CENG 6101 Project Management

Scheduling of Non-Repetitive Construction Projects: CPM

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TO DO: Scheduling

1. How do we start?
2. How do we select activities?
3. Determining activity durations?
4. Precedence diagramming for overlapping activities.
5. How to assess predecessor relationships?
6. CPM calculations

Review of Planning and Scheduling

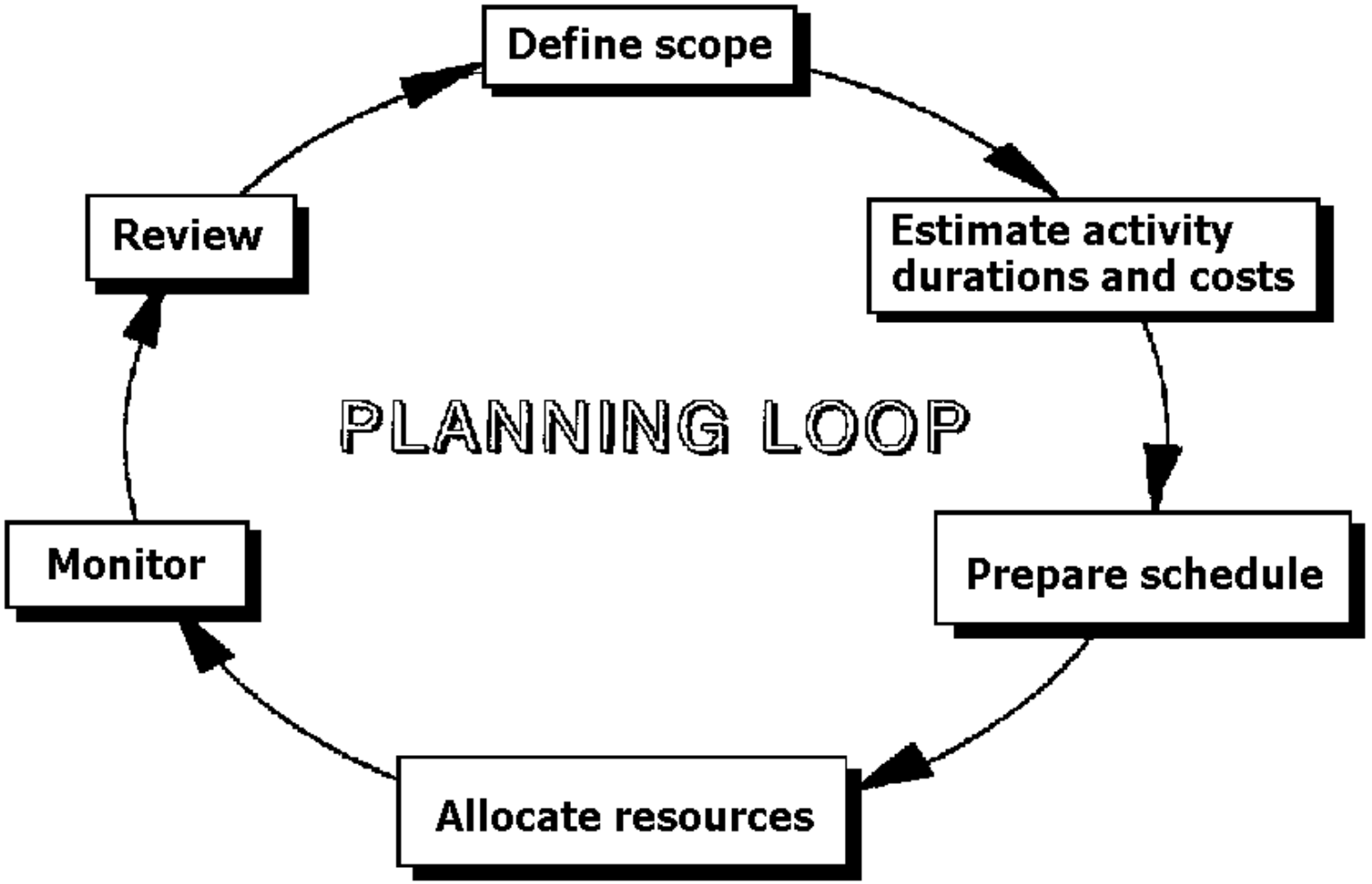
In previous lecture, we examined:

- Objective and function of planning
- Steps in planning and scheduling a project
- Purposes of schedules

In this lecture, we will examine:

- Techniques of planning and scheduling
- Critical Path Method - review

Planning Loop



Review of Planning and Scheduling

Planning and Scheduling Techniques:

- Master Control Schedule
  - Network describing broad scope of project, from which sub networks may be derived
- Checklists
  - Identify tasks to be undertaken, who is responsible for undertaking task, target completion dates

Review of Planning and Scheduling

Checklist:

ITEM	BY WHOM	BY WHEN	COMMENTS
General/Procedural • Contract Document Review • Objectives Procedures & Meetings • Document Control			
Timing Schedules • Preliminary Planning • Pre-Construction Planning • Construction Planning			
Financial/Contractual • Head Contract Administration • Sub-contract and Purchasing Administration • Cost Planning and Reporting			
Technical • Design Drawings & Specifications • Scope of Works • Engineering			
Site Operations • Staffing and Labour Procurement • Mobilisation • Site Administration			

Review of Planning and Scheduling

- Bar charts (Gantt charts)
  - Simple – time-scaled display of activities
  - Linked – show logic between activities
- Milestone schedules
  - Highlight key dates
  - Milestone events typically shown on a bar chart as:

  - Milestones should represent critical events

BAR CHARTS

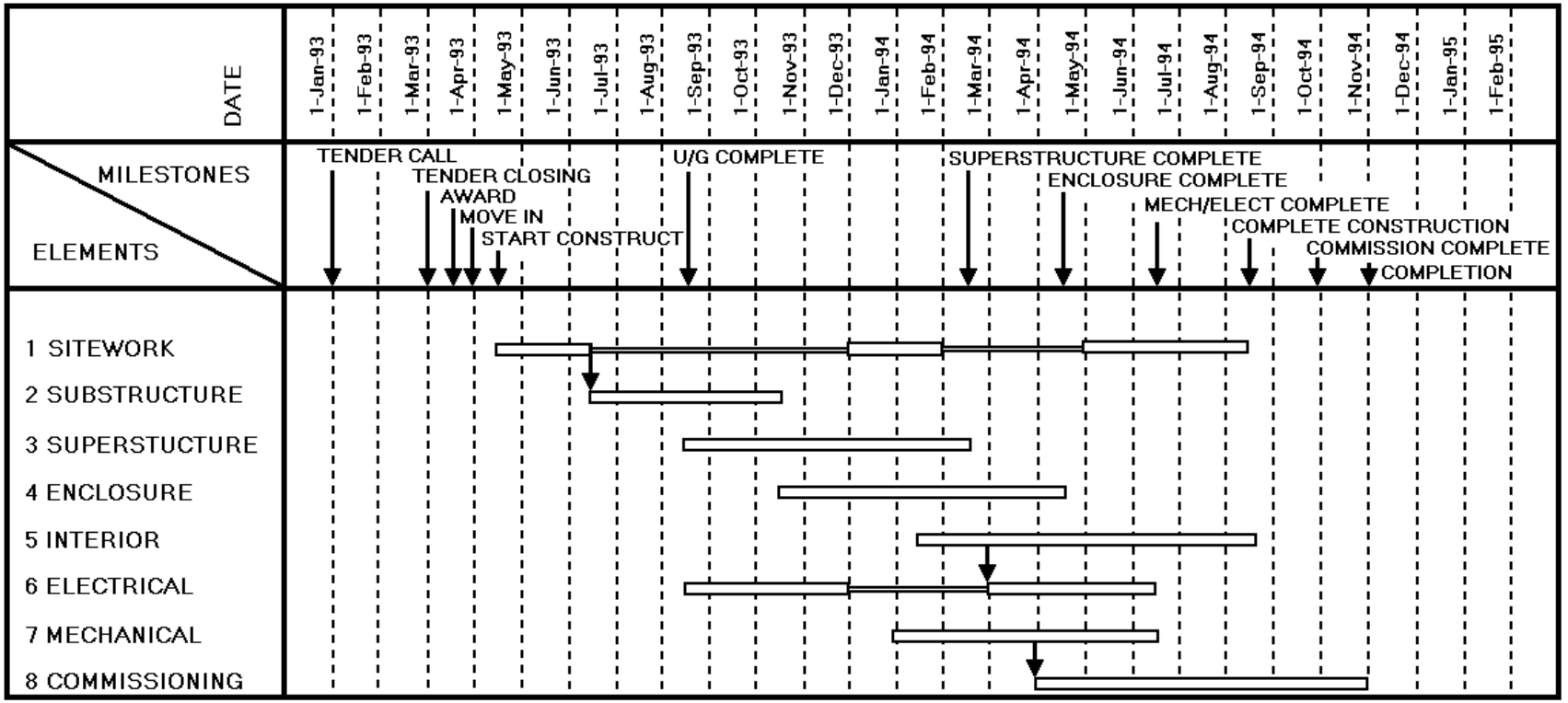


Figure 4.1 Simple Bar Chart

Review of Planning and Scheduling

- Network diagrams
  - CPM (critical path method): activity on arrow, activity on node
  - PERT – probabilistic activity durations
- Line of balance
  - For repetitive construction projects

Activity on Arrow Diagram

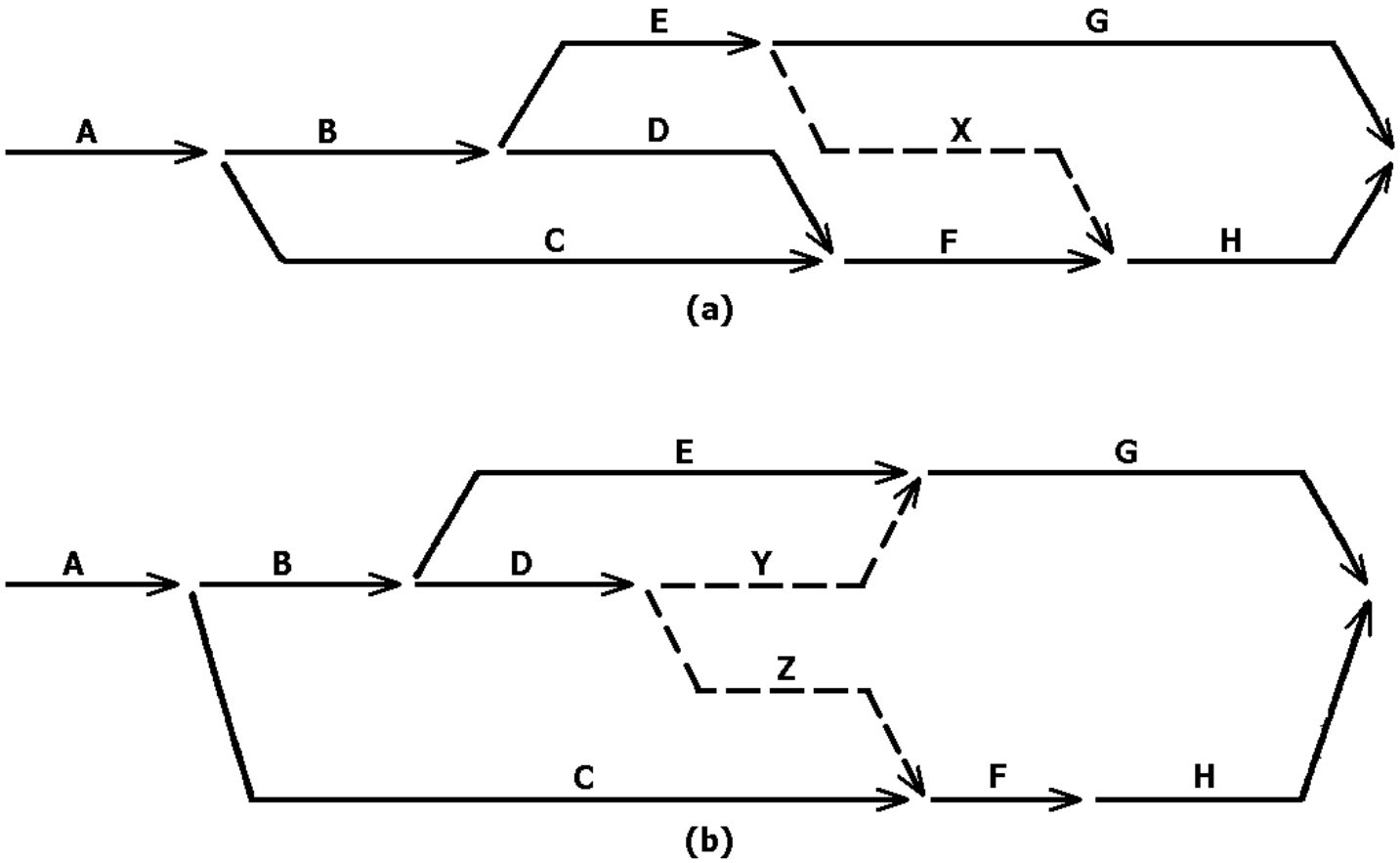


Figure 5.3 Networks Illustrating the Use of Dummy Activities

Activity on Arrow Diagram

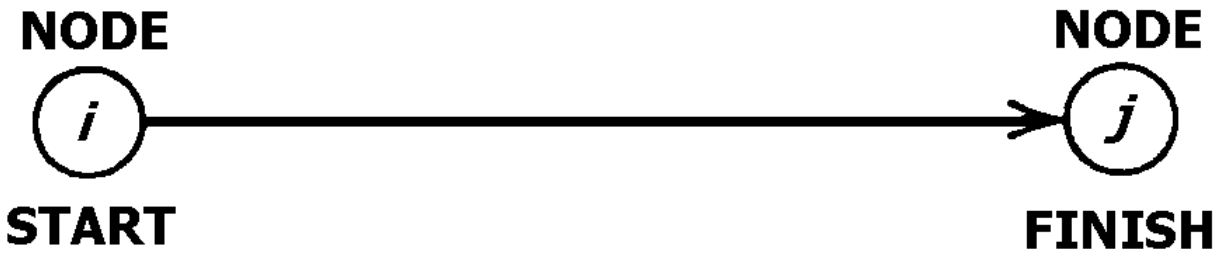


Figure 5.5 Nodes Using *i-j* Notation

Figure 5.15 AOA Node Symbols

Activity on Node Diagram

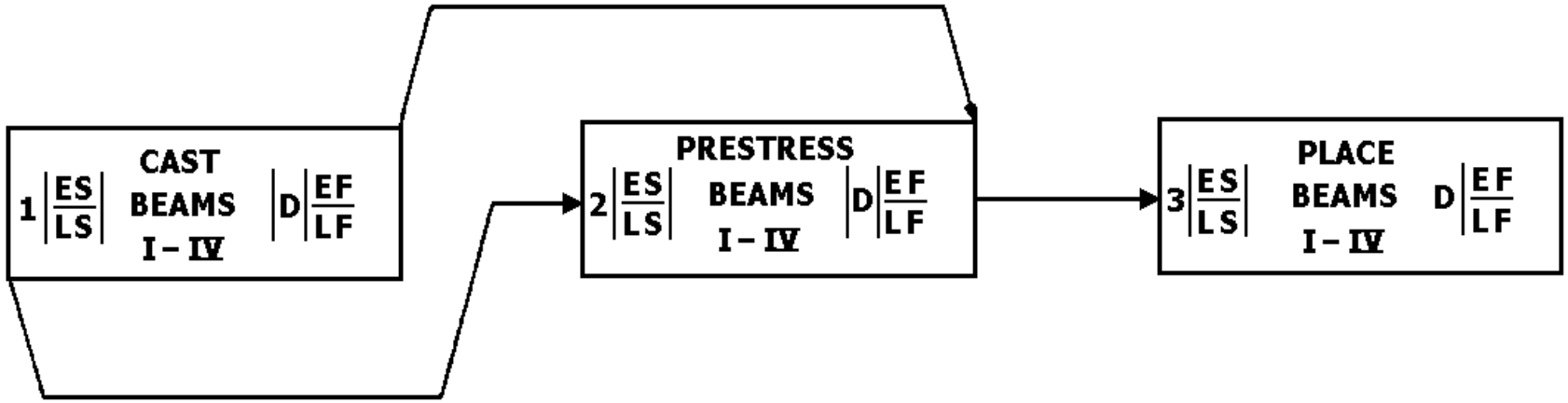


FIGURE 7.2 **PDM Model for Production on Beams**

Activity on Node Notation

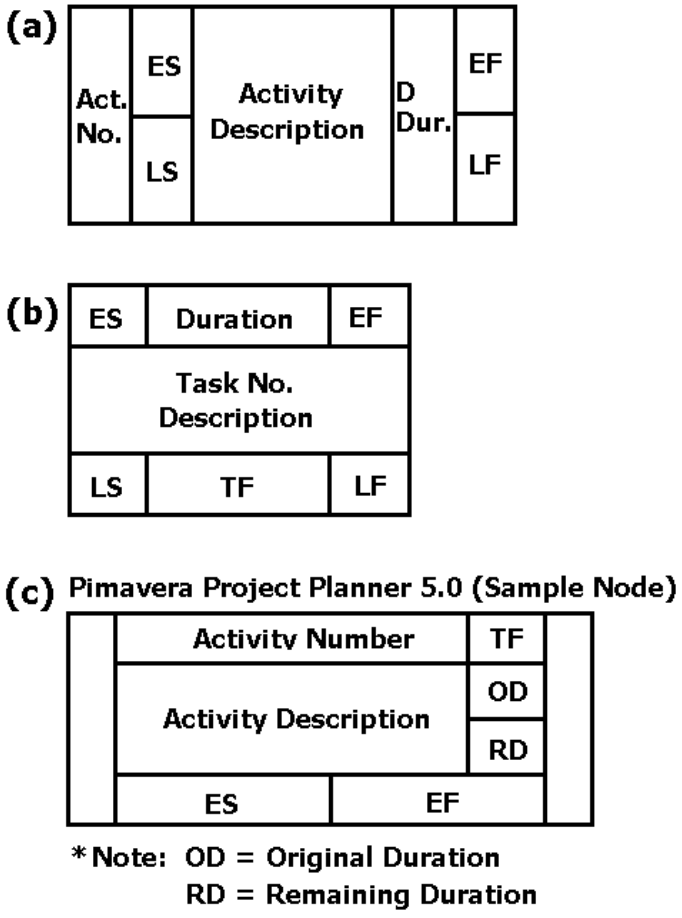
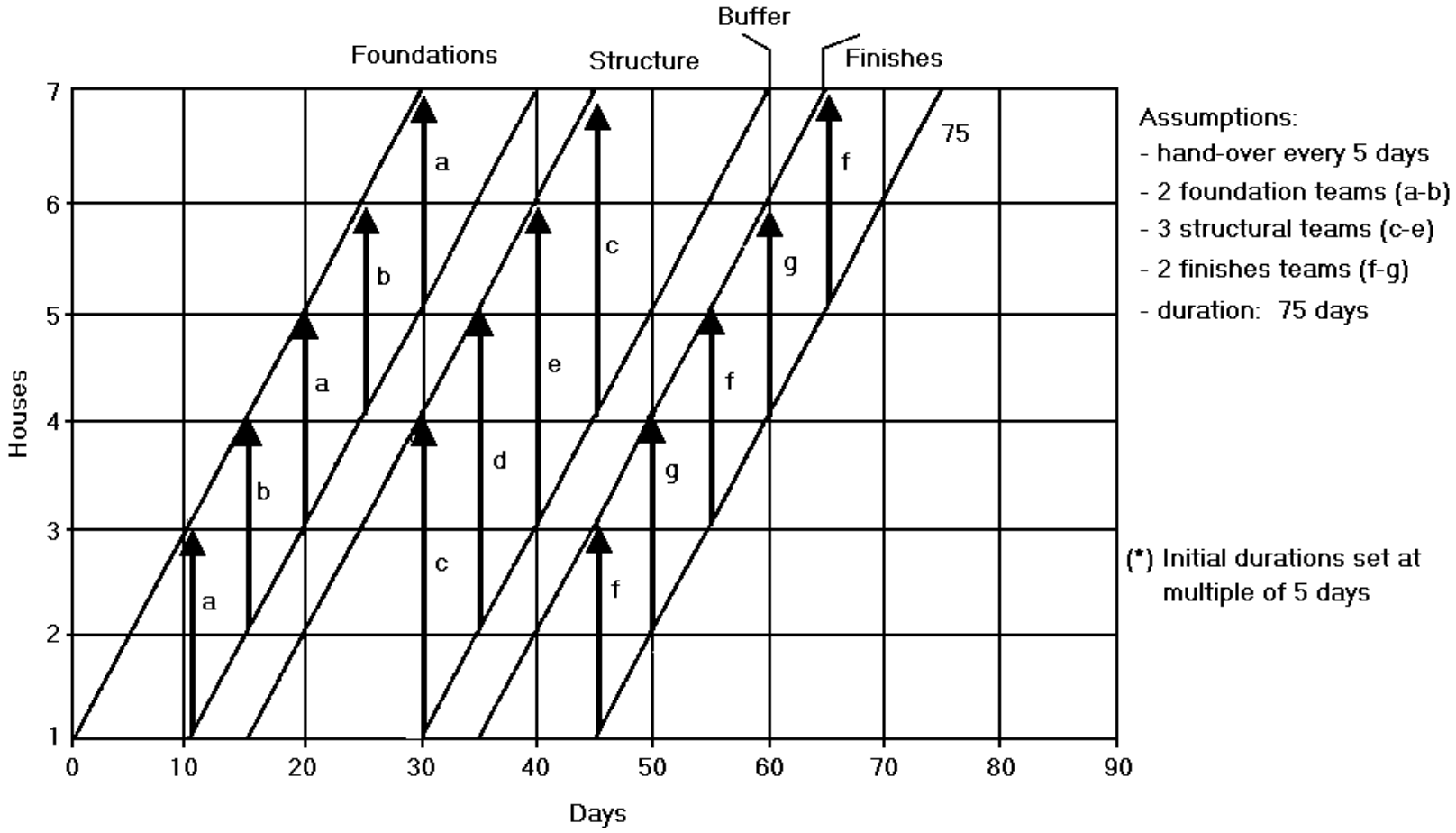


FIGURE 7.3 Example of Nodes

Line of Balance Diagram



Line of balance diagram

Techniques for Construction Network Scheduling

How do we start?

- Create a plan for constructing the project by defining:
  - Tasks to be accomplished
  - How they will be accomplished
  - Time frame for accomplishing them
- Determine types of resources needed
  - → Determined in part by construction methods chosen
  - e.g. building roof – either trusses – cost more and crane required OR rafters and joists – more workers and time

Planning and Scheduling Non-repetitive Construction Projects

Five types of resources:

Material, Workers (labour), Equipment, Money, Time

- Planner must schedule each resource – create:

  Time (network) schedule
  Material delivery
  Equipment availability
  Worker (labour) availability
  Money (cash-flow) availability

- Make sure all resources available to meet time (network) schedule of project

  → We will focus on time (network) schedule

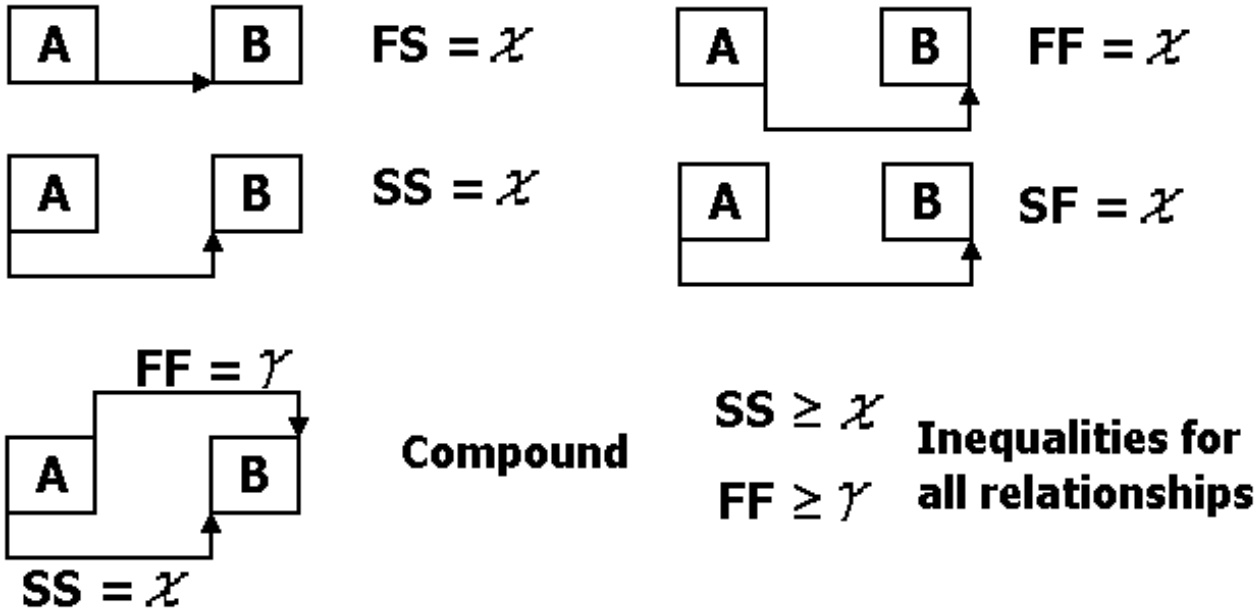
Planning and Scheduling Non-repetitive Construction Projects

How do we select activities?

- Based on experience, to reflect unit of work that is easily distinguishable and fits into scheduling technique – any activity you plan, you must be able to monitor at that level of detail

1. Select activities and specify logic relationship.
2. Create list of activities and predecessors (including procurement, permits, site access etc.).

3. Define interrelationships between activities



Assumption: Activities are uninterruptable – once they start, must finish

4. Determine opportunities for overlapping activities

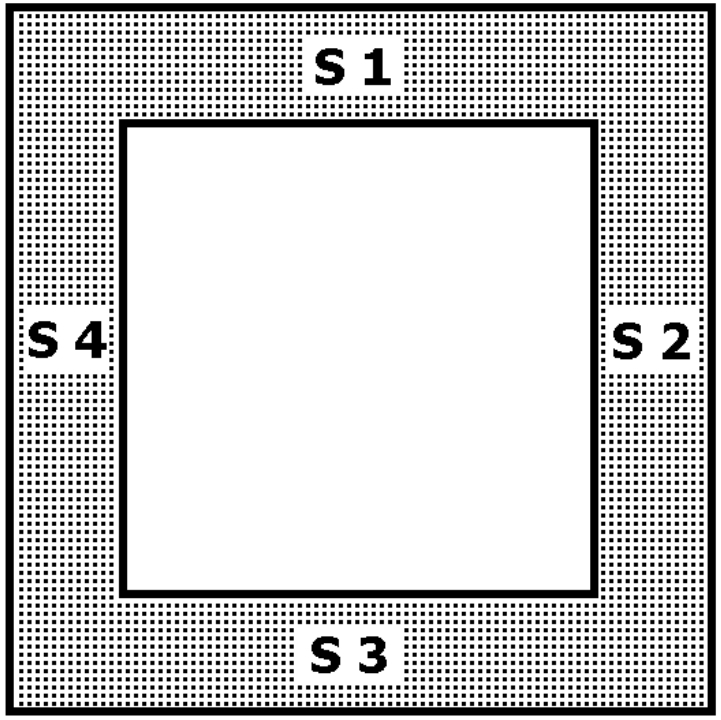


FIGURE 2-2 Overlapping Activities

Example:

Activities to build a footing

A. Excavate using backhoe
B. Build formwork
C. Place rebar
D. Place concrete

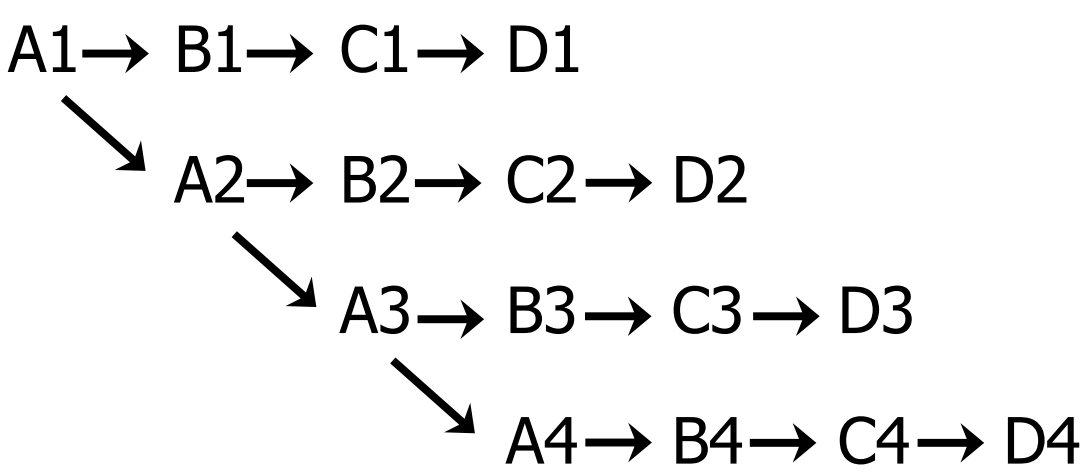
Planning and Scheduling Non-repetitive Construction Projects

A → B → C → D

or

S1 → S2 → S3 → S4

Each side involves activities A, B, C and D



5. Determine duration units that best fit majority of activities on schedule
   Construction: workdays
   Manufacturing: shifts
   Design work: calendar days, weeks, or months
   - For network (CPM) calculations, need all activity durations expressed in same units (unless using different calendars); may have to convert some

   e.g. delivery of materials in 30 calendar days

   → convert to number of working days (depends on number of days worked per week and holidays in month)

6. Determine activity durations

Sources of information:

1. Past (historical) records
2. Standards and/or cost guides
3. Supervisors/field workers
4. Experience

Time for an activity (activity duration):

Planning and Scheduling Non-repetitive Construction Projects

Activity duration

$$T = A + \frac{Q}{PL}$$

Setup or non-productive time

Scope (quantity)

L=Labour and/or equipment crew size

*P=Productivity

e.g. strip footing

Productivity	Type	Production rate (2-person crew) = PL
10 m/p-hour	Straight	160 m/day
5 m/p-hour	Irregular	80 m/day

*Productivity is output per unit of input for a "production unit". Could be determined by equipment, labour, design characteristics (i.e. maximum rate of concrete pour).

Trade off – in variables, increasing **L** (crew size) may not necessarily decrease **T** (time) if it leads to overcrowding and reduced productivity

Planning and Scheduling Non-repetitive Construction Projects

Activity durations determined by:

Quantity of work

Quantity & productivity of resources – labour, equipment

Technology (construction methods)

Complexity of work

Duration of workday/work week

Should there be a limit on activity durations?

- Minimum and maximum limit on durations to allow for effective monitoring
- Duration determined by how activity is defined
  e.g. build foundation – 60 days (difficult to control the work) vs place rebar piece # 1162 – 0.01 h (large network diagram, long time to update schedule)

Planning and Scheduling Non-repetitive Construction Projects

- Need compromise that maximises usefulness of schedule for control while minimising effort necessary to create and update schedule

  ~ 15 day maximum duration for activities in construction schedule

7. Account for weather and contingencies in schedule

- Add or subtract days for items such as
  - Expected weather
  - Expected interruption
  - Other contingencies (known or unknown delays which may or may not occur)

Planning and Scheduling Non-repetitive Construction Projects

e.g. for weather

- Estimate number of lost days of work due to poor weather for duration of project based on past records

e.g. previous season(s) for road works projects

- Distribute these days amongst activities in network schedule
  - Add a few shorter activities (for delays) and stagger them throughout project

Planning and Scheduling Non-repetitive Construction Projects

- Increase durations of all activities by a %
- Increase duration of activities most affected by bad weather (e.g. concrete work) and leave other activities (e.g. inside work) alone

– Since CPM schedules need updating, best approach is:

1. Draw CPM diagram and calculate.
2. Identify critical activities – determine project length.

3. Determine how critical activities affected by bad weather:
   - Cancelled
   - Slowed by x %
   - No effect
4. Estimate chance that those activities most affected by bad weather will fall during period when bad weather likely to occur.
5. Increase durations of activities that control project (critical activities) and most likely to be affected during life of project to absorb number of days of expected delay.

Planning and Scheduling Non-repetitive Construction Projects

- Use common sense for other contingencies

  e.g. vacations that make construction work hazardous or undesirable

- Can add an activity (called “wait”) in series with critical activities

- As schedule is updated, activities can be moved around as better information becomes available

8. Define the network logic

- Sequence activities in most cost-effective manner
- Need experience and knowledge of technology/construction methods
- Can use historical data/past projects
- Create a list of all activities and their predecessors
- Define the precedence relationships: FS, SS, FF, SF, compound
- Draw network diagram and perform CPM calculations

Critical Path Method (CPM)

1. Determine activities required to complete project
2. Estimate duration based on scope, crew size, shift length, productivity
3. Determine sequence of and relationship between activities
4. Draw Activity on Arrow (AOA) or Activity on Node (AON) diagram showing logic
5. Define project calendar

Critical Path Method (CPM)

6. Do forward pass: calculate early start (ES) and early finish (EF) times for each activity
7. Do backward pass: calculate late start (LS) and late finish (LF) times for each activity
8. Calculate total float (TF) and free float (FF)
9. Develop bar chart from network diagram
10. Assign resources to bar chart and develop resource histograms
11. Develop progress curve for project
12. Monitor performance and update schedule

Float

- Float, also know as slack, is spare time in sequence of events and is a product of the activity durations, sequences and dependencies in a network.

- Contingency, also know an buffer, is an allowance specifically added to a schedule or network to take account of unforeseen circumstances.

- Types of Floats:
  - Total, Free, Interfering , Independent, Intermittent, Negative, Terminal, Internal

Float

- Total Float
  - The amount of time an activity can be delayed without affecting the completion of the project.

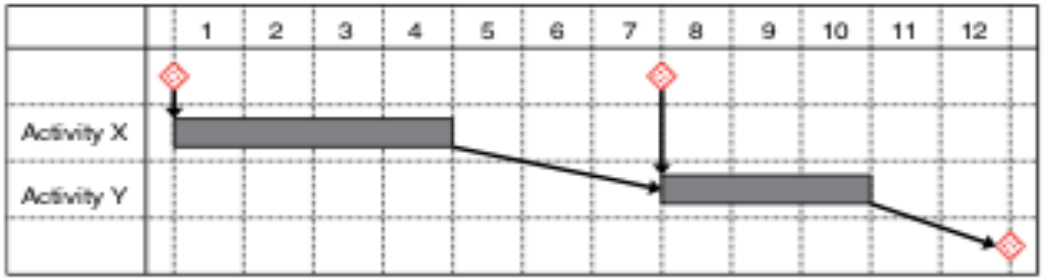


Figure 4.6 Activities scheduled at the earliest start dates.

Figure 4.7 Total float.

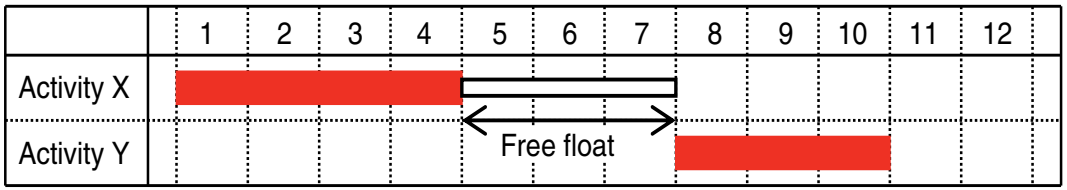
Figure 4.8 Total float fully utilised (activities at latest start dates).

Activity X

Total Float = 5 weeks

Float

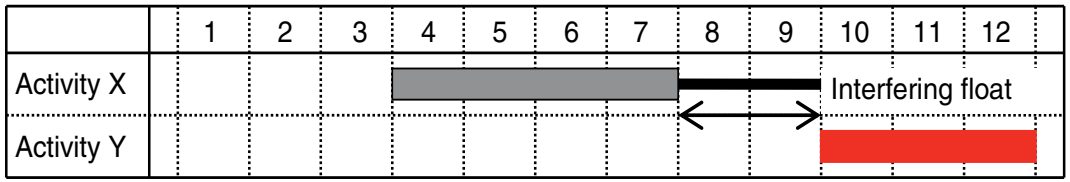
- Free Float
  - The amount of time an activity can be moved without affecting the completion of the project and without affecting the timing of any other activity



Activity X

Free Float = 3 weeks

- Interfering Float
  - Is the part of the total float, that, if used, will not affect the completion date of the project but will affect the start and/or completion of the following activities



Activity X

Free Float = 2 weeks

Float

- Independent Float
  - Specifically exist when preceding activities are scheduled at their latest dates and succeeding activities are scheduled at their earliest dates and the time available for the activity to be carried out exceeds its duration.

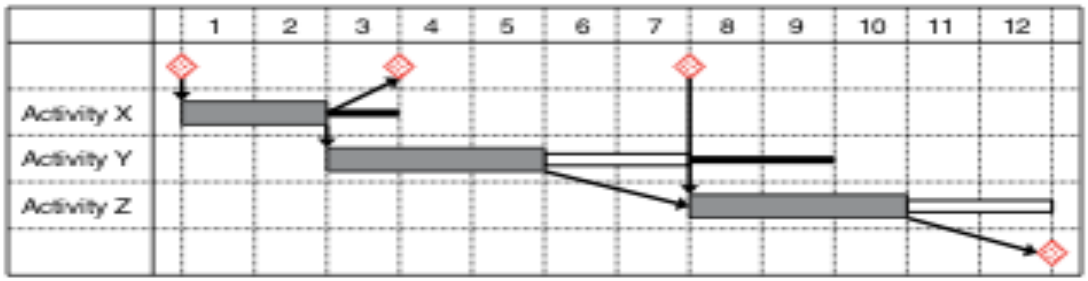


Figure 4.12 Activities at earliest dates: free float and interfering float.

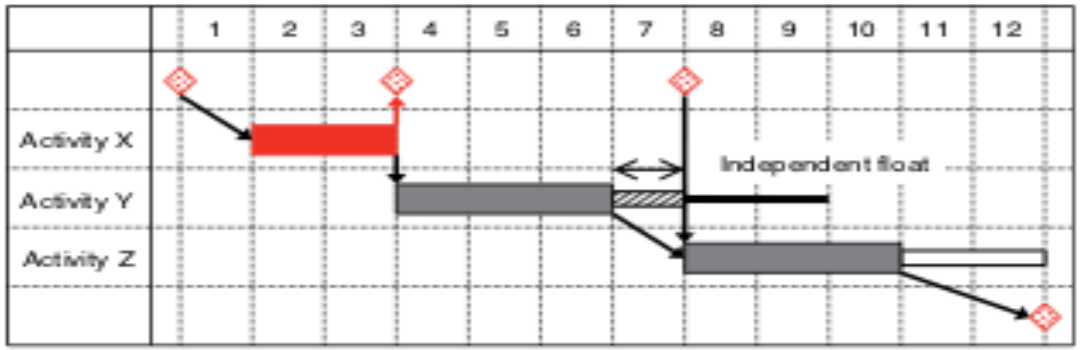


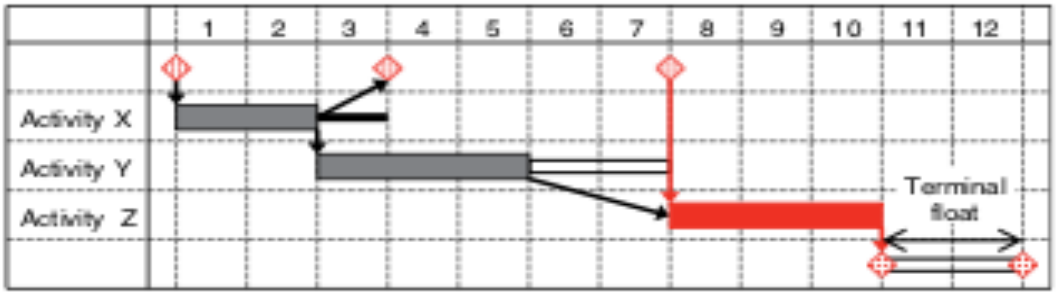
Figure 4.13 Independent float.

Activity Y

Independent Float = 1 weeks

Float

- Negative Float
  - If a project end date is constrained and the project falls into delay, then negative float will be generated
- Internal Float
  - Are added extra times into an activity duration to address uncertainties, is more of a contingency
- Terminal Float
  - Is the spare time in a programme between planned completion date and the contract completion date – the project is planned to complete early



Project

Terminal Float = 2 weeks

CPM Calculations

- CPM determines critical path for project = minimum time required to complete entire project (i.e., longest path or sequence of events through project)
- Let start times = beginning of day
- Let end times = beginning of next day

CPM Calculations

- Forward pass:
  - For first activity, ES = 0
  - ES = latest of EF of all predecessors to activity
  - EF = ES + duration of activity
- Backward pass:
  - For last activity, LF = EF
  - Since ES = 0 for first activity,
  - EF of last activity = project duration (number of working days)
  - LF = earliest of LS times of all successors to activity
  - LS = LF - duration of activity

CPM Calculations

- Floats:
- Total float (TF) = LS - ES = LF – EF
- Free float (FF) = ES of next earliest successor – EF of activity
- FF <= TF; if TF = 0, activity is critical and forms part of critical path; for critical activities, TF=FF=0

CPM Activity Relationships

- Used to overlap activities to reduce overall project duration
- Finish to Start (FS) = an activity can only start a specified amount of time after another finishes (e.g. concrete curing time)
- Start to Start (SS) = an activity can only start a specified amount of time after another starts (e.g. lead time between trenching and piping; done in parallel but trenching equipment must get out of way)

CPM Activity Relationships

- Finish to Finish (FF) = an activity can finish only a specified amount of time after another finishes (e.g. lag time between rough in electrical and drywall finishing)
- Start to Finish (SF) = an activity can finish only a specified amount of time after another starts (can be represented by others)
- Can have multiple simultaneous relationships (e.g. SS and FF)

Critical Path Method (CPM)

House Construction Project

Job Name	Description	Immediate Predecessors	Time (days)
a	Excavate, pour footers	—	4
b	Pour concrete foundations	*a*	2
c	Erect frame and roof	*b*	4
*d**	Lay brickwork	*c*	6
e	Install drains	*b*	1
f	Pour basement floor	*e*	2
g	Install rough plumbing	*e*	3
*h**	Install rough wiring	*c*	2
*i**	Install air conditioning	*c, f*	4
j	Fasten plaster and plaster board	*g, h, i*	10
k	Lay finished flooring	*j*	3
*l***	Install kitchen equipment	*k*	1
*m***	Install finished plumbing	*k*	2
n	Finish carpentry	*k*	3
o	Finish roofing and flashing	*d*	2
p	Fasten gutters and downspouts	*o*	1
q	Lay storm drains	*b*	1
*r**	Sand and varnish floors	*n, s*	2
s	Paint	*l, m*	3
*t**	Finish electrical work	*s*	1
u	Finish grading	*p, q*	2
v	Pour walks, and landscape	*u*	5

Critical Path Method (CPM)

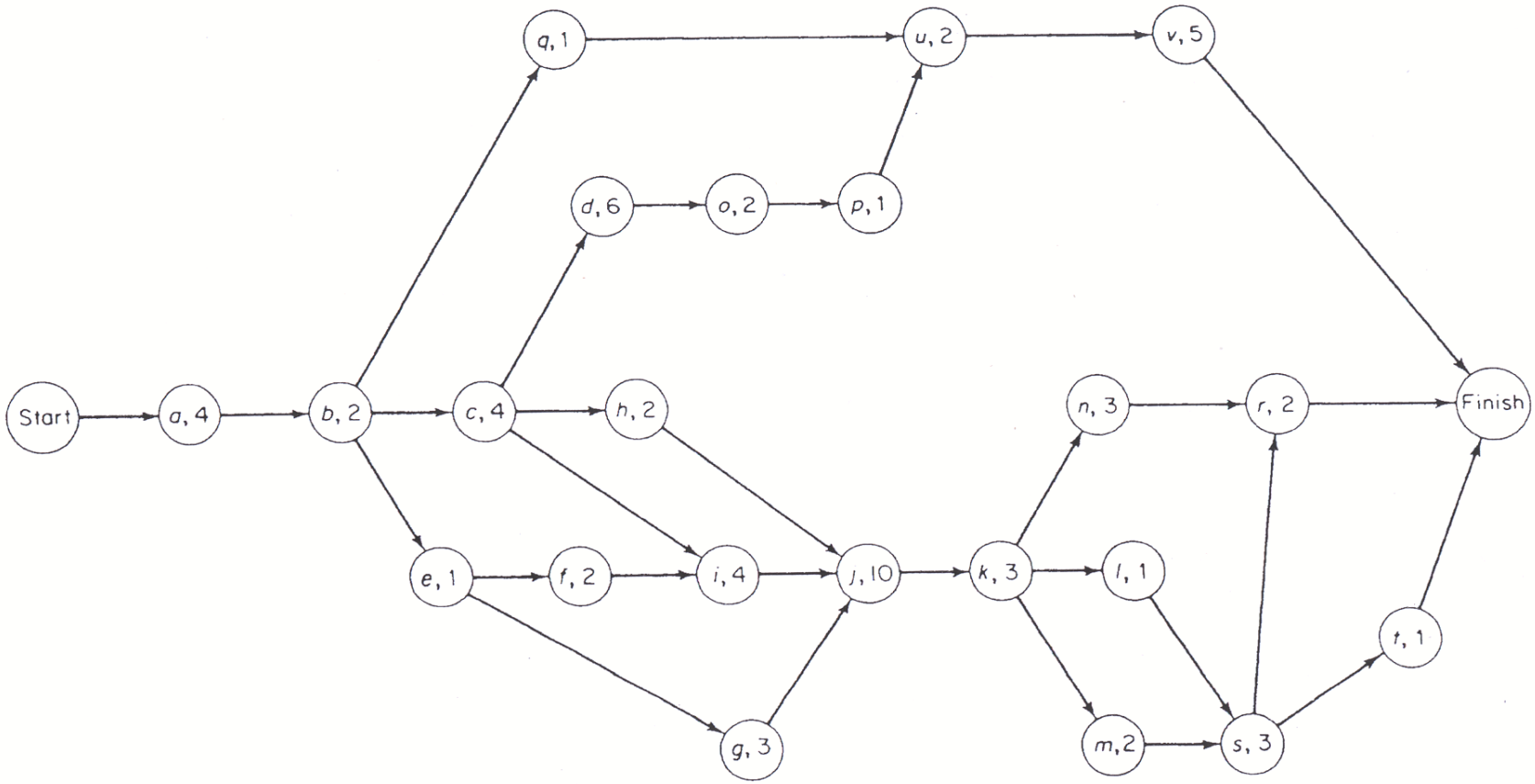


FIGURE 2-11. AON Diagram—House Construction Project

Critical Path Method (CPM)

House Construction Project

Job Name	Alternate	Immediate Predecessors	Time (days)
a	(1, 2)	—	4
b	(2, 3)	a	2
c	(3, 4)	b	4
d	(4, 5)	c	6
e	(3, 6)	b	1
f	(6, 7)	e	2
g	(6, 8)	e	3
h	(4, 8)	c	2
D_1 (dummy)	(4, 7)	c	0
i	(7, 8)	D_1, f	4
j	(8, 9)	g, h, i	10
k	(9, 10)	j	3
l	(10, 12)	k	1
D_2 (dummy)	(10, 11)	k	0
m	(11, 12)	D_2	2
n	(10, 13)	k	3
o	(5, 14)	d	2
p	(14, 15)	o	1
q	(3, 15)	b	1
D_3 (dummy)	(16, 13)	s	0
r	(13, 18)	D_3, n	2
s	(12, 16)	l, m	3
t	(16, 18)	s	1
u	(15, 17)	p, q	2
v	(17, 18)	u	5

Critical Path Method (CPM)

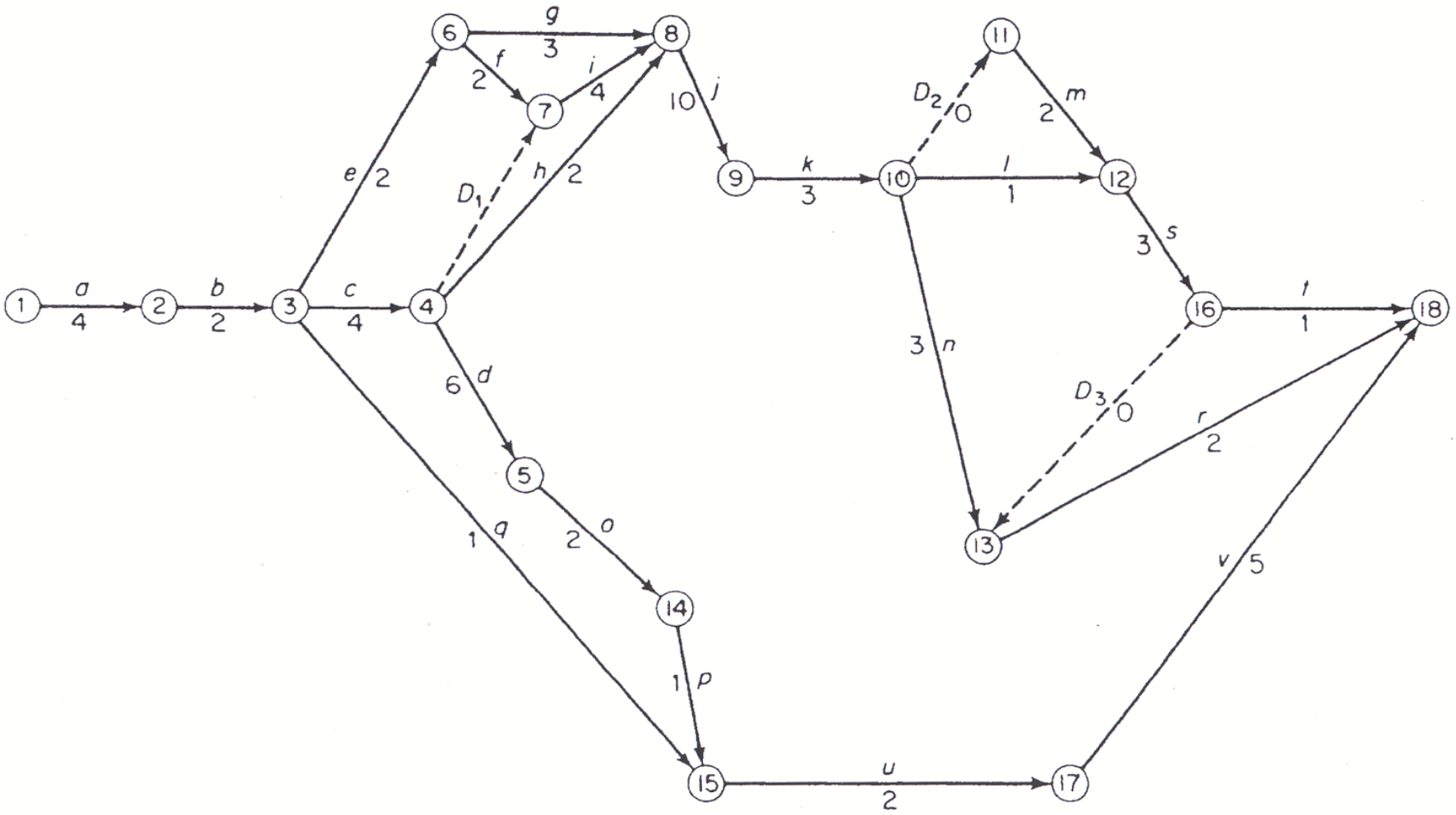


FIGURE 2-12. Arrow Diagram—House Construction Project

SS, FF, SF, FS

Can apply lead-lag factor to relationship

= amount of time one activity must lead or lag another

= amount of time that must expire before action expressed by relationship can occur

Precedence Relationships: Lead and Lag

When activity *i* precedes activity *j*

formwork → pour concrete

FF_{ij} = *j* finishes this amount of time after *i* finishes

= lag time for finish-to-finish relationship

excavation → formwork

SS_{ij} = activity *i* starts this amount of time earlier than start of activity *j*

= lead time for start-to-start relationship

Precedence Relationships: Lead and Lag

pour concrete → strip formwork (curing time)

FS_{ij} = activity *j* starts this amount of time after *i* finishes

= lag time for finish-to-start relationship

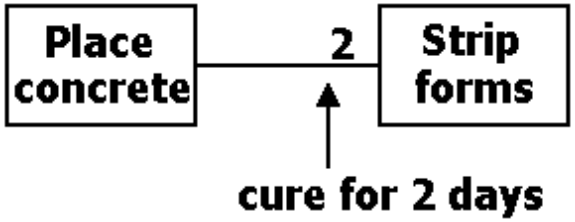
rough-in electrical → drywall

SF_{ij} = activity *i* starts this amount of time earlier than *j* finishes

= lead time for start-to-finish relationship

Examples

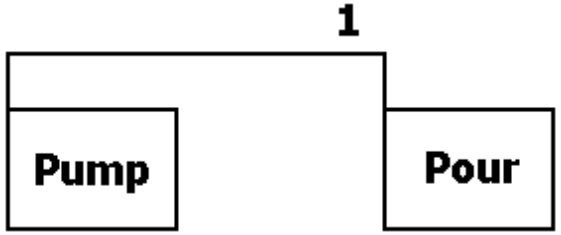
FS = 2



SS = 1

– Parallel activities but one must start before the other

e.g. pump a pit 1 day before starting concrete pour and keep pumping while pouring

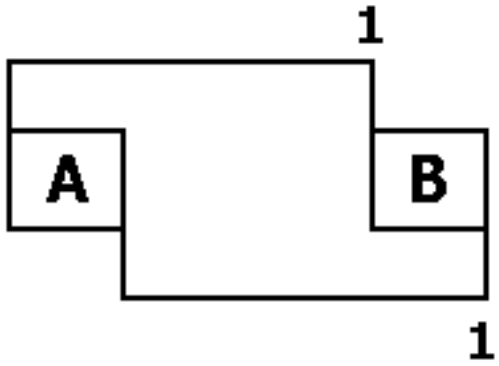


SS = 1 and FF = 1

e.g. A: Clear and grub – 4 days

B: Lay out site – 4 days

Want to start laying out site 1 day after start clearing, but can not finish until 1 day after clearing finishes



How to assess predecessor relationships?

1) Preceding activities.

Which activities must be finished before this activity may begin? What is the time lag? (Finish to start)

Which activities must be started before this activity may begin? What is the lead time? (Start to start)

Which activities must be finished before this activity may be completed? What is the lag time? (Finish to finish)

Which activities must be started before this activity is completed? What is the lead time? (Start to finish)

2) Succeeding activities.

Which activities can begin after the finish of this activity? What is the time lag? (Finish to start)

Which activities can begin after the start of this activity? What is the lead time? (Start to start)

Which activities can be completed after the finish of this activity? What is the lag time? (Finish to finish)

Which activities can finish after the start of this activity? What is the lead time? (Start to finish)

3) Concurrent activities.

Which activities can be carried out at the same time?

(Start to start equals zero, that is SS = 0 in this case.)

CPM Calculations – Forward Pass

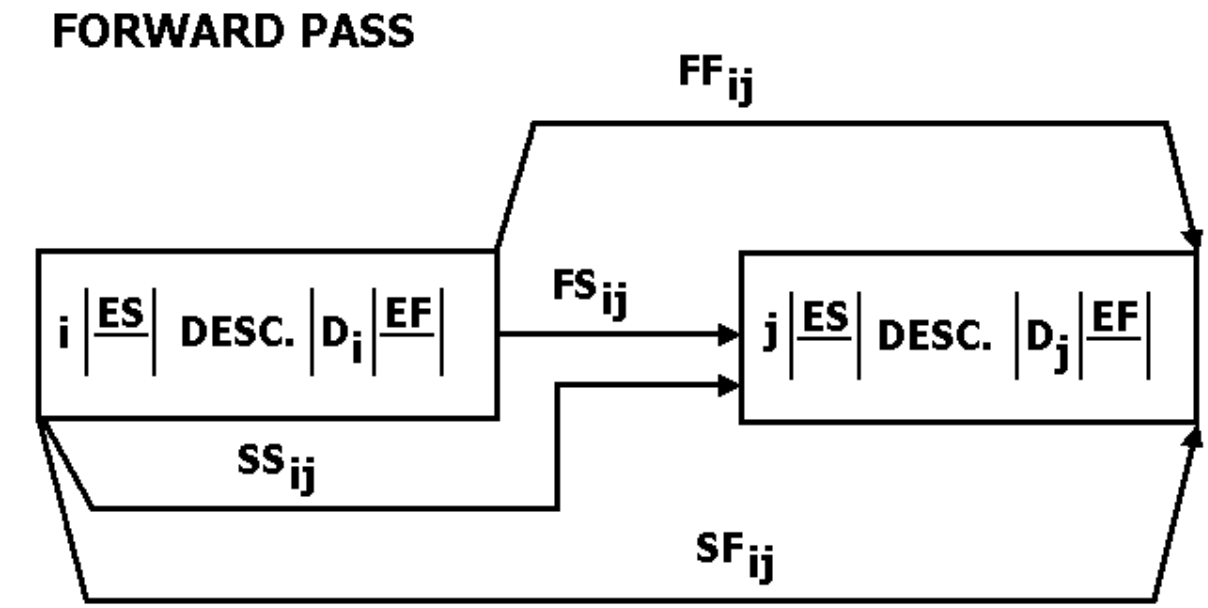


FIGURE 7.4 Lead/Lag Relationships for Forward Pass

CPM Calculations – Backward Pass

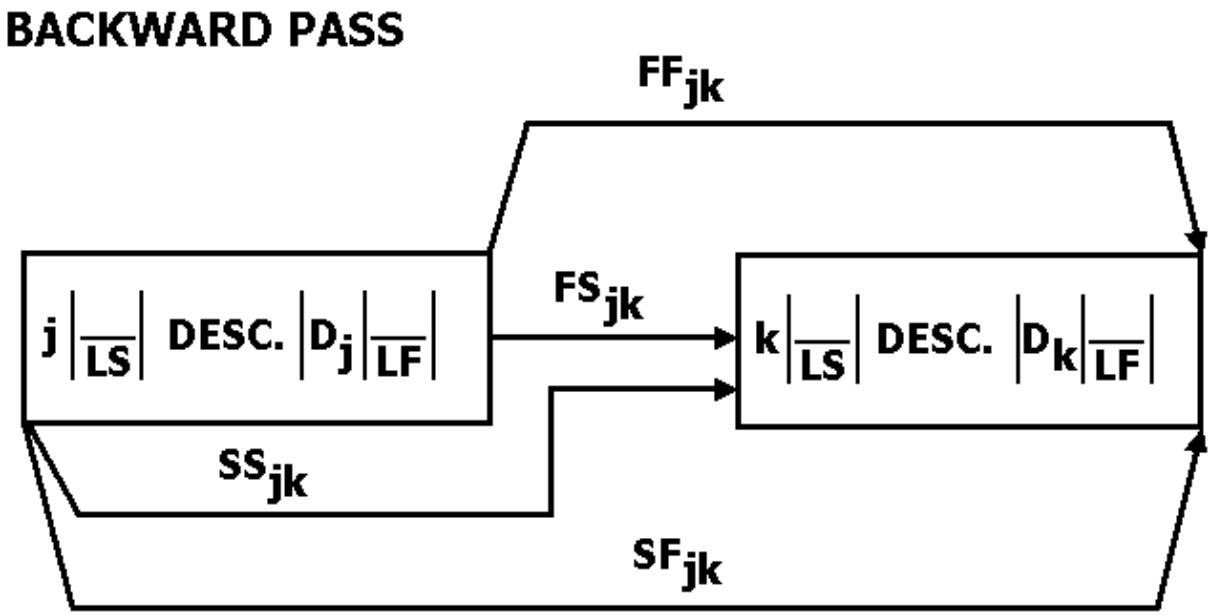


FIGURE 7.5 Lead/Lag Relationships for Backward Pass

Planning and Scheduling Non-repetitive Construction Projects

Forward Pass – ES and EF

- Predecessors of activity being analysed have subscript **i**
- Activity being analysed has subscript **j**

Backward Pass – LS and LF

- Successors of activity being analyzed have subscript **k**
- Activity being analysed has subscript **j**

When more than one arrow incident on an activity, greatest value taken on forward pass, least value taken on backward pass

LF = earliest completion time for entire project

$\therefore$ EF = LF on terminal (last) activity

Forward Pass (assumes activities can be interrupted)

$$ES_j = \begin{cases} ES_i + SS_{ij} \\ \text{or} \\ EF_i + FS_{ij} \end{cases}$$

Whichever is greater

$$EF_j = \begin{cases} EF_i + FF_{ij} \\ \text{or} \\ ES_i + SF_{ij} \\ \text{or } ES_j + D_j \end{cases}$$

Whichever is greater

If there is neither FS_{ij} nor SS_{ij} and activity can not be split, then

$$ES_j = EF_j - D_j$$

And if there is no FS_{ij} and if activity can be split, then

$$ES_j = \text{project start time}$$

Do not consider a given constraint if that particular relationship does not apply

Backward Pass (assumes activities can be interrupted)

$$LF_j = \begin{cases} LF_k - FF_{jk} \\ \text{or} \\ LS_k - FS_{jk} \end{cases}$$

Whichever is smaller

$$LS_j = \begin{cases} LS_k - SS_{jk} \\ \text{or} \\ LF_k - SF_{jk} \\ \text{or } LF_j - D_j \end{cases}$$

Whichever is smaller

If there is neither FF_{jk} nor FS_{jk} and activity can not be split, then

$$LF_j = LS_j + D_j$$

If activity can be split, then

$$LF_j = \text{project completion time}$$

- Uninterruptable activities are those that can not be split
- Interruptible activities can be interrupted and resumed

4. Float – Critical Path

Start float = SF = LS – ES

Finish float = FF = LF – EF

For uninterrupted activity SF = FF

Total float = TF = LF – EF

TF = LS – ES

} Equal for uninterruptable activity

Critical Activity: (no start float)

1. ES = LS (no finish float)
2. EF = LF

   (TF = 0)
3. LF – ES = D

Value of lead-lag factor can be given in time units or as a % of preceding or succeeding activity's duration

e.g.

SS_{ij} = 10% → Activity *j* can not start until activity *i* is 10% complete

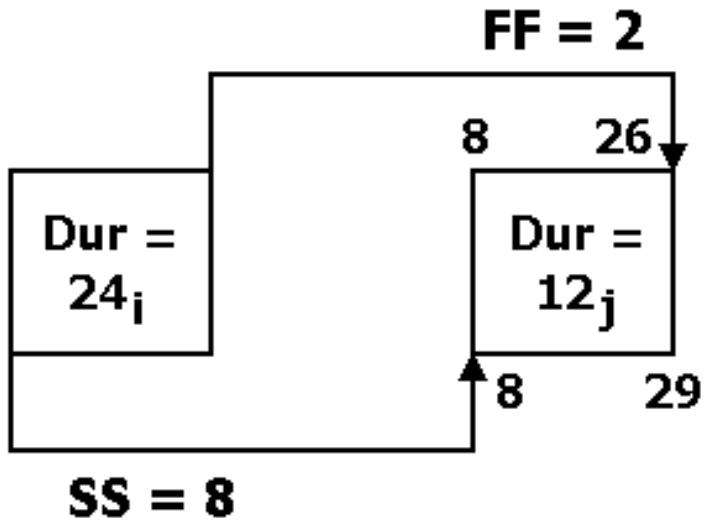
FS_{ij} = 25% → Activity *j* can start after completion of activity *i* and lag time of 25% of duration of activity *i*

FF_{jk} = 5% → Activity *k* can only finish after completion of activity *j* and a lag time of 5% of activity *k*'s duration

FF_{jk} = % of either *j* or *k*'s duration, depending on logic intended

- Better to use number of days for lead/lag relationships

- Scheduling software useful in doing network calculations with different precedence relationships and lead-lag factors



Activity *j* can not finish until 2 days after *i* finishes. i.e. conduits in walls – can not finish placing conduits in walls until walls are complete

If activity *j* can not be interrupted then it can not start until it can proceed until it is finished (to respect FF constraint)

ES = 8 EF = 26

LS = 8 LF = 29

(LS and LF dates based on successors)

Implies that the activity is interruptible, but these are planning boundaries only → you can still execute project as you wish

ES is earliest possible start and

EF is earliest possible finish

3 possibilities to meet these dates:

1. Delay activity *j* and start it later than ES (if LS allows you to – not in this case)
2. Interrupt the activity – most activities are interruptible
3. Use fewer resources to slow activity down and increase its duration

Critical Path Method (CPM)

House Construction Project

Job Name	Description	Immediate Predecessors	Time (days)
a	Excavate, pour footers	—	4
b	Pour concrete foundations	*a*	2
c	Erect frame and roof	*b*	4
*d**	Lay brickwork	*c*	6
e	Install drains	*b*	1
f	Pour basement floor	*e*	2
g	Install rough plumbing	*e*	3
*h**	Install rough wiring	*c*	2
*i**	Install air conditioning	*c, f*	4
j	Fasten plaster and plaster board	*g, h, i*	10
k	Lay finished flooring	*j*	3
*l***	Install kitchen equipment	*k*	1
*m***	Install finished plumbing	*k*	2
n	Finish carpentry	*k*	3
o	Finish roofing and flashing	*d*	2
p	Fasten gutters and downspouts	*o*	1
q	Lay storm drains	*b*	1
*r**	Sand and varnish floors	*n, s*	2
s	Paint	*l, m*	3
*t**	Finish electrical work	*s*	1
u	Finish grading	*p, q*	2
v	Pour walks, and landscape	*u*	5

Critical Path Method (CPM)

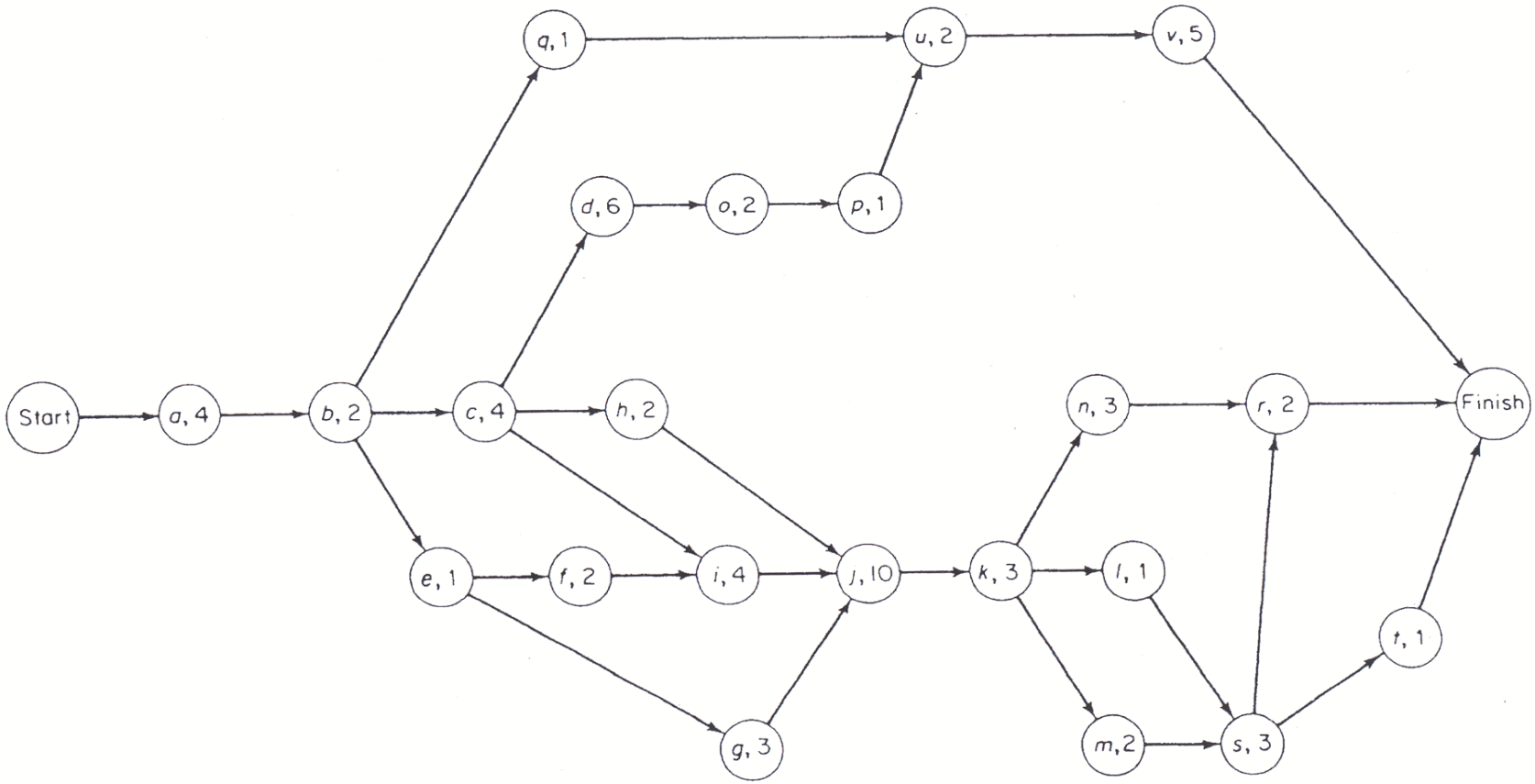


FIGURE 2-11. AON Diagram—House Construction Project

Critical Path Method (CPM)

CPM Example

Job Name	ES, EF	LS, LF	TF	FF
a	0, 4	0, 4	0	0
b	4, 6	4, 6	0	0
c	6, 10	6, 10	0	0
d	10, 16	18, 24	8	0
e	6, 7	7, 8	1	0
f	7, 9	8, 10	1	0
g	7, 10	11, 14	4	4
h	10, 12	12, 14	2	2
i	10, 14	10, 14	0	0
j	14, 24	14, 24	0	0
k	24, 27	24, 27	0	0

Critical Path Method (CPM)

CPM Example

Job Name	ES, EF	LS, LF	TF	FF
l				
m				
n				
o				
p				
q				
r				
s				
t				
u				
v				

Critical Path Method (CPM)

CPM Example: Solution

Job Name	ES, EF	LS, LF	TF	FF
a	0, 4	0, 4	0	0
b	4, 6	4, 6	0	0
c	6, 10	6, 10	0	0
d	10, 16	18, 24	8	0
e	6, 7	7, 8	1	0
f	7, 9	8, 10	1	1
g	7, 10	11, 14	4	4
h	10, 12	12, 14	2	2
i	10, 14	10, 14	0	0
j	14, 24	14, 24	0	0
k	24, 27	24, 27	0	0

Critical Path Method (CPM)

CPM Example: Solution

Job Name	ES, EF	LS, LF	TF	FF
l	27, 28	28, 29	1	1
m	27, 29	27, 29	0	0
n	27, 30	29, 32	2	2
o	16, 18	24, 26	8	0
p	18, 19	26, 27	8	0
q	6, 7	26, 27	20	12
r	32, 34	32, 34	0	0
s	29, 32	29, 32	0	0
t	32, 33	33, 34	1	1
u	19, 21	27, 29	8	0
v	21, 26	29, 34	8	8

Reading Assignment

- Read the paper:

  Zack, James G. 1992. Schedule ‘games’ people play, and some suggested ‘remedies’. *Journal of Management in Engineering*, 8(2): 138-152.
- Be prepared to discuss it.

CPM Example

- The following activities occur in sequence on a project:
  - A. Excavate foundation (14 days)
  - B. Place forms (10 days)
  - C. Pour concrete (8 days)
- Placing the forms can begin 4 days after excavation begins. Excavation must finish 2 days prior to placing the forms are finished. Pouring concrete can begin 4 days after placing the forms begins, and placing the forms must finish 1 day prior to the completion of the concrete pour. Assuming that activities can be interrupted, calculate the shortest duration of the project and determine which activities are critical.

References:

- *CIV E 601: Project Management, Lecture Notes,* Fayek, A. R. University of Alberta, 2013.
- *Project Management: Techniques in Planning and Controlling Construction Projects*, 2nd Edition, Ahuja, Dozzi, and AbouRizk, John Wiley and Sons, 1994.
- Baldwin, A. and Bordoli, D. (2014). *A Handbook for Construction Planning and Scheduling*, John Wiley and Sons.