Product, process and schedule design III.

- Chapter 2 of the textbook
- Schedule design
  - Production quantity
  - Equipment requirements
  - Operator requirements
- Facilities design
## Product, process and schedule design II.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Documentation</th>
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<tr>
<td>• Product determination</td>
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<tr>
<td>• Detailed design</td>
<td>• Exploded assembly drawing</td>
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<td></td>
<td>• Exploded assembly photograph</td>
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<td></td>
<td>• Component part drawing</td>
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<td><strong>Process design</strong></td>
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<td>• Process identification</td>
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<td>• Bill of materials</td>
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<td>• Route sheet</td>
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<td>• Process sequencing</td>
<td>• Assembly chart</td>
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<td>• Operation process chart</td>
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</tr>
</tbody>
</table>
## Schedule Design

<table>
<thead>
<tr>
<th>Steps</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Schedule design</strong></td>
<td>• Quantity of the product</td>
</tr>
<tr>
<td></td>
<td>• High volume production (Scrap estimates)</td>
</tr>
<tr>
<td></td>
<td>• Low volume production (Reject allowance)</td>
</tr>
<tr>
<td></td>
<td>• Equipment requirements</td>
</tr>
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<td></td>
<td>• Equipment fractions</td>
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<tr>
<td></td>
<td>• Operator requirements</td>
</tr>
<tr>
<td></td>
<td>• Machine assignments</td>
</tr>
</tbody>
</table>
Process requirements – Quantity determination

- **Reject Allowance Problem**
  - Determination the number of additional units to allow when the number of items to produce are very few and rejects randomly occur
    - For *low volume* production
    - The cost of scrap is very high

- **Scrap Estimates**
  - Determination of the quantity to be manufactured for each component
    - For *high volume* production
    - The estimation of scrap
Based on the given system above, what is the minimum number of inputs required?

\[ I = O + S \]

If \( S \) is a fraction of \( I \), then

\[ I = O + P_s \times I \]

\[ I = \frac{O}{1 - P_s} \]

Where \( P_s \) is the probability of producing scrap items
In order to be able to produce the desired number of final products we have to consider the scraps from the beginning. Total needed input can generally be calculated using the following equation

\[ Input = \frac{FinalOutput}{(1 - P_{S_1})(1 - P_{S_2})...(1 - P_{S_n})} \]
Scrap estimates - problem

- Market estimate of 97,000 components
- 3 operations: turning, milling and drilling
- Scrap estimates: $P_1=0.04$, $P_2=0.01$ and $P_3=0.03$

Total input to the production?

Production quantity scheduled for each operation?

\[
\text{Input} = \frac{\text{Final Output}}{(1 - P_{s_1})(1 - P_{s_2})\ldots(1 - P_{s_n})}
\]

\[
I_1 = \frac{97,000}{(1 - 0.03)(1 - 0.01)(1 - 0.04)} = 105,219
\]
Scrap estimates - problem

- Production quantity scheduled for each operation:

\[ I_3 = \frac{97,000}{1 - 0.03} = 100,000 \]
\[ I_2 = \frac{100,000}{1 - 0.01} = 101,000 \]
\[ I_1 = \frac{101,000}{1 - 0.04} = 105,219 \]

<table>
<thead>
<tr>
<th>Operation</th>
<th>Production Quantity Scheduled (units)</th>
<th>Expected Number of Good Units Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>105,219</td>
<td>101,010</td>
</tr>
<tr>
<td>Milling</td>
<td>101,010</td>
<td>100,000</td>
</tr>
<tr>
<td>Drilling</td>
<td>100,000</td>
<td>97,000</td>
</tr>
</tbody>
</table>
Equipment fractions

- The quantity of equipment required for an operation
- Most of the time facilities need fraction of machines
  - e.g.: 3.5 machine
- How can we determine the number of machines we need in order to produce Q items

\[
F = \frac{Total\ Time}{Time\ Available}
\]

\[
F = \frac{S \times Q}{E \times H \times R}
\]

Where
- \(F\)… the required number of machines per shift
- \(S\) … the standard time per unit produced [min]
- \(Q\)… the number of units to be produced per shift
- \(E\) … actual performance (as % of standard time)
- \(H\) … amount of time available per machine [min]
- \(R\) … reliability of machine (as % “uptime”)
A machined part has a standard machinery time of 2.8 min per part on a milling machine. During an 8-hr shift 200 units are to be produced. Out of the 8 hours available for the production, the milling machine will be operational 80% of the time. During the time the machine is operational, parts are produced at a rate equal to 95% of the standard rate.

How many milling machines are required?

- $S=2.8$ min, $Q=200$ units, $H=480$ min, $E=0.95$ and $R=0.8$

$$ F = \frac{S \times Q}{E \times H \times R} = \frac{2.8 \times 200}{0.95 \times 480 \times 0.8} = 1.535 $$

- We need 1.535 machines per shift.
Total equipment requirements

- Combining the equipment fractions for *identical* equipment types
- Problem:

<table>
<thead>
<tr>
<th>Operation Number</th>
<th>Equipment Fraction</th>
<th>Next Highest Whole Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>1.1</td>
<td>2</td>
</tr>
<tr>
<td>206</td>
<td>2.3</td>
<td>3</td>
</tr>
<tr>
<td>274</td>
<td>0.6</td>
<td>1</td>
</tr>
</tbody>
</table>

- How many machines do we need?
- Answer: 4, 5 or 6. Other factors need to be considered: setup time, cost of equipment, etc.
Operator Requirements

• If the order quantity (Q) is known
  ◦ Required number of machines can be found
  ◦ How do we find the number of required operators?

• Depending on the nature of the work, determination of the number of required operators might differ
  • Some machines can work alone: CNC machines
  • Some tasks require the involvement of an operator 100% of the time - driving a forklift
Operator Requirements

- It is conceptually the same as the machine requirement

\[ F = \frac{Total\ Time}{Time\ Available} \]

Where

\[ N \] … the required number of operators per shift
\[ T \] … the time required for an operation [min]
\[ P \] … the required number of operations per day
\[ H \] … amount of time available per day [min]
\[ C \] … time the person is available (% of utilization)

- To perform the exact manpower requirement analysis, we need to know how many machines a worker can operate at the same time.

⇒ Machine assignment problem
Machine assignment problem

- Decisions regarding the assignment of machines to operators can affect the number of employees.
Machine assignment problem

Human-Machine chart or Multiple Activity chart

a … Concurrent activity (both machine and operator work together: load, unload machines)

b … Independent operator activities (walking, inspecting, packing)

t … Independent machine activities (automatic machining)

L.....Loading
T.....Walking
UL.....Unloading
I&P.....Inspection & Packing
Machine assignment problem

\(a\) … Concurrent activity

\(b\) … Independent operator activities

\(t\) … Independent machine activities

\((a+b)\) … Operator time per machine: time an operator devotes to each machine

\((a+t)\) … Machine cycle time (repeating time): time it takes to complete a cycle

L…..loading
T…..walking
UL…unloading
I&P…inspection & packing
Machine assignment problem – Problem 1

- Three machines: A, B and C
- Loading/Unloading times for each machine are:
  - $a_A = 2$ min, $a_B = 2.5$ min and $a_C = 3$ min
- Machining times
  - $t_A = 7$ min, $t_B = 8$, and $t_C = 9$ minutes
- Inspection times
  - $b_A = 1$, $b_B = 1$, and $b_C = 1.5$ minutes

- Determine the cycle length (cycle time)
- Construct a multiple activity chart
How can we estimate the minimum cycle length?

- Compute the total time operator needs to work during the full cycle $= \Sigma (a_i + b_i)$
  
  $T_o = (2+1) + (2.5+1) + (3+1.5) = 11$ minutes

  (the minimum possible cycle length is 11 minutes)

- Compute machine cycle time (total operating time) for each machine $(a + t)$
  
  - Machine A: $2+7 = 9$ minutes
  - Machine B: $2.5+8 = 10.5$ minutes
  - Machine C: $3+9 = 12$ minutes

  Machine cycle time is **12 minutes** (the minimum possible cycle length is 12 minutes)

- Cycle time is the higher of the two:
  
  $T_C = 12$ minutes
**Loading/Unloading:**
- $a_A = 2\text{min}$
- $a_B = 2.5\text{min}$
- $a_C = 3\text{min}$

**Machining times**
- $t_A = 7\text{min}$
- $t_B = 8\text{min}$
- $t_C = 9\text{min}$

**Operator independent times:**
- $b_A = 1\text{min}$
- $b_B = 1\text{min}$
- $b_C = 1.5\text{min}$
Machine assignment problem

- If we know the activities needed and the time required to complete each activity, we can determine the *ideal number of machines per operator* $n'$ (for identical machines)

$$n' = \frac{\text{Machine cycle time}}{\text{Operator time per machine}}$$

- If found $n'$ is not an integer value (it will not be in most cases), how do we determine the *number of machine for each person* $(m)$?

  - If $m < n'$ then *operator* will be idle
  - If $m > n'$ then *machines* will be idle

- This question can be answered more accurately if we know the cost of machining and of the operator
Machine assignment problem – Problem 2

- Identical machines
- Walking time 0.5 min
- Loading 1 min
- Unloading 1 min
- Automatic machining 6 min
- Inspection and packing 0.5 min

Determine the ideal number of machines per operator \( n' \)

- \( a=1+1=2 \) min, \( t=6 \) min, \( b=0.5+0.5=1 \) min

\[
n' = \frac{(a + t)}{(a + b)} = \frac{(2 + 6)}{(2 + 1)} = \frac{8}{3} = 2.67
\]
Machine assignment problem

- $T_c$ … Cycle time
- $I_o$ … Idle operator time
- $I_m$ … Idle time for machines during one cycle ($T_c$)

\[
T_c = \begin{cases} 
(a + t) & \text{when } m \leq n' \\
 m(a + b) & \text{when } m > n'
\end{cases} \quad \text{(Operator idle)}
\]

\[
I_m = \begin{cases} 
0 & \text{when } m \leq n' \\
T_c - (a + t) & \text{when } m > n'
\end{cases} \quad \text{(Machines idle)}
\]

\[
I_o = \begin{cases} 
T_c - m(a + b) & \text{when } m \leq n' \\
0 & \text{when } m > n'
\end{cases}
\]
Machine assignment problem – Problem 2 cont.

- a=2 min, t=6 min, b=1 min

- Determine the cycle time and idle times for machines and an operator if 3 machines are assigned to an operator

- m>n’ (3>2.67) -> machines will be idle

\[ T_c = m(a + b) = 3(2 + 1) = 9 \text{ min} \]

\[ I_m = T_c - (a + t) = 9 - (2 + 6) = 1 \text{ min} \]

\[ I_o = 0 \]
**Machine assignment problem**

- $C_o$ is cost per operator hour
- $C_m$ is cost per machine hour
- $\varepsilon = C_o/C_m$
- $TC(m)$ is cost per unit produced based on an assignment of $m$ machines per operator

\[
TC(m) = \begin{cases} 
(C_o + mC_m)(a + t) / m & \text{when } m \leq n' \\
(C_o + mC_m)(a + b) & \text{when } m > n' 
\end{cases}
\]

Each machine produces one unit during $T_c : \Rightarrow time per unit T_c/m$

If cycle time is $(a+t) \Rightarrow (a+t)/m$ is time to produce a unit for each machine.

If cycle time is $m(a+b) \Rightarrow (a+b)$ is the time to produce a unit for each machine.

Based on this equation we may experiment to determine the number of assigned machines.
Machine assignment problem

- Let \( n \) be the integer portion of \( n' \)

\[
\phi = \frac{TC(n)}{TC(n+1)}
\]

\[
\phi = \frac{(C_o + nC_m)(a + t)}{n[C_o + (n + 1)C_m](a + b)}
\]

Then

\[
\phi = \left(\frac{\varepsilon + n}{\varepsilon + n + 1}\right)\left(\frac{n'}{n}\right)
\]

If \( \Phi < 1 \) then \( TC(n) < TC(n+1) \)
If \( \Phi > 1 \) then \( TC(n) > TC(n+1) \)

We should assign
- \( n \) machines
- \( n+1 \) machine

to each operator
Machine assignment problem – Problem 2

- $C_o = $15 per hour
- $C_m = $50 per hour

Determine the number of machines assigned to an operator to minimize the cost

$$\varepsilon = \frac{C_o}{C_m} = \frac{15}{50} = 0.3$$

$$\phi = \left( \frac{\varepsilon + n}{\varepsilon + n + 1} \right) \left( \frac{n'}{n} \right) = \left( \frac{0.3 + 2}{0.3 + 2 + 1} \right) \left( \frac{2.67}{2} \right) = 0.93$$

- Since $\Phi < 1$ then $TC(n) < TC(n+1)$ and thus only 2 machines should be assigned to an operator
Machine assignment problem – Problem 3

- Loading Mixer: 6 minutes
- Mixing and Unloading: 30 minutes \( t = 30 \)
- Cleaning: 4 minutes \( a = 6 + 4 = 10 \)
- Position for filling: 6 minutes \( b = 6 \)
- \( Co = $12/hr \)
- \( Cm = $25/hr \)

- Maximum number of mixers without creating idle time for mixers?
- How many mixers to minimize cost?
- If 2 machines are assigned per operator, what will be the cost per unit?
- If the cost per machine is unknown, for what range of values Cm will the optimum assignment remain the same?
Machine assignment problem – Problem 3

- Maximum number of mixers without idle mixers
  \[ a = 6 + 4 = 10; \quad b = 6; \quad \text{and} \quad t = 30 \]
  \[ n' = \frac{(a + t)}{(a + b)} = \frac{(10 + 30)}{(10 + 6)} = \frac{40}{16} = 2.5 \]
  Max of 2 mixers can be assigned to 1 operator without idle mixer time.

- Number of mixers to minimize cost
  \[ \varepsilon = \frac{C_o}{C_m} = \frac{12}{25} = 0.48 \]
  \[ \phi = \left( \frac{\varepsilon + n}{\varepsilon + n + 1} \right) \left( \frac{n'}{n} \right) = \left( \frac{0.48 + 2}{0.48 + 2 + 1} \right) \left( \frac{2.5}{2} \right) = 0.89 \]
  Since \( \Phi = 0.89 < 1 \), only 2 mixers should be assigned to an operator to minimize cost.
If \( m = 2 \), the cost of a unit?

- Since \( m < n' \) (2 < 2.5)

\[
TC(m) = (C_o + mC_m)(a + t) / m
\]

\[
TC(2) = (12 + 2 \times 25)(\frac{10+30}{60}) / 2 = 20.66
\]

- The cost of a unit will be $20.66.
Machine assignment problem – Problem 3

If the cost per machine is unknown, for what range of values \( C_m \) will the optimum assignment remain the same?

- In order for \( n=2, \Phi \leq 1 \)

\[
\phi = \left( \frac{\epsilon + n}{\epsilon + n + 1} \right) \left( \frac{n'}{n} \right)
\]

\[
(\epsilon + n) * n' \leq (\epsilon + n + 1) * n
\]

\[
(\epsilon + 2) * 2.5 \leq (\epsilon + 2 + 1) * 2
\]

\[
\left( \frac{12}{C_m} + 2 \right) * 2.5 \leq \left( \frac{12}{C_m} + 3 \right) * 2
\]

\[
6 \leq C_m
\]

- For a machine cost of $6 or more per machine-hour, the optimum assignment will be 2 machines per operator.
Facilities design

- Up to this point
  - We know what we are producing (*Product design*)
  - How we are producing it (*Process design*)
  - How many we are producing (*Schedule design*)

- With the available information we can now start designing the facilities
Facilities design

- 7 management and planning tools that are used for system planning and improvement
  
  1. **Affinity diagram**
     - Used to gather verbal data (ideas and issues) and organize into groups.

  2. **Interrelationship diagram**
     - Try to relate the items and identify which item impacts the other.

  3. **Tree diagram**
     - Detailed study of items that need to be accomplished to reach the goal.
     - Relationship between these items
Facilities design

4. **Matrix diagram**
   - Organize information based on characteristics, functions, and tasks of items to compare and see the relationships

5. **Contingency diagram**
   - Maps the events and possible contingencies that might occur during the implementation of the project

6. **Activity network diagram**
   - Used to develop a work schedule for the facility design effort
   - Used to plan entire design process visually

7. **Prioritization matrix**
   - A tool for comparison of criteria
   - Determines the most important criteria
Activity Network Diagram

Legend:
A: Schedule shutdown periods for equipment movement and installation
B: Interview, evaluate, select, and hire new employees
C: Train new employees
D: Interview, evaluate, and select equipment vendors
E: Order equipment
F: Interview, evaluate, select, and hire construction contractors
G: Meet to review installation plan (Facilities Design Team, contractors, new employees, vendor representatives, and management)
H: Executive installation plan and test system

D: Activity duration
ES: Early start
EF: Early finish
LS: Late start
LF: Late finish

Figure 2.22 Activity network diagram example for a production line expansion facilities design project.
## Prioritization matrix

### Criteria used to evaluate facilities design alternatives

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Total distance traveled</td>
<td>B Manufacturing floor visibility</td>
</tr>
<tr>
<td>C. Overall aesthetics of the layout</td>
<td>D. Ease of adding future business</td>
</tr>
<tr>
<td>E. Use of current equipment</td>
<td>F. Investment in new equipment</td>
</tr>
<tr>
<td>G. Space requirements</td>
<td>H. People requirement</td>
</tr>
<tr>
<td>I. Impact on WIP levels</td>
<td>J. Human factor risk</td>
</tr>
<tr>
<td>K. Estimated cost of alternatives</td>
<td></td>
</tr>
</tbody>
</table>

### Weights used in comparison of criteria

<table>
<thead>
<tr>
<th>Weight</th>
<th>Description</th>
<th>Equivalent Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equally important</td>
<td>1/5 = significantly less important</td>
</tr>
<tr>
<td>5</td>
<td>Significantly more important</td>
<td>1/10 = extremely less important</td>
</tr>
<tr>
<td>10</td>
<td>extremely important</td>
<td></td>
</tr>
</tbody>
</table>


### Prioritization matrix

**Table 2.12 Prioritization Matrix for the Evaluation of Facilities Design Alternatives**

<table>
<thead>
<tr>
<th>Criteria</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>
<th>I</th>
<th>J</th>
<th>K</th>
<th>Row totals (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>32. (9.9)</td>
</tr>
<tr>
<td>Visibility</td>
<td>1/5</td>
<td>1</td>
<td>5</td>
<td>1/5</td>
<td>1/5</td>
<td>1/10</td>
<td>1/5</td>
<td>1/5</td>
<td>1/10</td>
<td>1/5</td>
<td>1/5</td>
<td>7.6 (2.4)</td>
</tr>
<tr>
<td>Aesthetics</td>
<td>1/10</td>
<td>1/5</td>
<td>1</td>
<td>1/10</td>
<td>1/10</td>
<td>1/10</td>
<td>1/5</td>
<td>1/5</td>
<td>1/10</td>
<td>1/10</td>
<td>1/10</td>
<td>2.3 (0.7)</td>
</tr>
<tr>
<td>Fut. Buss.</td>
<td>1/5</td>
<td>5</td>
<td>10</td>
<td>1</td>
<td>1/5</td>
<td>1/5</td>
<td>1/5</td>
<td>1/5</td>
<td>1/10</td>
<td>1/5</td>
<td>1/10</td>
<td>17.4 (5.4)</td>
</tr>
<tr>
<td>Current eq.</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1/5</td>
<td>1</td>
<td>1/5</td>
<td>34.4 (10.7)</td>
</tr>
<tr>
<td>New eq.</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>41. (12.7)</td>
</tr>
<tr>
<td>Space</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1/5</td>
<td>1/5</td>
<td>1</td>
<td>5</td>
<td>1/5</td>
<td>1/5</td>
<td>1/5</td>
<td>23. (7.1)</td>
</tr>
<tr>
<td>People</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1/5</td>
<td>1/5</td>
<td>5</td>
<td>1</td>
<td>1/10</td>
<td>1/5</td>
<td>1/5</td>
<td>22.9 (7.1)</td>
</tr>
<tr>
<td>WIP</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>59. (18.3)</td>
</tr>
<tr>
<td>Human f.r.</td>
<td>1/5</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>39.2 (12.2)</td>
</tr>
<tr>
<td>Cost</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1/5</td>
<td>1/5</td>
<td>1</td>
<td>43.4 (13.5)</td>
</tr>
<tr>
<td><strong>Column total</strong></td>
<td>7.7</td>
<td>56.2</td>
<td>86.</td>
<td>51.3</td>
<td>14.9</td>
<td>6.8</td>
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<td>37.6</td>
<td>5.</td>
<td>10.1</td>
<td>14.</td>
<td>322.2</td>
</tr>
</tbody>
</table>

**Grand total**
## Prioritization matrix

### Table 2.13 Prioritization of Layout Alternatives Based on WIP Levels

<table>
<thead>
<tr>
<th>WIP Levels</th>
<th>P</th>
<th>Q</th>
<th>R</th>
<th>S</th>
<th>T</th>
<th>Row totals (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1/10</td>
<td>1/5</td>
<td>7.3 (9.9)</td>
</tr>
<tr>
<td>Q</td>
<td>1/5</td>
<td>1</td>
<td>1/5</td>
<td>1/10</td>
<td>1/10</td>
<td>1.6 (2.2)</td>
</tr>
<tr>
<td>R</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>10</td>
<td>5</td>
<td>22.0 (30.0)</td>
</tr>
<tr>
<td>S</td>
<td>10</td>
<td>10</td>
<td>1/10</td>
<td>1</td>
<td>1/5</td>
<td>21.3 (29.0)</td>
</tr>
<tr>
<td>T</td>
<td>5</td>
<td>10</td>
<td>1/5</td>
<td>5</td>
<td>1</td>
<td>21.2 (28.9)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>17.2</td>
<td>31</td>
<td>2.5</td>
<td>16.2</td>
<td>6.5</td>
<td>73.4 Grand total</td>
</tr>
</tbody>
</table>
Prioritization matrix

- In the previous slide, we compared the different layout alternatives to each other based on WIP levels
- We need to do the comparison for all the selected criteria
- Finally use the following format to determine the best alternative
The ranking of layouts will help determine the best alternative.

Best alternative - serving the objective best.

Best concept might change depending on the company and people.
Facilities design
Next lecture

- Flow, space and activity relationships I.