Work Flow and Batch Processing

Chapter 3

Sections:
1. Sequential Operations and Work Flow
2. Batch Processing
3. Defects in Sequential Operations and Batch Processing
4. Work Cells

Some Definitions

- Sequential operations (versus unit operations): series of separate processing steps that are performed on each work unit
  - Operations performed sequentially

- Work flow: physical movement of work units through the sequence of unit operations

- Batch processing: processing of work units in (finite) quantities or amounts

Sequential Operations in Industry

- To complete a work unit, the operations are performed sequentially (rather than simultaneously)
  - Manufacturing
  - Assembly
  - Construction
  - Mortgage applications
  - Medical services
  - Education
  - Transportation

Work Flow Patterns

- Pure sequential: all work units follow the same exact sequence of operations and workstations
  - Work flow is identical for all work units

- Mixed sequential: different work units are processed through different operations
  - Different work flows for different types of work units

Network Diagram

Indicates any of several possible quantitative relationships among operations in a multi-station work system

- Possible variables in a network diagram:
  - Quantities moving between operations
  - Flow rates of materials
  - Distances between work stations

Bottlenecks in Sequential Operations

- Bottleneck = slowest operation in the sequence

- The bottleneck operation limits the production rate for the entire sequence
  \[ R_{\text{sys}} = \min(R_{i}) \text{ for } i = 1, 2, \ldots, n \]
  where
  - \( R_{\text{sys}} \) = overall production rate of the system, pc/hr
  - \( R_{i} \) = production rate of operation \( i \), pc/hr
  - \( n \) = the number of operations in the sequence
Bottlenecks in Sequential Operations

- Slowest process limits the output of the other operations in the sequence.

- Blocking: production rate(s) of one or more upstream operations are limited by the rate of a downstream operation
  - Accumulating work-in-process (WIP) inventory before the bottleneck station makes no sense. The upstream operations must produce at a rate that is less than or equal to the bottleneck operation.

- Starving: production rate(s) of one or more downstream operations are limited by the rate of an upstream operation
  - The downstream operations can work no faster than the rate at which the bottleneck feeds work units to them.

Why a workstation is the slowest?

- Technological factors: limits on the speed of the equipment (feed rate restricts workpiece progression)
- Work allocation decisions: the ways in which the total work content in the sequence is divided among the stations
- Ergonomic limitations: the physical or mental restrictions of the human worker at the workstation

Batch Processing

- Batch processing: processing of work units in finite quantities or amounts
- Work units can be materials, products, information, or people
- Batch processing is common in production, logistics, and service operations
  - Batch production in manufacturing
  - Passenger air travel
  - Cargo transport
  - Book publishing
  - Payroll checks
  - Laundry
  - Grading of student papers

Types of Batch Processing

- Sequential batch processing: members of the batch are processed one after the other
- Simultaneous batch processing: members of the batch are all processed at the same time

Sequential
- Production machining
- Batch assembly
- Book printing
- Payroll checks
- Grading of student papers

Simultaneous
- Chemical batch processes
- Heat treating of multiple parts
- Passenger air travel
- Cargo transport
- Laundry
Batch Production

Alternating cycles of setup and production run experienced by a work system engaged in batch production (cycles are not necessarily identical).

Production is intermittent. This means equipment are not kept continuously running and work units are not continuously worked on.

Motivations of Batch Processing

- **Work unit differences**: different types of work units must be processed separately
- **Learning curve effect**: cycle time per work unit decreases as batch quantity \( Q \) increases (applies only to sequential batch production)
- **Equipment limitations**: limits on the quantities that can be processed
- **Material limitations**: the material must be processed as a unit

Disadvantages of Batch Processing

- **Setup**: Interruption due to changeovers between batches (tool change, loading, unloading etc.)
  - Setup times are lost productive time
  - Setup changeovers in batch production
  - Airplanes at a terminal unloading and loading passengers
- **Work-in-process**: inventory accumulated during the production
  - Multiple batches competing for the same equipment
  - Queues of work units form in front of each workstation, resulting in large inventories of partially processed units

Work Cells

- **Work cell**: a group of workstations dedicated to the processing of a range of work units within a given type
- **Part family**: the range of work units that are processed
  - Members of the part family are similar but not identical
- **Mixed sequential work flow system**
- **Work cells and part families are associated with group technology**

Group Technology

- An approach to manufacturing in which similar parts are identified and grouped together to take advantage of their similarities in design and production
- Instead of processing each part types in batches, the work units are processed individually and continuously, without the need for time-consuming changeovers between part types
- This is enabled by
  - The similarity of parts within a part family
  - The adaptability and flexibility of the workers and equipments in the cell that can accommodate the moderate differences among part family members

Work Cell Layouts

- **In-line**: straight line flow of work units
  - High speed
  - meaningful only if all work units follows the same sequence of operations
  - consume large space
- **U-shaped**: shape of work flow is “U”
  - Similar to in-line except for shape – saves space
  - Better communication among workers
  - promotes teamwork
  - Better in realizing mixed sequential flow
- **Loop**: continuous flow of work units around a loop layout
- **Rectangular**: similar to loop layout
Manual Assembly Lines

- Work systems consisting of multiple workers organized to produce a single product or a limited range of products
- Assembly workers perform tasks at workstations located along the line-of-flow of the product
  - Usually a powered conveyor is used
  - Some of the workstations may be equipped with portable powered tools.
- Factors favoring the use of assembly lines:
  - High or medium demand for product
  - Products are similar or identical
  - Total work content can be divided into work elements
  - To automate assembly tasks is impossible

Why Assembly Lines are Productive

- Specialization of labor
  - When a large job is divided into small tasks and each task is assigned to one worker, the worker becomes highly proficient at performing the single task (learning curve)
- Interchangeable parts
  - Each component is manufactured to sufficiently close tolerances that any part of a certain type can be selected at random for assembly with its mating component.
  - Thanks to interchangeable parts, assemblies do not need fitting of mating components

Some Definitions

- Work flow
  - Each work unit should move steadily along the line
- Line pacing
  - Workers must complete their tasks within a certain cycle time, which will be the pace of the whole line
- Cycle time
  - Interval at which, completed products leave the production line
  - Time between two consecutive finished units in a production line
  - Time allowed for each station to complete its operation

Manual Assembly Line

- A production line that consists of a sequence of workstations where assembly tasks are performed by human workers
- Products are assembled as they move along the line
  - At each station a portion of the total work content is performed on each unit
- Base parts are launched onto the beginning of the line at regular intervals (cycle time)
  - Workers add components to progressively build the product

Manual Assembly Line

- Configuration of an n-workstation manual assembly line
  - The production rate of an assembly line is determined by its slowest station.
- Assembly workstation: A designated location along the work flow path at which one or more work elements are performed by one or more workers

Two assembly operators working on an engine assembly line (photo courtesy of Ford Motor Company)
Manning level

- There may be more than one worker per station.

- **Utility workers**: are not assigned to specific workstations.

  - They are responsible for
    1. helping workers who fall behind,
    2. relieving for workers for personal breaks,
    3. maintenance and repair

\[ M = \frac{w_u + \sum_{i=1}^{n} w_i}{n} \]

Where:
- \( M \) = average manning level of the line,
- \( w_u \) = number of utility workers assigned to the system,
- \( n \) = number of workstations,
- \( w_i \) = number of workers assigned specifically to station \( i \), for \( i = 1, \ldots, n \)

**Work Transport Systems-Manual Methods**

- Manual methods
  - Work units are moved between stations by the workers (by hand) without powered conveyor

  - Problems:
    - Starving of stations
    - The assembly operator has completed the assigned task on the current work unit, but the next unit has not yet arrived at the station
    - Blocking of stations
    - The operator has completed the assigned task on the current work unit but cannot pass the unit to the downstream station because that downstream worker is not yet ready to receive it.

- To reduce starving, use buffers
- To prevent blocking, provide space between upstream and downstream stations.

But both solutions can result in higher WIP, which is economically undesirable.

**Work Transport Systems-Mechanized Methods**

- **Continuously moving conveyor**: operates at constant velocity
  1. Work units are fixed to the conveyor
     - The product is large and heavy
     - Worker moves along with the product
  2. Work units are removable from the conveyor
     - Work units are small and light
     - Workers are more flexible compared to synchronous lines, less flexible than asynchronous lines

- **Synchronous transport** (intermittent transport – stop-and-go line): all work units are moved simultaneously between stations.
  - Problem:
    - Task must be completed within a certain time limit. Otherwise the line produces incomplete units.
    - Excessive stress on the assembly worker.
    - Not correct for monotonous lines (repetitive), but often ideal for automated production lines

- **Asynchronous transport**: a work unit leaves a given station when the assigned task is completed.
  - Work units move independently, rather than synchronously (most flexible one)
  - Variance in worker task times
  - Small queues in front of each station

**Coping with Product Variety**

- **Single model assembly line (SMAL)**
  - Every work unit is the same

- **Batch model assembly line (BMAL)** – multiple model line
  - Two or more different products
  - Products are so different that they must be made in batches with setup between batches

- **Mixed model assembly line (MMAL)**
  - Two or more different models
  - Differences are slight so models can be made simultaneously with no setup time (no need for batch production)
Coping with Product Variety

- Advantages of mixed models over batch order models
  - No production time is lost during changeovers
  - High inventories due to batch ordering are avoided
  - Production rates of different models can be adjusted as product demand changes.
- Disadvantages of mixed models over batch order models
  - Each station is equipped to perform variety of tasks (costly)
  - Scheduling and logistic activities are more difficult in this type of lines.

Analysis of Single Model Lines

- The formulas and the algorithms in this section are developed for single model lines, but they can be extended to batch and mixed models.
- The assembly line must be designed to achieve a production rate sufficient to satisfy the demand.

\[
R_p = \frac{D_a}{S_w \times H_{sh}}
\]

where
- \(D_a\) = annual demand
- \(R_p\) = hourly production rate
- \(S_w\) = number of shifts/week
- \(H_{sh}\) = number of hours/shift

Determining Cycle Time

Now our aim is to convert production rate, \(R_p\), to cycle time, \(T_c\).

- One should take into account that some production time will be lost due to:
  - equipment failures
  - power outages,
  - material unavailability,
  - quality problems,
  - labor problems.
- Line efficiency (uptime proportion): only a certain proportion of the shift time will be available.

\[
T_u = \frac{R_u}{R_p}
\]

where production rate, \(R_u\), is converted to a cycle time, \(T_u\), accounting for line efficiency, \(E\).

Number of Stations Required

- Work content time (\(T_{wc}\)): The total time of all work elements that must be performed to produce one unit of the work unit.

\[
w^* = \text{Minimum Integer} \geq \frac{T_{wc}}{T_c}
\]

where
- \(T_{wc}\) = work content time, min;
- \(T_c\) = cycle time, min/station

If we assume one worker per station then this gives the minimum number of workers.

Theoretical Minimum Not Possible

- Repositioning losses: Some time will be lost at each station every cycle for repositioning the worker or the work unit, thus, the workers will not have the entire \(T_c\) each cycle.
- Line balancing problem (imperfect balancing): It is not possible to divide the work content evenly among workers, and some workers will have an amount of work that is less than \(T_c\).

Repositioning Losses

- Repositioning losses occur on a production line because time is required each cycle to reposition the worker, the work unit, or both.
  - On a continuous transport line, time is required for the worker to walk from the upstream line entering the station.
  - In conveyor systems, time is required to remove work units from the conveyor and position it at the station for the worker to perform his task.
Repositioning Losses

- Repositioning time = time available each cycle for the worker to position
- Service time = time available each cycle for the worker to work on the product

\[ T_r = \frac{T_s}{n} \leq T_c - T_r \]

where \( T_{si} = \text{service time for station } i \), \( i = 1, 2, ..., n \)

Repositioning efficiency

\[ E_r = \frac{T_c - T_r}{T_c} \]

Cycle Time on an Assembly Line

- Components of cycle time at several stations on a manual assembly line

Line Balancing Problem

Given:
- The total work content consists of many distinct work elements
- The sequence in which the elements can be performed is restricted
- The line must operate at a specified cycle time

The Problem:
- To assign the individual work elements to workstations so that all workers have an equal amount of work to perform

Assumptions About Work Element Times

1. Element times are constant values
   - But in fact they are variable
2. Work element times are additive
   - The time to perform two/more work elements in sequence is the sum of the individual element times
   - Additivity assumption can be violated (due to motion economies)

Work Element Times

\[ T_{we} = \sum_{k=1}^{n} T_{ek} \]

where \( T_{ek} = \text{work element time for element } k \)

Work elements are assigned to station \( i \) that add up to the service time for that station

\[ T_s = \sum_{k=1}^{n} T_{ek} \]

The station service times must add up to the total work content time

\[ T_{wc} = \sum_{i=1}^{e} T_s \]

Constraints of Line Balancing Problem

- Different work elements require different times.
  - When elements are grouped into logical tasks and assigned to workers, the station service times, \( T_s \), are likely not to be equal.
  - Simply because of the variation among work element times, some workers will be assigned more work.
  - Thus, variations among work elements make it difficult to obtain equal service times for all stations.
Precedence Constraints

- Some elements must be done before the others.
- Restrictions on the order in which work elements can be performed
- Can be represented graphically (precedence diagram)

Example:

```
<table>
<thead>
<tr>
<th>No.</th>
<th>Work Element Description</th>
<th>T_e (min)</th>
<th>Must Be Preceded by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Place frame in workholder and clamp</td>
<td>0.2</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Assemble plug, ground to power cord</td>
<td>0.4</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>Assemble brackets to frame</td>
<td>0.7</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Wire power and to source</td>
<td>0.1</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>5</td>
<td>Assemble valve to bracket</td>
<td>0.1</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>6</td>
<td>Assemble valve to valve</td>
<td>0.1</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>7</td>
<td>Assemble valve to bracket</td>
<td>0.1</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>8</td>
<td>Assemble valve to valve</td>
<td>0.1</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>9</td>
<td>Align valve and attach to motor</td>
<td>0.27</td>
<td>6, 7, 8</td>
</tr>
<tr>
<td>10</td>
<td>Assemble motor to motor</td>
<td>0.38</td>
<td>5, 6, 7, 8</td>
</tr>
<tr>
<td>11</td>
<td>Attach cover, impact, and test</td>
<td>0.5</td>
<td>9</td>
</tr>
<tr>
<td>12</td>
<td>Place in trim pan for packaging</td>
<td>0.12</td>
<td>1</td>
</tr>
</tbody>
</table>
```

Example: A problem for line balancing

- Given: The previous precedence diagram and the standard times. Annual demand=100,000 units/year. The line will operate 50 wk/yr, 5 shifts/wk, 7.5 hr/shift. Uptime efficiency=96%. Repositioning time=0.08 min.

- Determine
  (a) total work content time,
  (b) required hourly production rate to achieve the annual demand,
  (c) cycle time,
  (d) theoretical minimum number of workers required on the line,
  (e) service time to which the line must be balanced.

Example: Solution

(a) The total work content time is the sum of the work element times given in the table 

\[ T_w = \sum T_e \]

(b) The hourly production rate

\[ R_R = \frac{100,000}{30(7.5)} = 53.33 \text{ units/hr} \]

(c) The corresponding cycle time with an uptime efficiency of 96%

\[ T_c = \frac{60}{1.08} = 56.25 \text{ min} \]

(d) The minimum number of workers:

\[ w_m = \text{Minimum Integer} \geq \frac{4.0}{1.08-3.7} = 4 \text{ workers} \]

Measures of Balance Efficiency

- It is almost impossible to obtain a perfect line balance
- **Line balance efficiency**, \( E_b \):

\[ E_b = \frac{T_c}{T_w} \]

Perfect line: \( E_b = 1 \)

- **Balance delay**, \( d \):

\[ d = \frac{w_m - w}{w} \]

Perfect line: \( d = 0 \)

- Note that \( E_b + d = 1 \) (they are complements of each other)
Overall Efficiency

Factors that reduce the productivity of a manual line

- Line efficiency (Availability), $E_L = \frac{T_e}{T_s}$
- Balance efficiency (balancing), $E_B$
- Repositioning efficiency (repositioning), $E_R$

Overall Labor efficiency on the assembly line = $E_L \times E_B \times E_R$

Continuously Moving Conveyors - Workstation Considerations

- Total length of the assembly line
  $L = \sum L_i$
  where $L_i =$ length of station, m
- Constant speed conveyor: (if the base parts remain fixed during their assembly)
  Feed rate
  $f_p = \frac{1}{T_c}$
  where $T_c =$ cycle time, min
- Center-to-center spacing between base parts
  $s_p = \frac{v_c}{f_p} = \frac{v_c}{T_c}$
  where $s_p =$ center-to-center spacing between base parts, m/part and $v_c =$ velocity of the conveyor, m/min

Continuously Moving Conveyors - Tolerance Time

- Defined as the time a work unit spends inside the boundaries of the workstation
- Provides a way to allow for product-to-product variations in task times at a station
  $T_t = \frac{L_s}{v_c}$

where $T_t =$ tolerance time, min; $L_s =$ station length, m (ft); $v_c =$ conveyor speed, m/min (ft/min)

Line Balancing Objective

- To distribute the total work content on the assembly line as evenly as possible among the workers
  $\min (wT_e - T_\text{tol})$
  or
  $\min \sum (wT_e - T_\text{tol})$

Subject to:

1. All precedence requirements are obeyed
2. All precedence requirements are obeyed

Line Balancing Algorithms – Heuristics

1. Largest candidate rule
2. Kilbridge and Wester method
3. Ranked positional weights method, also known as the Helgeson and Birne method

In the following descriptions, assume one worker per workstation

Largest Candidate Rule

1. List all work elements in descending order based on their $wT_e$ values; then, start at the top of the list and selecting the first element that satisfies precedence requirements and does not cause the total sum of $wT_e$ to exceed the allowable $T_t$ value
   When an element is assigned, start back at the top of the list and repeat selection process
2. When no more elements can be assigned to the current station, proceed to next station
3. Repeat steps 1 and 2 until all elements have been assigned to as many stations as needed
Solution for Largest Candidate Rule

Example:

Ranked Positional Weights Method

- A ranked position weight (RPW) is calculated for each work element
- RPW for element \( k \) is calculated by summing the \( T_e \) values for all of the elements that follow element \( k \) in the diagram plus \( T_e \) itself
- Work elements are then organized into a list according to their RPW values, starting with the element that has the highest RPW value
- Proceed with same steps 1, 2, and 3 as in the largest candidate rule

<table>
<thead>
<tr>
<th>Station</th>
<th>Work Element</th>
<th>( T_e ) (sec)</th>
<th>( T_e ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.4</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.8</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.1</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>0.12</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Solution for Ranked Positional Weights Method

<table>
<thead>
<tr>
<th>Work Element</th>
<th>R/PW</th>
<th>(T_{p}) (min)</th>
<th>Proceeded by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.30</td>
<td>0.2</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>3.00</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2.67</td>
<td>0.4</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>1.97</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>8</td>
<td>1.26</td>
<td>0.6</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>1.20</td>
<td>0.3</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>1.21</td>
<td>0.32</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>1.00</td>
<td>0.11</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
<td>0.39</td>
<td>3.8</td>
</tr>
<tr>
<td>11</td>
<td>0.89</td>
<td>0.27</td>
<td>6.7</td>
</tr>
<tr>
<td>12</td>
<td>0.62</td>
<td>0.5</td>
<td>9.10</td>
</tr>
</tbody>
</table>

Example:

Other Considerations in Line Design

- **Methods analysis**
  - To analyze methods at bottleneck or other troublesome workstations
  - Improved motions,
  - Better workplace layout,
  - Special tools to facilitate manual work elements
  - Product design

- **Utility workers**
  - To relieve congestion at stations that are temporarily overloaded

- **Preassembly of components**
  - Prepare certain subassemblies off-line to reduce work content time on the final assembly line

Other Considerations - continued

- **Storage buffers between stations**
  - To permit continued operation of certain sections of the line when other sections break down
  - To smooth production between stations with large task time variations

- **Parallel stations**
  - To reduce time at bottleneck stations that have unusually long task times

- **Worker (Labor) Shifting with cross-training**
  - Temporary (or periodic) relocation to expedite or to reduce subassembly stocks

Most Follower Rule
We omit

- Worker Requirements in 4.2.2
- 4.3.2 Kilbridge and Western Method
- 4.5 Alternative Assembly Systems