete</td>
<td>--</td>
</tr>
<tr>
<td>D</td>
<td>place concrete</td>
<td>G,H</td>
</tr>
</tbody>
</table>
Exercise

Draw a PDM for the following activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Predecessor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>--</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>D</td>
<td>B, C</td>
</tr>
<tr>
<td>E</td>
<td>C</td>
</tr>
<tr>
<td>F</td>
<td>D, E</td>
</tr>
<tr>
<td>G</td>
<td>E</td>
</tr>
<tr>
<td>H</td>
<td>F, G</td>
</tr>
</tbody>
</table>
Activities Relationships

Types of relations between activities:

1) Finish to start \( \rightarrow \) FS
2) Start to Finish \( \rightarrow \) SF
3) Finish to Finish \( \rightarrow \) FF
4) Start to Start - SS
1) Finish to start \( \text{FS Relationship} \)

- The traditional relationship between activities.
- Implies that the preceding activity must finish before the succeeding activities can start.
- Example: the plaster must be finished before the tile can start.

Finish to start with delay relationship

```
Pour concrete 1 day          Deshuttering 2 days
  |                        |
  FS/28                    
Pour concrete 1 day          Deshuttering 2 days
```

Deshuttering should start after 28 days of concrete curing

28 days is delay time or LAG means that: deshuttering can start 28 days after Concrete has been poured
Finish to start with delay relationship

Finish to Start with Lag

3

Activity A
Activity B

3) Star to Finish SF relationship

^ Appear illogical or irrational.
^ Typically used with delay time OR LAG.
^ The following examples proofs that it is logical.
2) Star to Finish (SF) relationship

- Erect formwork
- Steel reinforcement
- Order concrete
- Pour concrete

The concrete supplier stipulates 5 days order before delivery.

3) Finish to Finish (FF) relationship

- Both activities must finish at the same time.
- Can be used where activities can overlap to a certain limit.
**Finish to Finish FF relationship**

- Set flagpole In the hole
- Position flagpole In the hole
- Backfill hole

**Finish to Finish with delay relationship**

- Erect scaffolding
- Remove Old paint
- sanding
- painting
- inspect
- Dismantle scaffolding
4) Start to Start (SS) relationship

Both activities must start at the same time.

Start to Start with Lag

Start to Start

Activity A

3

Activity B

Activity A

Activity B

Start to Start (SS) relationship

Clean surface ➔ Spread grout

SS

Set tile ➔ Clean floor area
**Precedence Network Calculations**

- The basic information that should be calculated in the precedence network are:

  1) Early activity start (ES)
  2) Early activity finish (EF)
  3) Late activity start (LS)
  4) Late activity finish (LF)
  5) Free Float (FF)
  6) Total Float (TF)

---

**Precedence Network Calculations**

- **ES**: the earliest time that an activity can start as determined by the latest of the early finish times of all immediately preceding activities.
- **EF**: the earliest time that an activity can finish, determined by \( EF = ES + D \)
- **LS**: the latest time that an activity can start without delaying the project completion.
  \( LS = LF - D \).
- **LF**: the latest time that an activity can be finished without delaying the project completion, as determined by the earliest of the late starts of the immediately succeeding activities.

---
Precedence Network Calculations

- **FF**: the amount of time that an activity can be delayed before it impacts the start of any succeeding activities.
- **TF**: the amount of time that an activity can be delayed before it impacts the project completion.
- **Lag**: the amount of time that exists between the EF of an activity and the ES of a specified succeeding activity.

\[ \text{LAG}_{AB} = \text{ES}_B - \text{EF}_A \]

Precedence Network Calculations

- The previously mentioned information can be illustrated in the activity nod in the network:

<table>
<thead>
<tr>
<th>Activity description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES</td>
</tr>
<tr>
<td>Duration</td>
</tr>
<tr>
<td>LS</td>
</tr>
<tr>
<td>EF</td>
</tr>
<tr>
<td>FF</td>
</tr>
<tr>
<td>TF</td>
</tr>
<tr>
<td>LF</td>
</tr>
</tbody>
</table>
Precedence Network Calculations

A **Reminder:** The manual calculations assumes that the relationships between activities are Finish to Start (FS) Type.

1) **Forward pass calculations**
   2) Calculate the Lag \( LAG_{ab} = ES_b - EF_a \)
   3) Calculate the Free Float (FF) \( FF = \text{min.} \ LAG \)
   4) **Backward pass calculations**
   5) Calculate total Float \( TF = LS - ES \ OR \ LF - EF \)

---

### Precedence Network Calculations

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ES</strong></td>
<td>0</td>
<td>2</td>
<td>7</td>
<td>11</td>
<td>11</td>
<td>16</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td><strong>Dur.</strong></td>
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<td>2</td>
<td>5</td>
<td>11</td>
<td>4</td>
<td>5</td>
<td>3</td>
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<td>16</td>
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<td>16</td>
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<tr>
<td><strong>LF</strong></td>
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<td>11</td>
<td>16</td>
<td>16</td>
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<td>20</td>
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<td>0</td>
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<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Precedence Network Calculations

6) Determine the Critical Path

The critical path passes through the critical activities where TF = 0

ES  Dur.  LS
EF  FF  TF = F

Activity

Bar / Gantt chart Early Start / Finish
EF = ES + D
Bar / Gantt chart

Late Start / Finish

$LS = LF - D$

Activity

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
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<tr>
<td>C</td>
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<td>12</td>
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<tr>
<td>G</td>
<td>14</td>
</tr>
<tr>
<td>H</td>
<td>16</td>
</tr>
</tbody>
</table>

Time

2 4 6 8 10 12 14 16 18 20

Activity

Bar / Gantt chart
Exercise

1) Forward pass calculations

4) Backward pass calculations

2) Calculate the Lag \( \text{LAG}_{AB} = \text{ES}_B - \text{EF}_A \)

3) Calculate the Free Float (FF) \( \text{FF} = \min \text{LAG} \)

6) Determine the Critical Path

5) Calculate total Float \( \text{TF} = \text{LS} - \text{ES} \text{ OR LF} - \text{EF} \)
Constraints

- The reason why two activities must be done in particular order can be termed as **constraint**.

- Without constraints on a project, all activities theoretically can begin on the first day of construction.

Types of construction Constraints

1) Physical constraints.
2) Resource constraints.
3) Safety constraints.
4) Financial constraints.
5) Environmental constraints.
6) Management constraints.
7) Contractual constraints.
8) Regulatory constraints.
Physical constraints.

- Physical constraints exist due to physical process of construction.

- Physical constraints defined by "HOW" the project is to be carried out. (Method of construction).

- You need to erect formwork before you can cast concrete.

Resource constraints

- These constraints imposed wherever two activities cannot be carried out simultaneously because insufficient resources are available.

- E.g. two activities require a crane to be performed and you have just one crane. So, they should not be performed at the same time.

- E.g. The amount of required concrete per day exceeds the production capacity of a batch plant.
Safety constraints.

- Safety constraints imposed by safety requirements through performing the work.
- Sometime imposes that two activities could not be performed at the same time due to non-safe work conditions. (E.g. overhead and ground level work at the same area.)
- Imposes specific sequence of the work. (e.g. erecting of scaffolding before external paints can start)
- Imposes non-working days due to extremely hot or cold days.

Financial constraints

- Financial constraints: high cost activities could be delayed due to non-availability of cash requirements during construction.

- The amount of cost a company can pay within a specific period of time usually limited. So, try to avoid overlap between high cost activities.
Environmental constraints.

- Environmental constraints include restrictions to the work to avoid environmental violations.

- E.g. not working in certain area during specific times to avoid affecting proliferation of eagles and fish run.

Management constraints.

- Management constraints reflect decisions of management that result in a reasonable benefit of the company.

- E.g. the management decided to borrow from your project resources to be utilized in another project.

- E.g. the management decided to extend the new year holiday another 2 days.
Contractual constraints

- The owner may impose constraints on the construction process.

- E.g. the owner may require a particular phase of the project to be fully completed and occupied before starting construction of the next phase.

- And he may require to minimize the noise and dust because that portion is occupied and in operation.

Regulatory constraints.

- These type of constraints related to the regulations of the area of construction. Imposed by municipality, government, etc.

- E.g. if the construction site in the downtown, heavy vehicles like concrete mixers prohibited to access the site in a specific times of the day. So, you can just cast concrete at night.
Impacts of constraints on the network

In the initial definition of the network, it is desirable to minimize the number of constraints, because excessive constraints have the following impact of the project.

1) Reduce scheduling flexibility.
2) Lengthen project duration.
3) Generally increase project costs.
4) Confuse basic scheduling logic.

Impacts of constraints on the network

The imposition of constraints in the network results in linear ordering of activities. Which is not desired. (recall: the linear order of activities prolong the project duration and set most of the activities as critical).
Impacts of constraints on the network

- Only physical constraints should be considered in the early preparation of the network.
- Other constraints can be deferred until actual schedule of activities. Where it can be determined that:
  1. the constraints are not met by the schedule.
  2. It can be addressed by shifting of activities within their available float time.

Resource Management

Resources Allocation & Leveling
Resources Allocation & Leveling

- So far, the network analysis has been considered using one resource only which is time.

- Construction activities in practice use other resources like labor, material, equipment and money.

- Moreover, the network analysis considered no limitations of the traditional resources (labor, material, equipment and money) which is not the case in practice.

Resources Allocation & Resources Leveling

- A time only network assumes that any other needed resources are available at any time.

- E.g. if the excavation activity requires three large mechanical excavators, A time only network assumes that these excavators are available on site at the required time. This seems to be uneconomic situation.
Resource Profile

Not preferred resources demand (Histogram)
preferred resources demand (Histogram)

resources aggregation diagram (Histogram)

It is a graphical representation of the resources aggregation vs. project's duration. And it shows the project resources demand along its duration for different time units, daily, weekly or monthly.

And its important to the contractor to know the amount of needed resources to carry out the job and to check their availability, in addition, the resources histogram shows the fluctuation in the resources demand and enables the scheduler to obtain even resources demand.
Resource Aggregation

Resources aggregation: is the summation of the resources that are used to carry out the program on a time period basis. For example, day to day, or week to week.
Priorities & Sorts

- The activities making up the network must be listed in order of their priority of resources allocation.
- The network shows the logical sequence of activities. (predecessor and successor).
- The listing of activities must therefore reflect the dependency of some activities.

Activities Sort

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>ES</th>
<th>TF</th>
<th>Resource unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>8 H</td>
</tr>
<tr>
<td>B</td>
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<tr>
<td>C</td>
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<td>H</td>
<td>1</td>
<td>20</td>
<td>0</td>
<td>4 H</td>
</tr>
</tbody>
</table>

Activity sort reflects the logic sequence of the network.
# Major Sort

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>ES</th>
<th>TF</th>
<th>Resource unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>8 H</td>
</tr>
<tr>
<td>B</td>
<td>9</td>
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<td>9 H</td>
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<td>C</td>
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<td>8 H</td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>20</td>
<td>0</td>
<td>4 H</td>
</tr>
</tbody>
</table>

Activity sort with ES time as Major sort

# Major & Minor Sorts

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>ES</th>
<th>TF</th>
<th>Resource unit</th>
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<tr>
<td>A</td>
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<td>1</td>
<td>0</td>
<td>8 H</td>
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<tr>
<td>B</td>
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<td>H</td>
<td>1</td>
<td>20</td>
<td>0</td>
<td>4 H</td>
</tr>
</tbody>
</table>

Activity sort with ES time as Major sort & TF as Minor Sort
Allocated resources

Time

Activity

Total Labor

Early start resources aggregation

84
Another histogram can be obtained if Late start considered. Shows different resources demand.

And many histograms can be obtained considering a different time in the network.

Each histogram shows different resources demand.
### Late start Sort

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>LS</th>
<th>TF</th>
<th>Resource unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>8 H</td>
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<td>B</td>
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Activity sort with LS time as Major sort & TF as Minor Sort

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**Time Diagram**

![Time Diagram](Image)

- **Total Labor**
  - A: 8
  - B: 9
  - C: 9
  - D: 16
  - E: 16
  - F: 16
  - G: 13
  - H: 9
  - **Total Labor**: 89
Late start resources aggregation diagram (Histogram)

Early start vs Late start resources aggregation diagram (Histogram)
Early start vs Late start resources aggregation diagram (Histogram)
Activities Sort

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<th>Resource unit</th>
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Activity sort with ES time as Major sort & TF and duration as Minor Sorts
### Total Labor

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*Activity sort with LS time as Major sort & TF and duration as Minor Sorts*
Late start resources aggregation diagram
Smoothing/Leveling

Let us program activity F to start by its late start day which is day 17.

And activity I to start by day 14.

The resulting resources aggregation histogram will be as follows:
Smoothing/Leveling

Let us program activity H to start by its late start time.

So its resources demand starts with its Late start date.

The resulting resource aggregation and histogram will be as follows:
Smoothing/Leveling

Let us program

1) activity D to start on 10th day.
2) activity B to start by its early start time 6th day.
3) activity H to start on 12th day.
4) activity E to start 10th day.
5) activity F to start by late start 16th day.
6) activity I to start by late start 18th day

The resulting resource aggregation and histogram will be as follows:
In case activity D is splittable activity. It could be interrupted to be carried out in two parts.

Let us program activity B to start on the 7th day.

And activity H to starts by its Late start day.

And activity E to start on the 14th day.

The resulting resource aggregation and histogram will be as follows:
Construction Project Management

Dr. Luay Dwaikat

Spring Semester 2016/2017

Early start resources aggregation

Total Labor

Time

Labor

2 4 6 8 10 12 14 16 18 20 22 24

2 4 6 8 10 12 14 16 18 20 22 24
Early Start or Early Finish

There are many solutions between the limits of Early Start and Late start.

The optimal solution is zero fluctuation histogram. Which is hard to be achieved.

It is preferred to solve the problem toward the Early start resources aggregation diagram.

WHY ?!

Early Start or Early Finish

Because if there are labor availability problems to be overcome, they will occur in the early beginning of the project.

By other words, if the program based on the Late Start date, it means that all the activities are Critical, and any labor problem will affect the project completion.
Remember

- The total project's duration should **NOT** be affected while resources are leveled.
- Do **Not** shift any critical Activity.

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Example: Schedule the following activities and level the resources
Answer the followings:

1) When will the project end?
2) How many labors will work in the project?
3) What is the average labor demand along the project?
4) In the ES schedule how much is the peak demand on the resource and when will occur?
5) Level the resource and schedule the activities based on the optimum resource usage?

Resources Leveling summary steps

1) Prepare a complete activity schedule. (network calculations)
2) sort the activities based on the ES as major sort and TF as minor sort.
3) Draw a bar chart of the project based on ES timing of the activities.
4) Draw the TF beside each non critical activity.
5) Write the resource usage above each bar of the related activity.
6) Aggregate (determine the resource sum) the resources in each time period. (e.g. day).
7) Calculate the total usage of resources = Σ time unit period usage.
8) Calculate the average resource usage = Σ usage / utilization period.
9) Shift non-critical activities within their TF to decrease the peaks and raise the valleys.
10) Aggregate resources in each time period after shifting any activity.
11) When shifting activities, it is preferred to start with the activities that have no successors, as shifting these activities will not affect other activities.
12) Shift activities only that will enhance the resource profile.
### Activities Sort

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### Time

![Time diagram showing resource aggregation](image)

Total Labor/DAY = 326
### Time Total Labor/DAY

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### Early start resources aggregation

#### Leveled resource aggregation diagram
When Resources are Limited

Resources Allocation

- The previous method of resources aggregation has been carried out within a fixed project duration.

- The basic objective was to optimize the use of the resources and to know the amount of resources needed to carry out the job on time period basis.

- And to maintain the network based duration.
Allocation within resources restraints

- Another situation which you may face in practice is the restricted resources availability.

- Where you have to carry out the job with the available resources only.

- In this case the project duration may be prolonged to suit the availability of the restricted resources.

Resources Allocation

Activity desc. | ES | Dur. | LS | EF | FF | TF | LF | Resources
---|---|---|---|---|---|---|---|---
A | 1 | 1 | 1 | 8H
 2 | 0 | 0 | 2
 2 | 0 | 0 | 2
 9H
B | 2 | 9 | 2 | 11 | 0 | 0 | 11
 9H
C | 2 | 5 | 5 | 7 | 0 | 3 | 10
 7H
D | 11 | 5 | 11 | 16 | 0 | 0 | 16
 5H
E | 16 | 4 | 16 | 20 | 0 | 0 | 20
 8H
F | 20 | 1 | 20 | 21 | 0 | 0 | 21
 4H
G | 11 | 6 | 14 | 17 | 3 | 3 | 20
 2H
H |
### Early start resources aggregation

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time</th>
<th>Total Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>8</td>
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<tr>
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<td>16</td>
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<td></td>
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<td></td>
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</tr>
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<td></td>
<td>12</td>
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</tr>
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<td></td>
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</tr>
<tr>
<td></td>
<td>20</td>
<td>7</td>
</tr>
</tbody>
</table>

### Early start resources aggregation diagram (Histogram)

<table>
<thead>
<tr>
<th>Time</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
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<th>14</th>
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<tbody>
<tr>
<td>Labor</td>
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<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>
Solve the schedule

Assume that the available labors in the company restricted to 10 helpers, and the company decided to carry out the job without resorting to hire more labor.

The resulting program will exceed the Early finish date based on the network.
Resources based scheduling
Scheduling limited resources

- two methods of examination:
  
  1) Series method
  
  2) Parallel method
Rules for scheduling activities with limited resources

1) schedule activities to start as soon as their predecessors have been completed.
2) if more than one activity using a specific limited resources can be scheduled, priority is given to the activity with early Late Start. (LS as Major Sort)
3) if two or more activities have the same Late start, give priority to the activity with least Total Float. (TF as Minor Sort)
4) if the activities have the same Total Float in the minor sort, give the priority to the activity with the Largest Number of Resources.
5) If the activities are tied in the number of resources, give priority to the activity that has already started.

Resources Allocation
### Activity list

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>LS</th>
<th>TF</th>
<th>Resource unit</th>
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<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>8 H</td>
</tr>
<tr>
<td>B</td>
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<td>2</td>
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<td>C</td>
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<td>3</td>
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<td>E</td>
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<td>4 H</td>
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<td>D</td>
<td>5</td>
<td>11</td>
<td>0</td>
<td>5 H</td>
</tr>
<tr>
<td>G</td>
<td>6</td>
<td>14</td>
<td>3</td>
<td>2 H</td>
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<td>F</td>
<td>4</td>
<td>16</td>
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<td>H</td>
<td>1</td>
<td>20</td>
<td>0</td>
<td>4 H</td>
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</tbody>
</table>

Activity sort with LS time as Major sort & TF as Minor Sort

### Resources aggregation diagram
Example:

Reschedule the following project considering 20 units of the given resource are available in one day.
### Activities Sort

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>LS</th>
<th>TF</th>
<th>Resource unit</th>
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<td>A</td>
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<td>9</td>
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<td>C</td>
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<td>G</td>
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</tr>
<tr>
<td>D</td>
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<td>H</td>
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<td>13</td>
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<td>8</td>
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<tr>
<td>J</td>
<td>4</td>
<td>15</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>16</td>
<td>11</td>
<td>7</td>
</tr>
</tbody>
</table>

### Resource Driven Schedule

- **B**: 6H
- **E**: 9H
- **F**: 9H
- **A**: 4H
- **C**: 5H
- **G**: 10H
- **D**: 2H
- **I**: 8H
- **H**: 3H
- **J**: 3H
- **K**: 3H
Chapter 7

Money and Network Schedules
Money and network schedules

- Reminder, cost was one of the elements of project constraints triangle (COST, TIME & QUALITY).

- An effective management tries to minimize and integrate the above mentioned elements.

Money and network schedules

- CPM provides a mean for relating time and money.

- The application of resources to a project (materials, manpower and machinery) related to another resource which is MONEY.

- The value of the resources for each activity represents a component of project cost.
Project Cash Flow

- It is quite significant to the contractor to know the amount of money that would be spent in each stage of the project. (Expenditures) CASH OUT

- And compare it to the amount of money that would be received. (income) CASH IN

- When studying cash flow, it is very important to determine the actual dates when the expenditures (cost) will take place.

Example

- Consider the construction of 8-week foundation activity with operation cost of 8800 $. The operation cost is broken down into the following elements:

  - Labor 1600 $ paid 200 $ weekly.
  - Equipments 4000 $ paid 500 $ weekly after 4 weeks
  - Materials 800 $ paid 100 $ weekly after 5 weeks
  - Subcontractors 2400 $ paid 300 $ weekly after 3 weeks

- Determine the expenses (cash out) of this activity.
A time-scaled plan is developed for this activity for the payments for labor, plant, material, and subcontractors. The cost will be plotted weekly with the delay specified in the example.

### Solution

<table>
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<th>weeks</th>
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<td>Equipment</td>
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<tr>
<td>Material</td>
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<tr>
<td>Subcontractor</td>
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<tr>
<td>Total payment</td>
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<tr>
<td>Cumulative Payments</td>
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</tr>
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</table>
### Solution

#### Foundation

<table>
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<tr>
<th>weeks</th>
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<th>5</th>
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<td>100</td>
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<tr>
<td>Subcontractor</td>
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<td>300</td>
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</tr>
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<td>6300</td>
<td>7200</td>
<td>8100</td>
<td>8700</td>
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</tbody>
</table>

#### Cumulative Cost (x 1000)

- Weeks: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13
- Cumulative Cost: 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26

#### S-Curve for the activity

- X-axis: Weeks (1 to 13)
- Y-axis: Cumulative Cost (x 1000)
Typical S-Curve

The curve represents the cumulative expenditures of a project direct and indirect Costs over time is called the S-curve

Developing S-Curve for a project

S-curve for a project can be developed using the following steps:

1. Constructing a simple bar chart for all the activities of the project
2. Assigning costs to each activity using activity duration.
3. Plotting the cumulative amounts of expenditures versus time by smoothly connecting the projected amounts of expenditures over time.
Example: Develop S-curve for the following project

<table>
<thead>
<tr>
<th>Activity</th>
<th>Duration</th>
<th>Predecessors</th>
<th>Total cost</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>3</td>
<td>-</td>
<td>3,000</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>-</td>
<td>10,000</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>-</td>
<td>4,000</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>A</td>
<td>16,000</td>
</tr>
<tr>
<td>E</td>
<td>7</td>
<td>B</td>
<td>21,000</td>
</tr>
<tr>
<td>F</td>
<td>6</td>
<td>B</td>
<td>12,000</td>
</tr>
<tr>
<td>G</td>
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<td>C</td>
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<tr>
<td>I</td>
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<td>D,E</td>
<td>12,000</td>
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<td>F,G</td>
<td>12,000</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>H</td>
<td>9,000</td>
</tr>
</tbody>
</table>
Construction Project Management  
Dr. Luay Dwaikat  
Spring Semester 2016/2017
**Project Income (Cash In)**

- The flow of money from the owner to the contractor is in the form of progress payments.

- Estimates of work completed are made by the contractors periodically (usually monthly).

- These estimates are based on evaluations of the percentage of total project completion or actual field measurements of quantities placed.

**Retention**

- Retention is the amount of money retained by the owner from every invoice, before a payment is made to the contractor.

- This is to ensure that the contractor will continue the work and that no problems will arise after completion.

- This retainage amount ranges from 5% to 10%.
**Project cash flow**

- A project's cash flow is the difference between the project's expenditures and income.

- Cash flow = Cash in \( \text{Cash out} \) = Income - Expenditures

**Cash Flow Analysis**

- Cash flow analysis consists of a detailed examination of funds disbursement (expenditures) and the receipt of revenue.

- Cash flow shows if surplus fund available during project, or if negative cash position will occur during construction.

- The cash position of contractor during project whether positive or negative is important.
Negative cash position

- Negative cash position means that the revenues obtained from a project insufficient to meet the financial obligations (expenditures) of the project.

- In this case other fund from the company or from outside sources must be used.

Positive cash position

- Positive cash position means that the revenues obtained from a project exceed the financial obligations (expenditures) of the project.

- In this case surplus (extra) fund available with the contractor.

- And the contractor may invest this surplus funds for short duration.
Overtrading

- Overtrading: arises when the current liabilities of a company exceed the current assets, even though the business is solvent.

Minimizing Contractor Negative Cash Flow

- It is very essential to the contractor to minimize his negative cash flow because this may hinder him during performing the contract due to lack of financial resources.

- the procedures the contractor may follow to minimize negative cash flow are:
Minimizing Contractor Negative Cash Flow

1) Asking for advanced or mobilization payment

2) Loading of rates, in which the contractor increases the prices of the earlier items in the bill of quantities. This ensures more income at the early stages of the project.

3) Adjustment of work schedule to late start timing in order to delay payments. In this case, the contractor should be aware that delay might happen will affect the project completion time and may subject him to liquidated damages.

4) Reduction of delays in receiving revenues.

5) Achievement of maximum production in the field to increase the monthly payments.

6) Reducing the retention.

7) Adjust the timing of delivery of large material orders to be with the submittal of the monthly invoice.

8) Delay in paying labor wages, equipment rentals, material suppliers and subcontractors.

Advanced Payments

- This is amount of money paid to the contractor for mobilization purposes. Then, it is deducted from contract progress payment.

- The contractor may request an advanced or mobilization payment from the owner. This shifts the position of the income profile so that no negative cash position will occur.
Effect of advanced payment on improving cash flow

Cumulative Expenditures & Income

Expenditures

Income

Advanced payment

Time-Cost Trade-Off

Some amount of knowledge brings more...
Projects managers seek the work to be carried out at minimum cost.

Therefore, they are prone to minimum cost duration (Normal Duration).

Unfortunately, minimum cost & minimum duration rarely coincide.

The cost of an activity depends mainly on the amount of used resources.

Adding more resources to an activity increases the cost, but not necessarily result in proportionate decrease in the duration.
For the following discussions it is important to remember:

- **Direct costs**: Related to putting the facility components in place. They represent the resources used by an activity. (material, labor and equipment).
Time-Cost Trade-Off

- Indirect job costs (job overhead): costs that could not be attributed to a specific work item. (such as, site offices, superintendents, security fence & etc)

- These costs are generally incurred whether or not productive work achieved.

- Longer project duration will result in higher indirect costs.

---

Time-Cost Trade-Off

- Operating Overhead costs (company overhead): If the cost cannot be attributed to any specific job, they are operating overhead costs, costs of running business. (head office costs, communications & etc).

- These costs continue as long as the company exists even one project is running.
Logic of Time-Cost Trade-Off

Assumption: increasing or decreasing project’s duration will lead to increased direct costs for the project.
Logic of Time-Cost Trade-Off

Assumption: decreasing a project’s duration will lead to lower indirect costs.
**Logic of Time-Cost Trade-Off**

**Assumption:** A project’s duration can be decreased by decreasing the duration of one or more critical activities on the critical path.

**Reducing Project Duration**

As the critical path of the network decreased, some non-critical activities lose some amount of their total float.
Logic of Time-Cost Trade-Off

**Assumption:** Decreasing a project’s duration may increase or decrease the total cost of a project depending upon whether the additional direct costs required to decrease the activity duration are greater or less than indirect costs savings of decreasing the project’s duration.

التقليل المدة لزمنية للمشروع يمكن أن يزيد أو يقلل من التكلفة الكلية للمشروع، وذلك يعتمد على ما إذا كانت التكاليف المباشرة الإضافية لتقليل مدة المشروع أكبر أو أقل من التوفير في التكاليف الغير مباشرة للمشروع.
Graph analysis

A project’s total costs combines direct costs and indirect costs. Therefore, the curve of total costs versus duration involves adding the cost amounts of direct and indirect costs curves.

A Remember, the direct costs curve has a negative slope (direct costs increase as duration decrease) and indirect costs curve has a positive slope (indirect costs decrease as duration decreases).

A So, the slope of the total costs curves at any point depends whether the slope of direct costs curve less than that of indirect cost curve.

Time-Cost Trade-off

A The previous analysis suggests that in performing Time-Cost Trade-off analysis, it is necessary to determine the cost of decreasing the critical path by one time unit (day, month & etc).

A The cost will vary depending upon which activity duration decreased.

A Usually, select the activity with least shortening costs. (lowest additional cost per day of shortening) to minimize the additional costs of shortening.
Reducing Project Duration

As the critical path of the network decreased, some non-critical activities lose some amount of their total float.

Thus, the extent to which an activity can be shortened and still has the effect of shortening the project is limited by the amount of total float exists in the parallel activities.
Reducing Project Duration

As the projects duration decreases, the number of critical paths through the network increases.

If more than one critical path exist, it is necessary to reduce all critical paths in the network simultaneously, which becomes expensive.
Four Different Solutions for Each Network

The schedule can be viewed in several different ways in order to satisfy the client. A client may wish to perform the project in the least cost, or in the least time. Or in any manner satisfies him.

1) **All Normal:** the original network and activity duration result in all normal solution, based on each activity being performed in its \( \text{NORMAL} \) least cost manner.

   *Remember,* it is not necessarily the least cost or least time solution to schedule a project.

2) **Least Cost:** considering both direct and indirect costs, it may be possible to find a project duration that minimizes these total costs. By paying more to decrease one or more critical activity (direct cost) and save greater indirect costs. (Means that the result will be total cost saving.)
Four Different Solutions for Each Network

3) **Least Time:** A project can be shortened beyond its least cost duration. Until a point reached where no activities in the critical path can be physically shortened regardless of how many resources are applied. (results in higher costs)
Four Different Solutions for Each Network

4) **All crash**: in this solution, every activity has been shortened as much as physically possible. Its duration the same as the least time solution, but its costs greater. Because the direct cost increases without further reductions in the indirect costs.

- A fully crashed schedule occurs when all activities shortened to their shortest possible duration.

---

**All crash**

- It is not an efficient approach since some non-critical activities will be shortened without having any shortening influence on the project duration.
Logically reducing Project Duration

The logical approach is to shorten those activities that contribute to reduce the project duration.

To begin the time-cost trade-off in a rational manner, basic calculations needed.

First compute the early start and early finish times for each activity.

Reducing Project Duration to shortest possible duration

```
<table>
<thead>
<tr>
<th>Activity</th>
<th>Dur.</th>
<th>ES</th>
<th>LS</th>
</tr>
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```

Reducing Project Duration to shortest possible duration
Reducing Project Duration to shortest possible duration

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<th>Crash Cost</th>
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<td>50</td>
</tr>
<tr>
<td>F</td>
<td>7</td>
<td>500</td>
<td>800</td>
<td>2</td>
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<td>150</td>
</tr>
<tr>
<td>G</td>
<td>8</td>
<td>200</td>
<td>1400</td>
<td>4</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>H</td>
<td>7</td>
<td>350</td>
<td>600</td>
<td>1</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>J</td>
<td>5</td>
<td>700</td>
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<td>75</td>
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</tr>
<tr>
<td>K</td>
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<td>500</td>
<td>1000</td>
<td>1</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>L</td>
<td>5</td>
<td>450</td>
<td>800</td>
<td>1</td>
<td>350</td>
<td>350</td>
</tr>
</tbody>
</table>
Logically reducing Project Duration

- By computing the link lag values between activities. \( \text{Lag} = \text{ES}_B - \text{EF}_A \). It is logical that there is at least one path between the first activity and last activity where lag values are 0.

- These activities forming the critical path. (other solution can be derived by computing TF).

- In the previous network. Activity A,B,F,H and L forming the critical path.

---

Logically reducing Project Duration

- To shorten the project’s duration it is essential to shorten one of the critical activities. A or B or F or H or L.

- Without shortening the project will end after 28 days with a cost of 5300 $.

- This is the normal duration cost. And any decrease in duration will increase the direct cost.

- The following table shows information about activities.
Identifying activities for 1st compression cycle

<table>
<thead>
<tr>
<th>Activity</th>
<th>A</th>
<th>B</th>
<th>F</th>
<th>H</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/day</td>
<td>∞</td>
<td>200$</td>
<td>150$</td>
<td>250$</td>
<td>350$</td>
</tr>
</tbody>
</table>

Cannot be shortened At any cost

Least cost activity to shorten

Logically reducing Project Duration

- From the previous table, it can be noticed that activity F has the least incremental shortening cost. (150 $ per day).

- E.g. Shortening F for 2 days costs 150 x 2 = 300 $.

- Bear in mind, activities for shortening selected based on cost per day. Not on cycle cost basis.
Logically reducing Project Duration

How many days activity F could be shortened?

The answer in computing the Network Interaction Limit (NIL).

So, reducing activity F by 2 days will affect the link lag values of the succeeding activities and TF of parallel activities.
### Summary of the first compression cycle

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Activity to shorten</th>
<th>Can be shortened</th>
<th>NIL</th>
<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>5300</td>
<td>28</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>150 $</td>
<td>300 $</td>
<td>5600</td>
<td>26</td>
</tr>
</tbody>
</table>
Identifying activities for 2nd compression cycle

<table>
<thead>
<tr>
<th>Activity</th>
<th>A</th>
<th>B</th>
<th>F</th>
<th>H</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/day</td>
<td>∞</td>
<td>200$</td>
<td>∞</td>
<td>250$</td>
<td>350$</td>
</tr>
</tbody>
</table>

![Project Network Diagram]

**Legend:**
- **ES:** Early Start
- **Dur.:** Duration
- **LS:** Late Start
- **FF:** Float Forward
- **TF:** Total Float
- **LF:** Late Finish
Summary of the 2nd compression cycle

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Activity to shorten</th>
<th>Can be shortened</th>
<th>NIL</th>
<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>5300</td>
<td>28</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>150 $</td>
<td>300 $</td>
<td>5600</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
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<td>1</td>
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<td>200</td>
<td>5800</td>
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</tbody>
</table>
Identifying activities for 3rd compression cycle

<table>
<thead>
<tr>
<th>Activity</th>
<th>A</th>
<th>B,C</th>
<th>F</th>
<th>H</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/day</td>
<td>∞</td>
<td>300</td>
<td>∞</td>
<td>250$</td>
<td>350$</td>
</tr>
</tbody>
</table>
Summary of the 3rd compression cycle

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Activity to shorten</th>
<th>Can be shortened</th>
<th>NIL</th>
<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>5300</td>
<td>28</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>150 $</td>
<td>300 $</td>
<td>5600</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>3</td>
<td>1</td>
<td>1</td>
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<td>200</td>
<td>5800</td>
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### Identifying activities for 4th compression cycle

<table>
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<th>A</th>
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<th>F</th>
<th>H</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/day</td>
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<td>300</td>
<td>∞</td>
<td>∞</td>
<td>350$</td>
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#### Activity Details

<table>
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<th>ES</th>
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<th>LS</th>
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<td>1</td>
</tr>
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<td>C</td>
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</tr>
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<td>D</td>
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<td>E</td>
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<td>F</td>
<td>8</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>G</td>
<td>5</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>H</td>
<td>13</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td>J</td>
<td>13</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>K</td>
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<td>3</td>
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<tr>
<td>L</td>
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<td>5</td>
<td>19</td>
</tr>
</tbody>
</table>

---

*Note: LS = Latest Start, ES = Early Start, Dur = Duration*
Summary of the 4th compression cycle

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Activity to shorten</th>
<th>Can be shortened</th>
<th>NIL</th>
<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
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</thead>
<tbody>
<tr>
<td>0</td>
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<tr>
<td>1</td>
<td>F</td>
<td>2</td>
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<td>26</td>
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<td>1</td>
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<td>H</td>
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<td>1</td>
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<td>250</td>
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<td>24</td>
</tr>
<tr>
<td>4</td>
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<td>2</td>
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<td>600</td>
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</table>
Identifying activities for 5th compression cycle

<table>
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<th>Activity</th>
<th>A</th>
<th>B, C</th>
<th>F</th>
<th>H</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/day</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
<td>350$</td>
</tr>
</tbody>
</table>

ES | Dur. | LS
AF | FF | TF | LF

A

B

C

D

E

F

G

H

J

K

L
Summary of the 5th compression cycle

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Activity to shorten</th>
<th>Can be shortened</th>
<th>NIL</th>
<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>5300</td>
<td>28</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>150 $</td>
<td>300 $</td>
<td>5600</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>3</td>
<td>1</td>
<td>1</td>
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<td>200</td>
<td>5800</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
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<td>1</td>
<td>2</td>
<td>1</td>
<td>250</td>
<td>250</td>
<td>6050</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>B,C</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>300</td>
<td>600</td>
<td>6650</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
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<td>1</td>
<td>1</td>
<td>350</td>
<td>350</td>
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<td>21</td>
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</table>
### Identifying activities for 6th compression cycle

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<th>H</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/day</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
</tr>
</tbody>
</table>

Assume the data given in the table, it is required to crash the project duration from its normal duration to a final duration of 121 days.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Pred.</th>
<th>Normal</th>
<th>Crash</th>
<th>Cost/day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Duration</td>
<td>Cost</td>
<td>Duration</td>
</tr>
<tr>
<td>A</td>
<td>--</td>
<td>12</td>
<td>1200</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
<td>20</td>
<td>1800</td>
<td>15</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
<td>40</td>
<td>16000</td>
<td>30</td>
</tr>
<tr>
<td>D</td>
<td>C</td>
<td>30</td>
<td>1400</td>
<td>20</td>
</tr>
<tr>
<td>E</td>
<td>D,F</td>
<td>50</td>
<td>3600</td>
<td>40</td>
</tr>
<tr>
<td>F</td>
<td>B</td>
<td>60</td>
<td>13500</td>
<td>45</td>
</tr>
</tbody>
</table>
Identifying activities for 1\textsuperscript{st} compression cycle

<table>
<thead>
<tr>
<th>Activity</th>
<th>A</th>
<th>B</th>
<th>F</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/day</td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>120</td>
</tr>
</tbody>
</table>
Summary of the 1st compression cycle

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Activity to shorten</th>
<th>Can be shortened</th>
<th>NIL</th>
<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>37500</td>
<td>143</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>2</td>
<td>D</td>
<td>2</td>
<td>100 $</td>
<td>200 $</td>
<td>37700</td>
<td>141</td>
</tr>
</tbody>
</table>

Identifying activities for 2nd compression cycle

<table>
<thead>
<tr>
<th>Activity</th>
<th>Cost/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>B</td>
<td>200</td>
</tr>
<tr>
<td>F</td>
<td>300</td>
</tr>
<tr>
<td>E</td>
<td>120</td>
</tr>
</tbody>
</table>
Project network

A

C

D

E

B

F

Project network
### Summary of the 2\textsuperscript{nd} compression cycle

<table>
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<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>37500</td>
<td>143</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>2</td>
<td>D</td>
<td>2</td>
<td>100 $</td>
<td>200 $</td>
<td>37700</td>
<td>141</td>
</tr>
<tr>
<td>2</td>
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<td>10</td>
<td>D</td>
<td>10</td>
<td>120</td>
<td>1200</td>
<td>38900</td>
<td>131</td>
</tr>
</tbody>
</table>

### Identifying activities for 3\textsuperscript{rd} compression cycle

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</tr>
</thead>
<tbody>
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<td>A</td>
<td>D</td>
</tr>
<tr>
<td>B</td>
<td>200 $</td>
</tr>
<tr>
<td>F</td>
<td>300 $</td>
</tr>
<tr>
<td>E</td>
<td>D</td>
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</table>
### Summary of the 3rd compression cycle

<table>
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<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
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<td>--</td>
<td>37500</td>
<td>143</td>
</tr>
<tr>
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<td>A</td>
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<td>∞</td>
<td>2</td>
<td>100 $</td>
<td>200 $</td>
<td>37700</td>
<td>141</td>
</tr>
<tr>
<td>2</td>
<td>H</td>
<td>10</td>
<td>∞</td>
<td>10</td>
<td>120</td>
<td>1200</td>
<td>38900</td>
<td>131</td>
</tr>
<tr>
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### Identifying activities for 4th compression cycle

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<th>E</th>
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<td>∞</td>
<td>∞</td>
<td>300</td>
<td>∞</td>
</tr>
</tbody>
</table>
Project network

A: 1 10 11
B: 11 15 26
C: 11 40 51
D: 51 30 81
E: 86 40 26
F: 26 55 81
Summary of the 4th compression cycle

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Activity to shorten</th>
<th>Can be shortened</th>
<th>NIL</th>
<th>Days shortened</th>
<th>Cost per day</th>
<th>Cost per cycle</th>
<th>Total cost</th>
<th>Project duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>--</td>
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<td>--</td>
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<td>1</td>
<td>A</td>
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<td>2</td>
<td>H</td>
<td>10</td>
<td>D</td>
<td>10</td>
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<td>38900</td>
<td>131</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
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<td>41400</td>
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</tbody>
</table>

Project Monitoring & Control

Earned Value Analysis
Project Monitoring and Control

- Project control can be divided as follows:

- First: monitoring, understanding what is happening on a project. Obtaining information about project by some means.

- Second: Control, is the action taken in response to the information obtained.

Monitoring Project status

- Some means of Information retrieval:

  - Photography
  - Check-off lists (Status Reports)
  - Bar chart.
## Check-off list

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>Scheduled Start</th>
<th>Scheduled Finish</th>
<th>Actual Start</th>
<th>Actual Finish</th>
<th>%</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.01</td>
<td>5th floor columns</td>
<td>24</td>
<td>28</td>
<td>26</td>
<td>30</td>
<td>50</td>
<td>Weather delay</td>
</tr>
<tr>
<td>14.02</td>
<td>5th Floor roof slab</td>
<td>32</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

## Earned Value Analysis
Earned Value Analysis

- Controlling project time without considering the cost may lead to cost overrun.

- So, Project time and cost **should not** be controlled separately.

- The Earned Value (EV) concept solve the dilemma

---

Input data for Earned Value Analysis

- Activity schedule, usually in the form of a bar chart.
- Budgeted cost for each activity.
- Percent complete for each activity.
- Cost to date for each activity.
Earned Value (EV)

In this techniques three measurements are important:

1. Budgeted cost of work Scheduled (BCWS) or known as (planned value PV)
2. Budgeted cost of work performed (BCWP) or known as (Earned Value EV)
3. Actual cost of work performed (ACWP) or (Actual Cost AC)
**ACWP**

Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8
---|---|---|---|---|---|---|---
20,000 | | | | | | | 
15,000 | | | | | | | 
10,000 | | | | | | | 
5,000 | | | | | | | weekly ac
9,000 | 2,000 | 2,500 | 2,500 | 1,000 | 
9,000 | 11,000 | 13,500 | 16,000 | 17,000 | 

**Earned Value Analysis**

Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8
---|---|---|---|---|---|---|---
20,000 | | | | | | | 
15,000 | | | | | | | 
10,000 | | | | | | | 
5,000 | | | | | | | bcws
10,000 | 12,000 | 14,000 | 16,000 | 18,000 | 19,000 | 20,000 | 

bcwp
9,000 | 10,000 | 12,000 | 14,000 | 15,000 | 
9,000 | 11,000 | 13,500 | 16,000 | 17,000 | 

acwp
Earned Value Key Values

- Budgeted Cost at Completion (BAC): The original cost estimate.
- Estimated at Completion (EAC): Is the forecast of the total actual cost required to complete the project based on performance to date and estimates of future.
Budgeted cost of work Scheduled (BCWS) (Planned Value PV)

- The cost estimate based on the original schedule.

Budgeted cost of work performed (BCWP) (Earned Value EV)

- Is a measure of the value of what you have actually accomplished. According to your original activities cost estimate.

- It is the value of the work you have achieved at any point in time.
Actual cost of work performed (ACWP) (Actual Cost AC)

The Actual cost is what you have actually paid to accomplish the work.

Cost Variance (CV)

The difference between the value of the work performed based on your schedule calculations, and the actual cost you have paid.

\[ CV = BCWP - ACWP \]
\[ = EV - AC \]
Schedule Variance (SV)

- The difference between the BCWP and the BCWS

- \[ SV = BCWP \setminus BCWS = EV \setminus PV \]

- It is important to note that negative variances is bad indication to the project performance.

CV & SV

Cost

Time

Current Time

BCWS

ACWP

SV

BCWP

EV

Cost Performance Index (CPI)

- Is a measure of project progress in terms of spending project's budget. It is the ratio of the value of the work that has been performed to the actual cost.

- CPI = BCWP/ACWP
  = EV / AC

- If your CPI > 1 under budget, CPI < 1 over budget

Schedule Performance Index (SPI)

- Is a measure of project progress in terms of project schedule. It is the ratio of performed work to the work that has been planned.

- SPI = BCWP/BCWS
  = EV / PV

- If your SPI > 1 ahead of schedule, SPI < 1 Behind Schedule
Project Percent Complete (Pct)

- Measures the project progress in term of percentage.

\[ PC = \left(\frac{EV}{BAC}\right) \times 100\% \]

The Big Concern (EAC)

- The EAC is the estimated Cost At Completion

\[ EAC = ACWP + (BAC - BCWP) \]

OR,

\[ EAC = \frac{BAC}{CPI} \]
Variance at Completion (VAC)

\[ \text{VAC} = \text{BAC} - \text{EAC} \]