Assembly Technology

Lecture 2: Manual Assembly

Outine

- Fundamentals of Manual Assembly Lines
- Analysis of Single Model Assembly Lines
- Line Balancing Algorithms
- Mixed Model Assembly Lines
- Workstation Considerations
- Other Considerations in Assembly Line Design
- Alternative Assembly Systems

Intended Learning Outcome

- Describe and characterize the manual assembly process as composition of handling and insertion operation.
- Discuss the constraints and main theories that apply to the analysis of the aforementioned sub-processes
- Describe the practical choices in the design process for manual assembly systems: station layout, line layout, balancing (applying algorithms to solve basic problem set up)

Assembly Lines

Factors favoring the use of assembly lines:

- High or medium demand for product
- Identical or similar products
- Total work content can be divided into work elements
- It is technologically impossible or economically infeasible to automate the assembly operations

Most consumer products are assembled on manual assembly lines

Manual Assembly Line Defined

A production line consisting of a sequence of workstations where assembly tasks are performed by human workers as the product moves along the line

Organized to produce a single product or a limited range of products

- Each product consists of multiple components joined together by various assembly work elements
- Total work content - the sum of all work elements required to assemble one product unit on the line

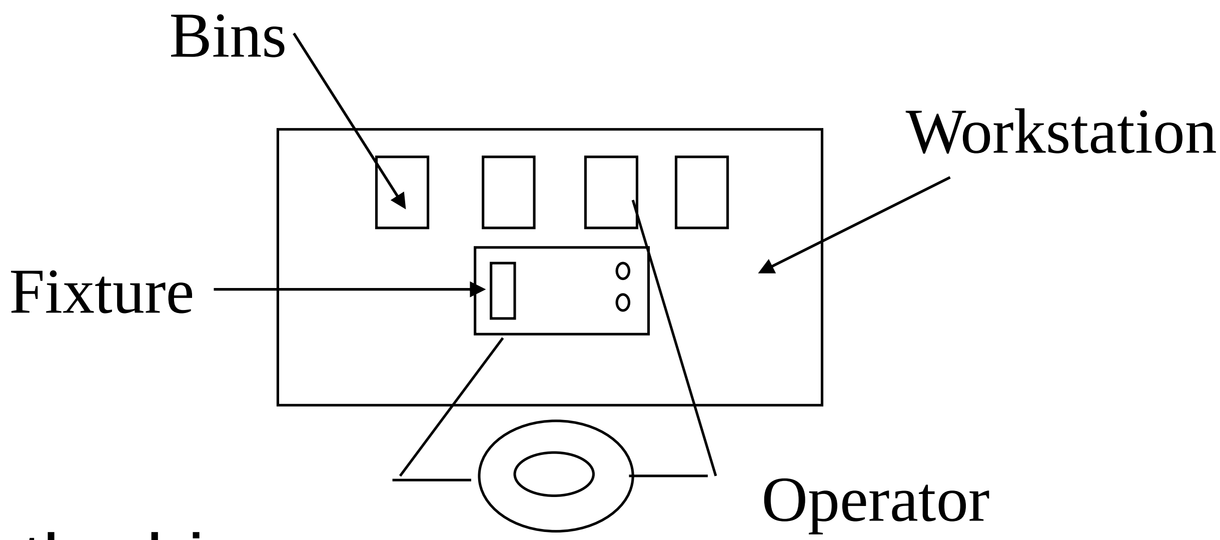
Manual assembly

The process of manual assembly can be divided naturally into two separate areas:

- Handling: acquiring, orienting and moving the parts.
- Insertion and fastening: mating a part to another part or group of parts

$$Total\ assembly\ time = \sum Handling\ time + \sum Insertion\ and\ fastening\ time$$

Manual Handling
(Affected primarily by geometry)



Operator

- Reaches into the bin
- Grasps the part
- Transports and orients the part
- Pre-positions it

Factors affecting handling time

Main factors include:

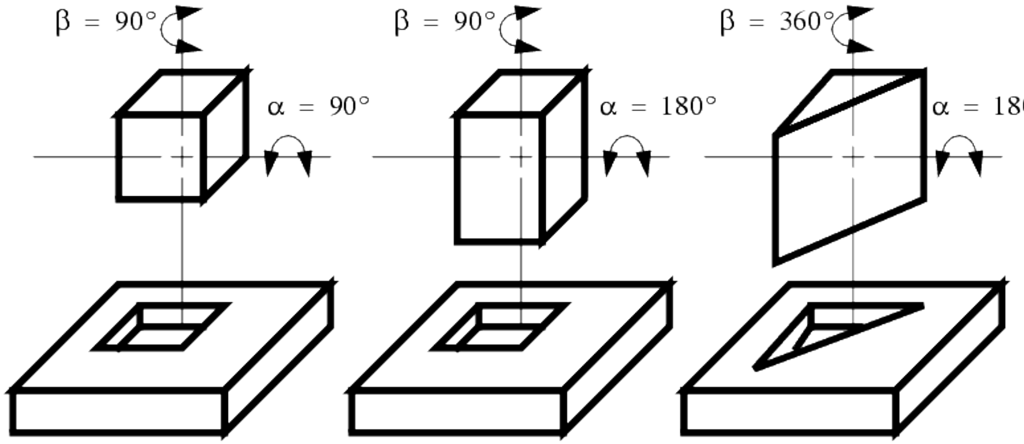
1. Symmetry
2. Thickness
3. Size
4. Weight

Example of manual assembly line

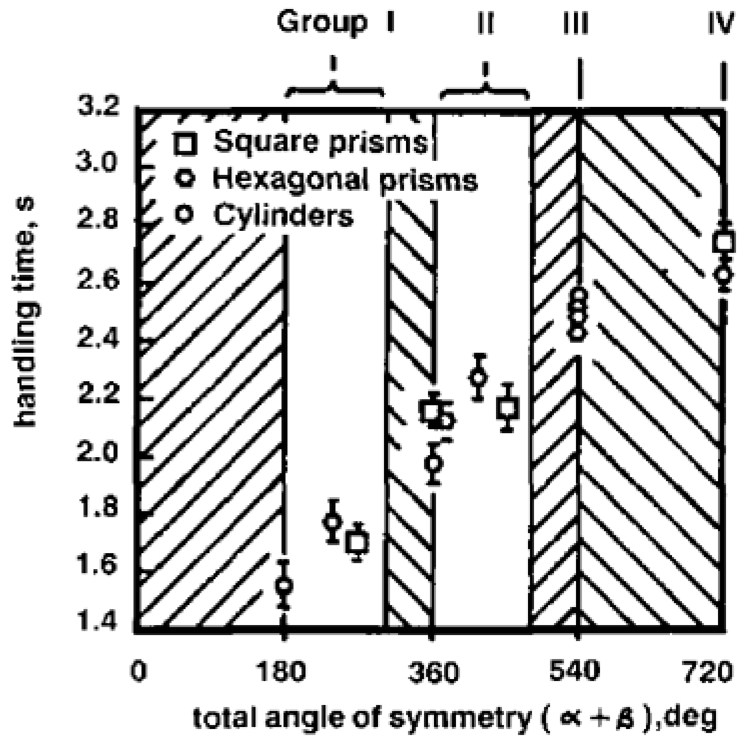
Factor affecting handling time (1)

Total angle of symmetry (α+ β)

- ALPHA (α): depends on the angle through which a part must be rotated about an axis perpendicular to the axis of insertion to repeat its orientation.
- BETA (β): depends on the angle through which a part must be rotated about the axis of insertion to repeat its orientation.



Factor affecting handling time (1)

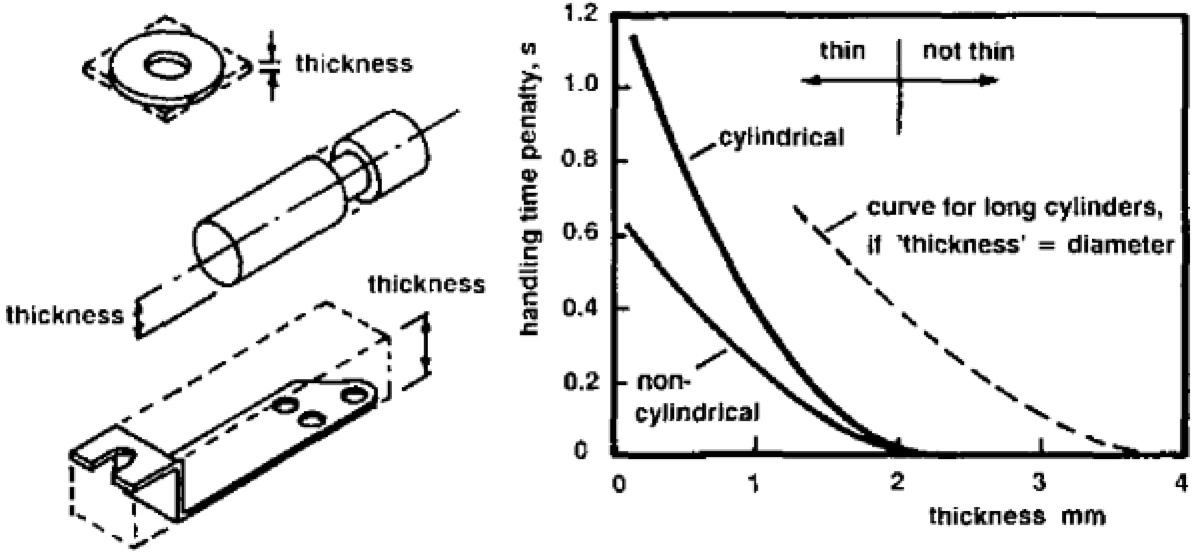


Effect of symmetry on the time required for part handling. Times are average for two individuals and shaded areas represent nonexistent values of the total angle of symmetry

Factor affecting handling time (2)

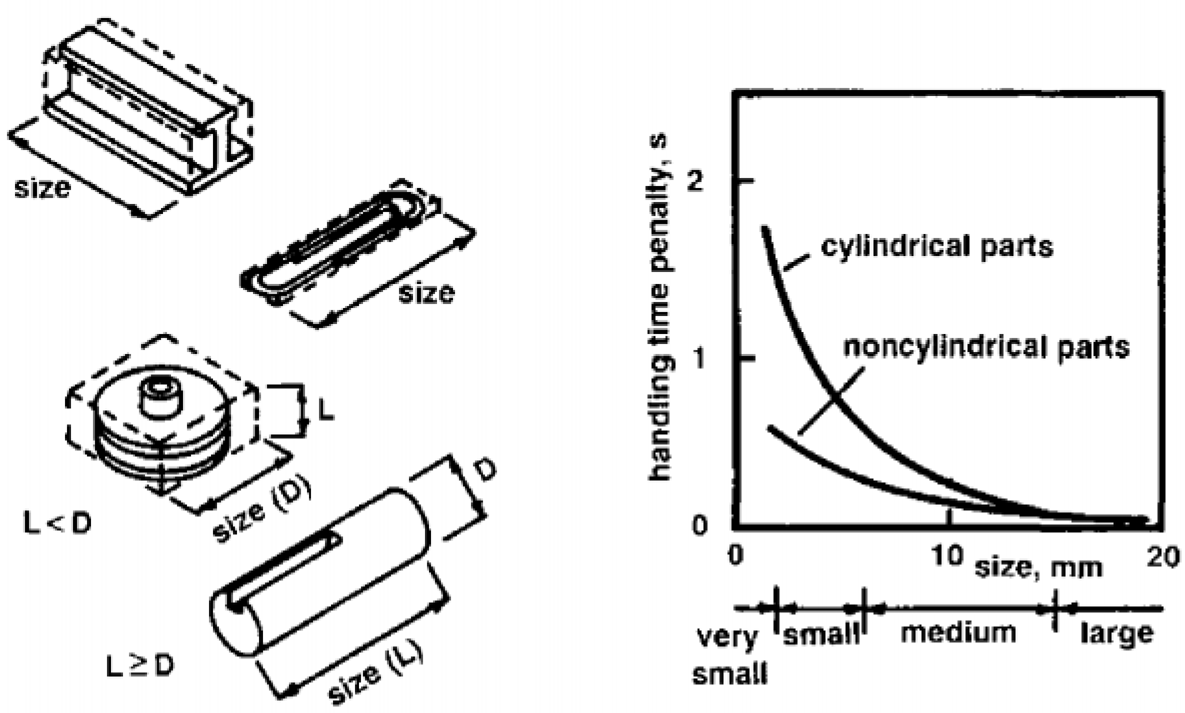
Thickness is defined for two kinds of component:

- In cylindrical is defined as its radius,
- In non-cylindrical parts is defined as the maximum height of the part with its smallest dimension extending from a flat surface



Factor affecting handling time (3)

The size (also called the major dimension) of a part is defined as the largest non-diagonal dimension of the part's outline when projected on a flat surface. It is normally the length of the part.



Factor affecting handling time (4)

The effect of increasing weight on grasping and controlling is found to be an additive time penalty and the effect on moving is found to be a proportional increase of the basic time. The following equation represent the total adjustment in handling time (t_{pw}):

$$t_{pw} = 0.0125W += 0.011W t_h$$

Where:

- W (Ib) is the weight of the part
- t_h (s) is the basic time for handling a "light" part when no orientation is needed and when it is to be moved a short distance.

* An average value for t_h is 1.13, and therefore the total time penalty due to weight would be approximately 0.025 W

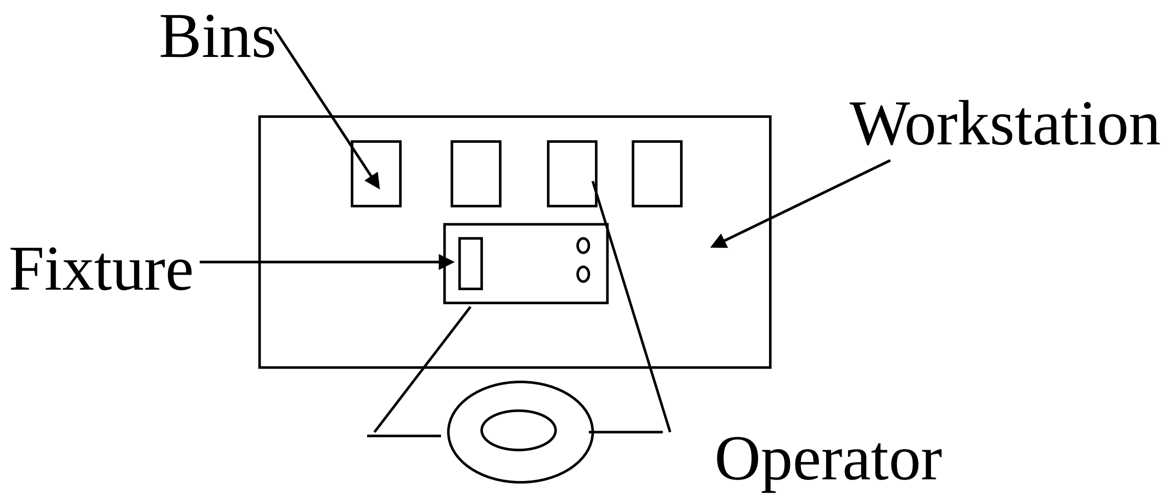
Parts requiring two hands manipulation

A part may require two hands for manipulation when:

- The part is heavy.
- Very precise or careful handling is required.
- The part is large or flexible.
- The part does not possess holding features, thus making one-hand grasp difficult.

Manual Insertion

(Affected by both the part geometry AND the part/parts to which it is placed/fastened/mated to)



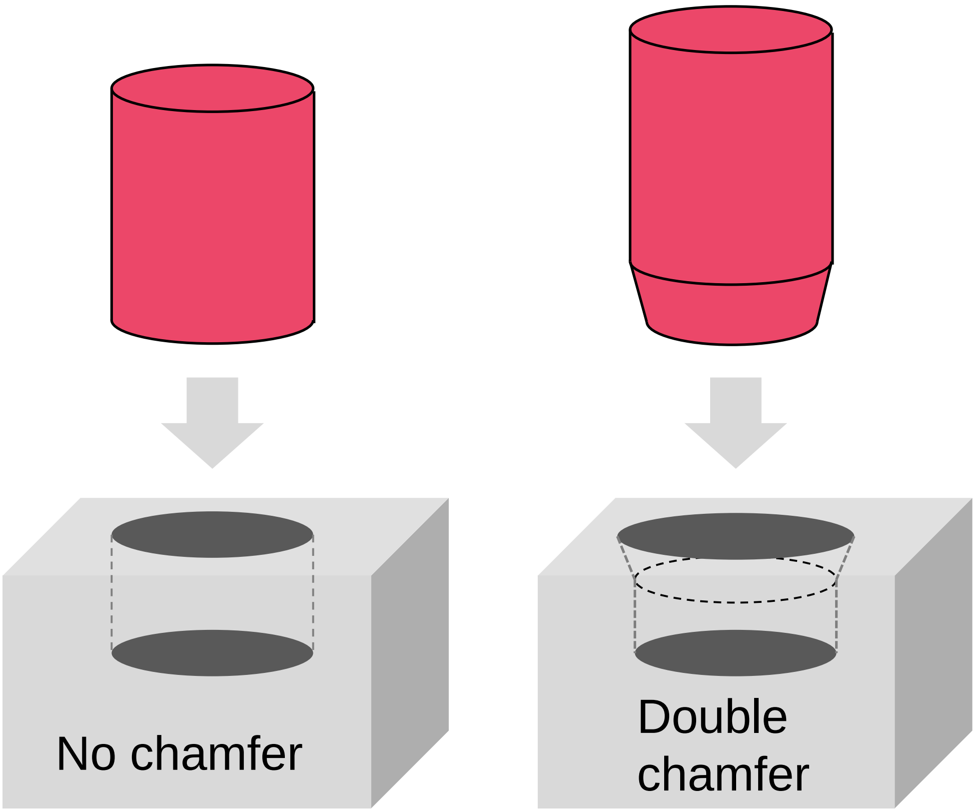
Operator

- places/fastens part onto a partially completed assembly/subassembly

Analysis of basic insertion: peg in hole

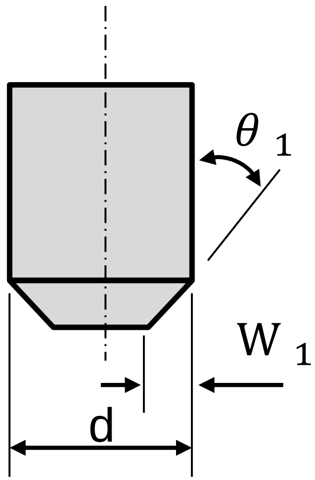
Two common assembly Operations are the insertion of a peg (or shaft) into a hole and the placement of a part with a hole onto a peg.

This Operation can be made easier by using a design feature called chamfer that can be defined as a transitional

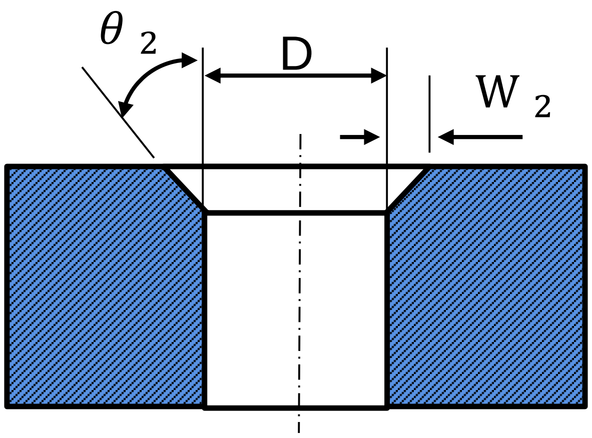


Chamfer design

Geometry of a peg



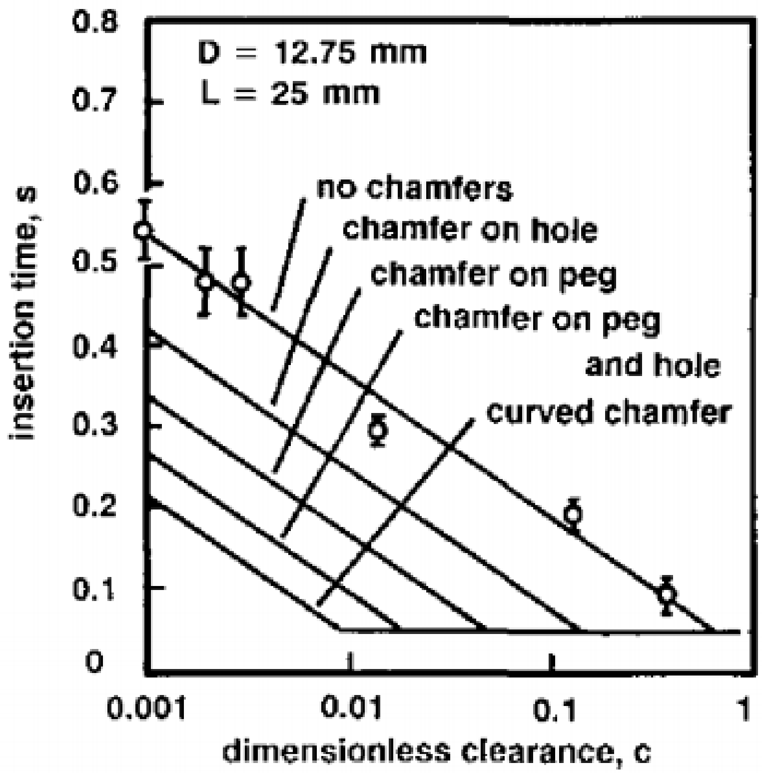
Geometry of a hole



In the design of a chamfered peg, d is the diameter of the peg, w_1 is the width of the chamfer, and θ_1 is the semiconical angle of the chamfer.

In a chamfered hole, D is the diameter of the hole, w_2 is the width of the chamfer, and θ_2 is the semi conical angle of the chamfer.

Chamfer design



Effect of clearance on insertion time

The dimensionless diametric clearance c between the peg and the hole is defined by:

$$c = (D - d)/D$$

Chamfer design

- For a given clearance, the difference in the insertion time for two different chamfer designs is always a constant.
- A chamfer on the peg is more effective in reducing insertion time than the same chamfer on the hole.
- The maximum width of the chamfer that is effective in reducing the insertion time for both the peg and the hole is approximately 0.1D
- For conical chamfers, the most effective design provides chamfers on both the peg and the hole, with $w_1 = w_2 = 0.1D$ and $\theta_1 = \theta_2 < 45$.
- The manual insertion time is not sensitive to variations in the angle of the chamfer for the range $10 < \theta < 50$.
- A radiused or curved chamfer can have advantages over a conical chamfer for small clearances.

Time of insertion

Empirical equations have been derived to estimate the manual insertion time t_i for both conical chamfers and curved chamfers. For conical chamfers where the width of 45° chamfers is 0.1d, the manual insertion time for a plain cylindrical peg t_i is given by

$$t_i = -70 \ln c + f(\text{chamfers}) + 3.7L + 0.75d \text{ ms}$$

or

$$t_i = 1.4L + 15 \text{ ms}$$

whichever is larger, and where

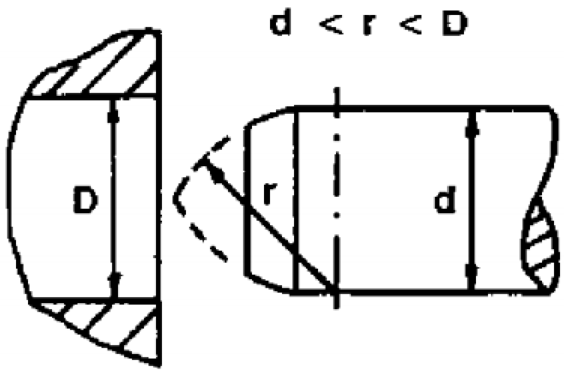
f(chamfers) = -100 (no chamfer)

- 220 (chamfer on hole)

-250 (chamfer on peg)

-370 (chamfer on peg and hole)

Time of insertion



For modified curved chamfers (see above) the insertion time is given by:

$$t_i = 1.4L + 15$$

Calculation example

Given: D = 20mm, d = 19.5mm, and L = 75mm. There are chamfers on both peg and hole.

From clearance eq.

$$c = (20 - 19.5)/20 = 0.025$$

From first eq.

Larger!

$$t_i = -70\ln(0.025) - 370 + 3.7(75) + 0.75(19.5) = \mathbf{181\ ms}$$

From second eq.

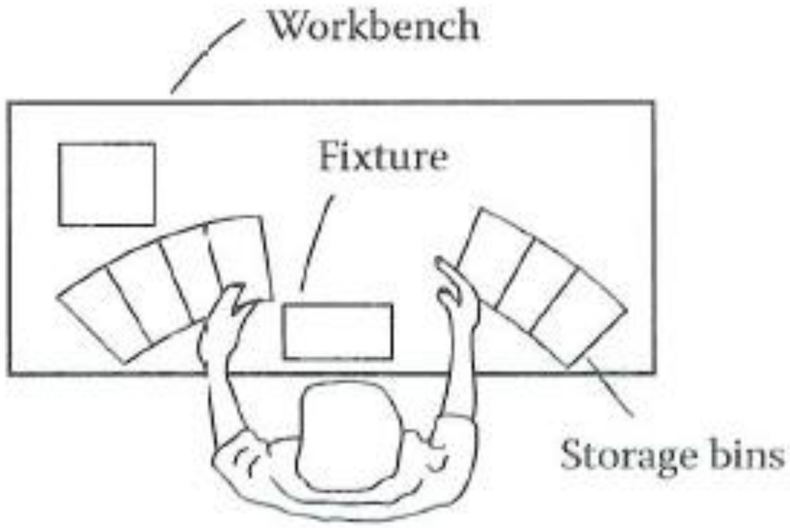
$$t_i = 120\text{ ms}$$

Manual assembly lines

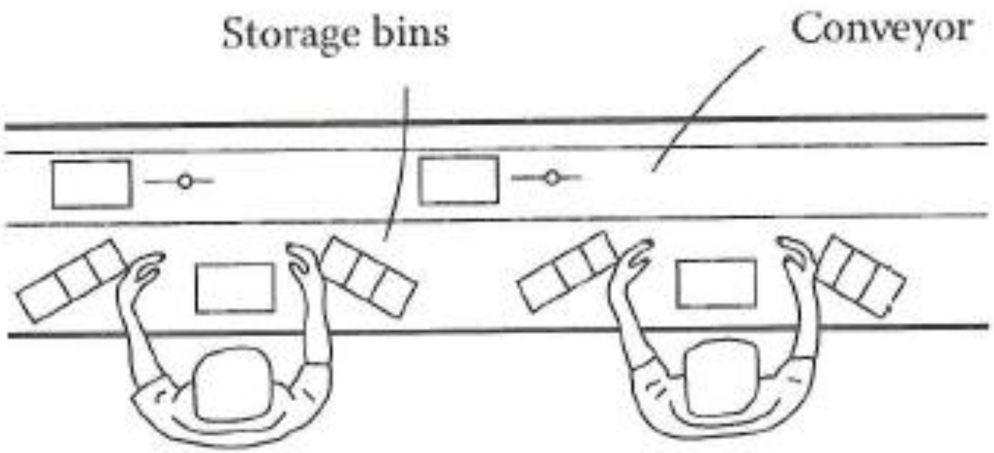
Possible approaches include:

1. Bench assembly
2. Multi-station assembly
3. Modular assembly center
4. Custom assembly
5. Flexible assembly
6. Multi-station assembly for large product

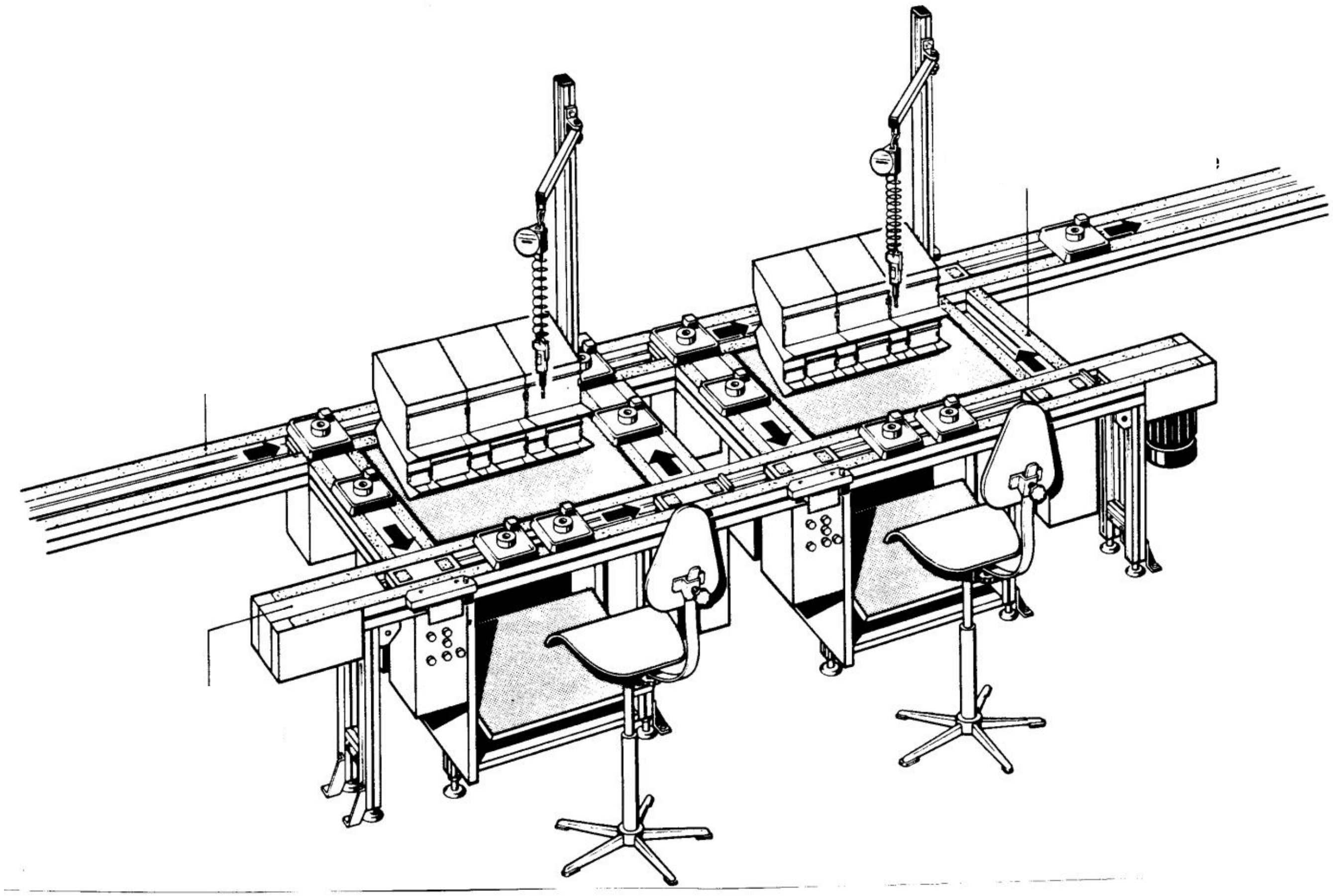
Bench assembly



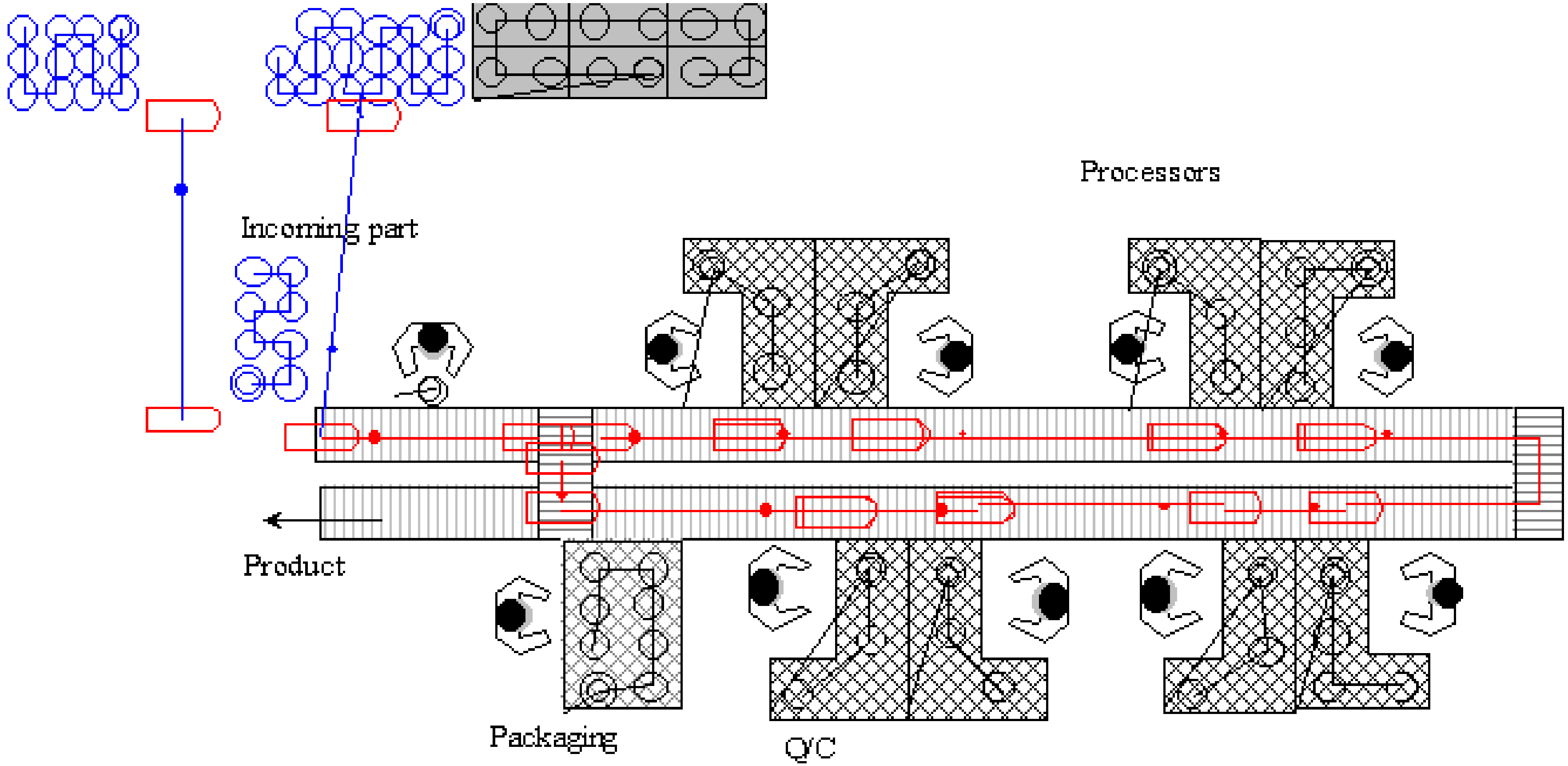
Multi-station assembly



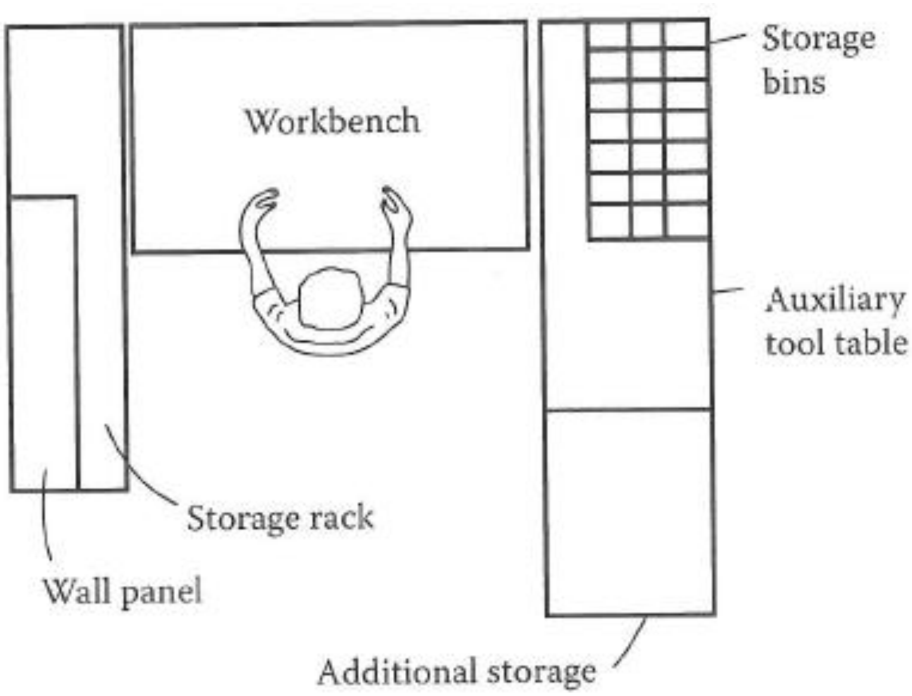
Typical multi-station assembly line



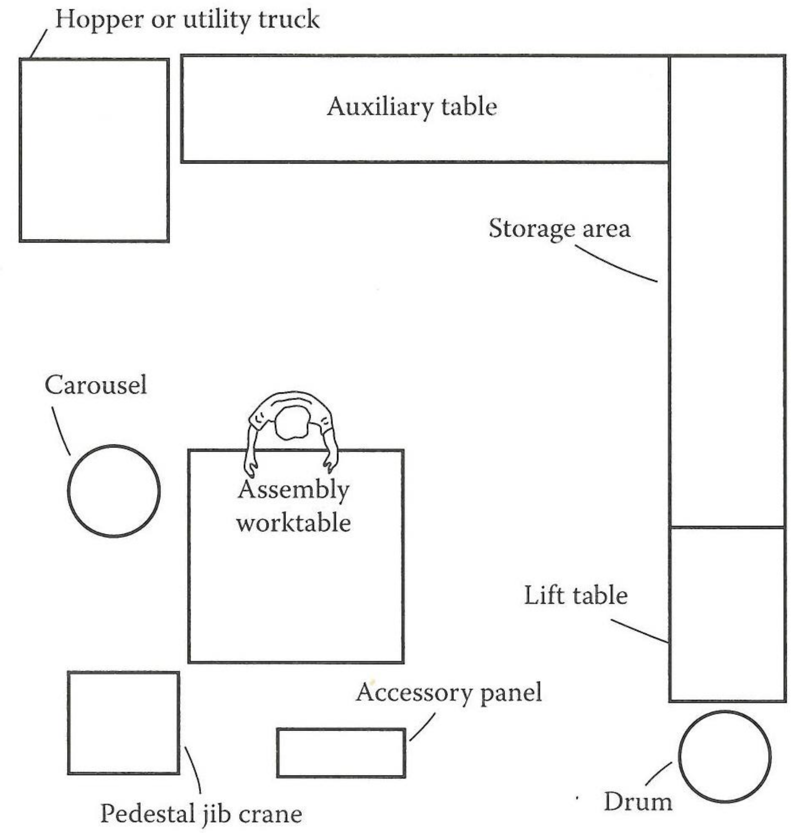
Typical multi-station assembly line



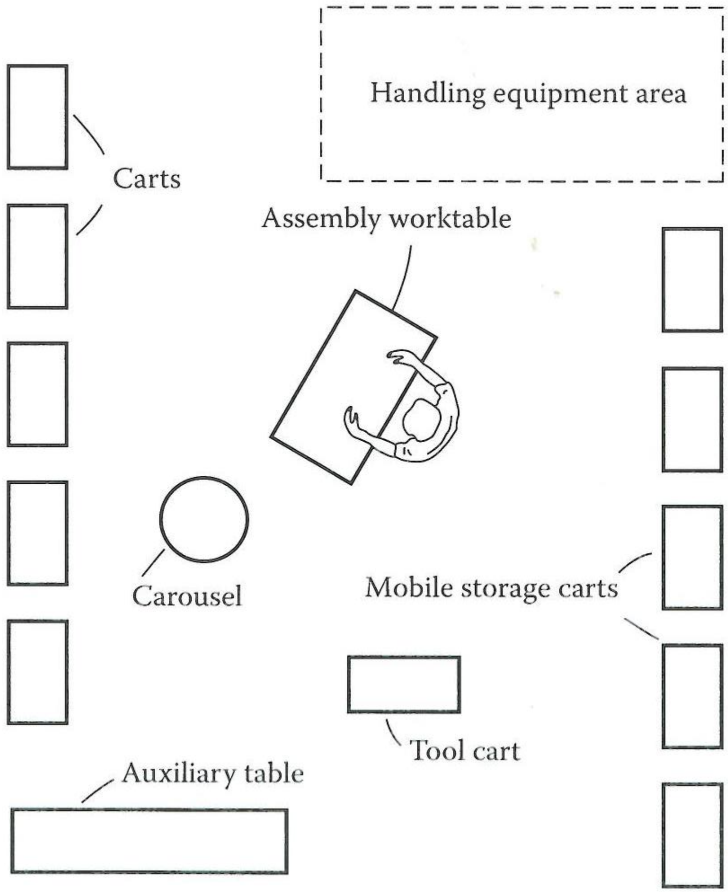
Modular assembly center



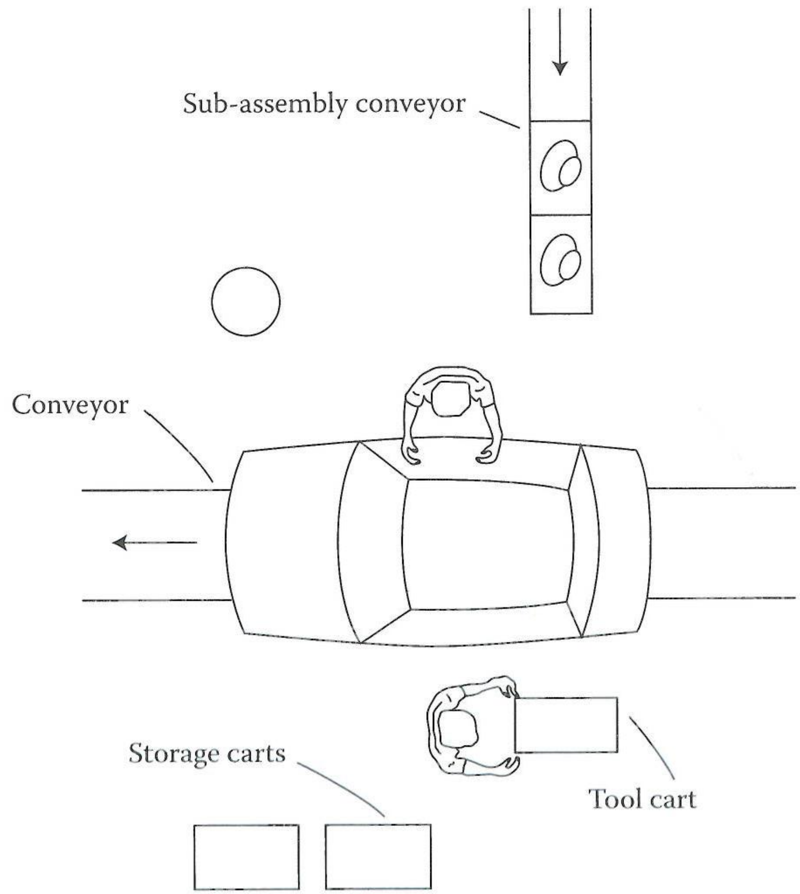
Custom assembly



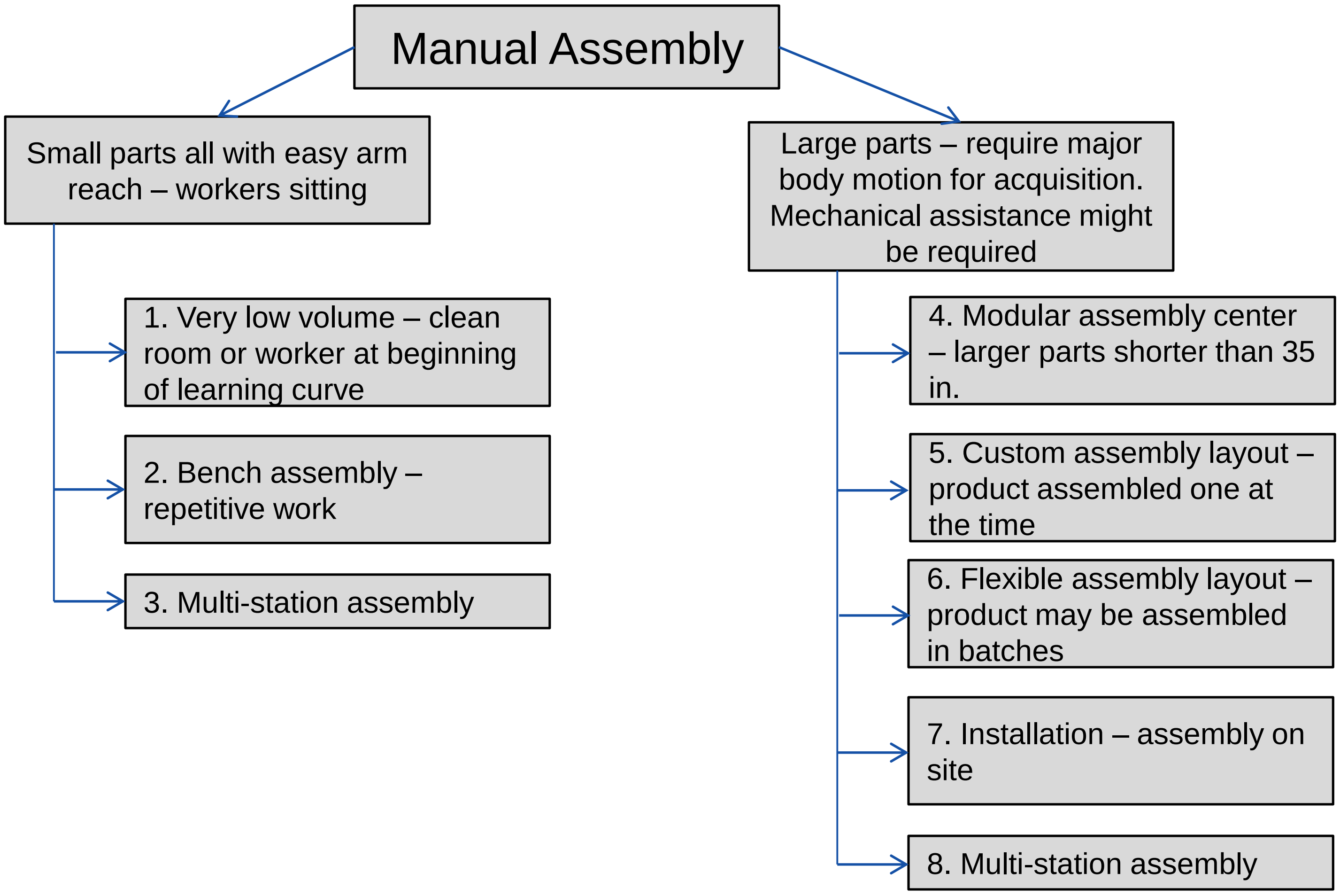
Flexible assembly



Multi-station assembly for large product



Manual assembly methods



Why Assembly Lines are so Productive

Specialization of labor

- Learning curve

Interchangeable parts

- Components made to close tolerances

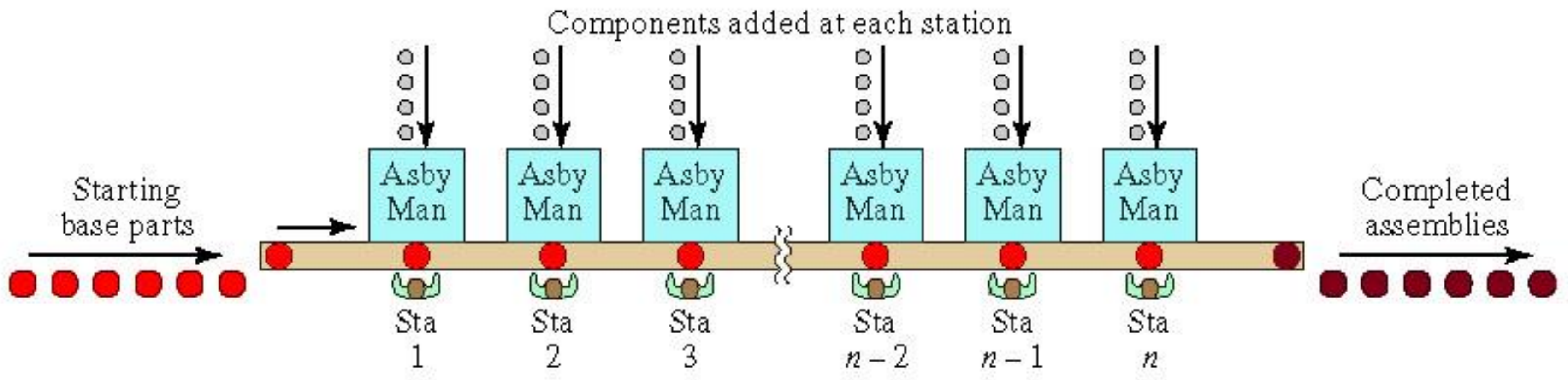
Work flow principle

- Products are brought to the workers

Line pacing

- Workers must complete their tasks within the cycle time of the line

Manual Assembly Line



Configuration of a manual assembly line with *n* manually operated workstations

Typical Products Made on Assembly Lines

- Automobiles
- Cooking ranges
- Dishwashers
- Dryers
- Furniture
- Lamps
- Luggage
- Microwave ovens
- Personal computers
- Power tools
- Refrigerators
- Telephones
- Toasters
- Trucks
- Video DVD players
- Washing machines

Manual Assembly Line

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

Assembly Workstation

A designated location along the work flow path at which one or more work elements are performed by one or more workers

Typical Operations performed at manual assembly stations

Adhesive application	Electrical connections	Snap fitting
Sealant application	Component insertion	Soldering
Arc welding	Press fitting	Stitching/stapling
Spot welding	Riveting	Threaded fasteners

Work Transport Systems

Two basic categories:

- Manual
- Mechanized

Manual Work Transport Systems

Work units are moved between stations by the workers without the aid of a powered conveyor

- Types:
  - Work units moved in batches
  - Work units moved one at a time
- Problems:
  - Starving of stations
  - Blocking of stations
  - No pacing

Mechanized Work Transport Systems

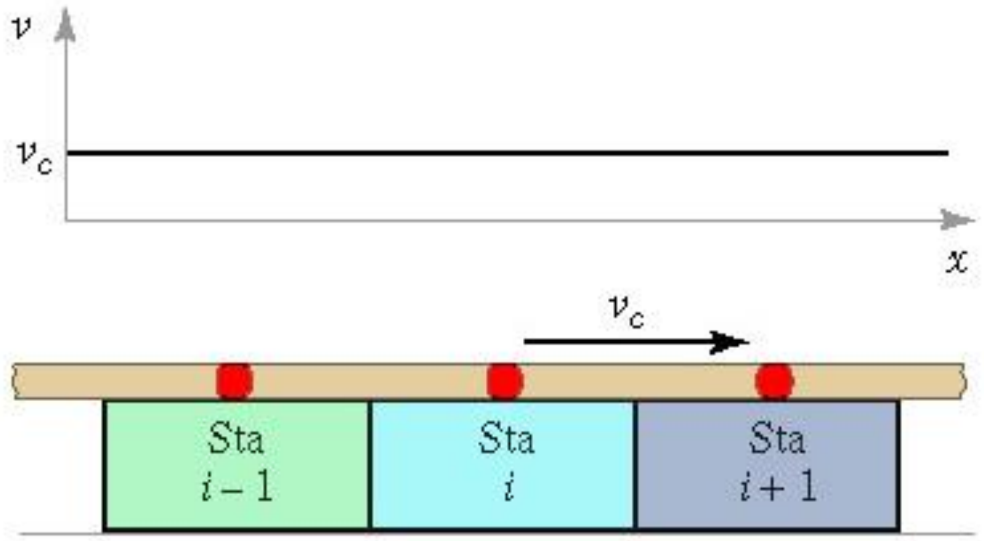
Work units are moved by powered conveyor or other mechanized apparatus

- Categories:
  - Work units attached to conveyor
  - Work units are removable from conveyor
- Problems
  - Starving of stations
  - Incomplete units

Types of Mechanized Work Transport

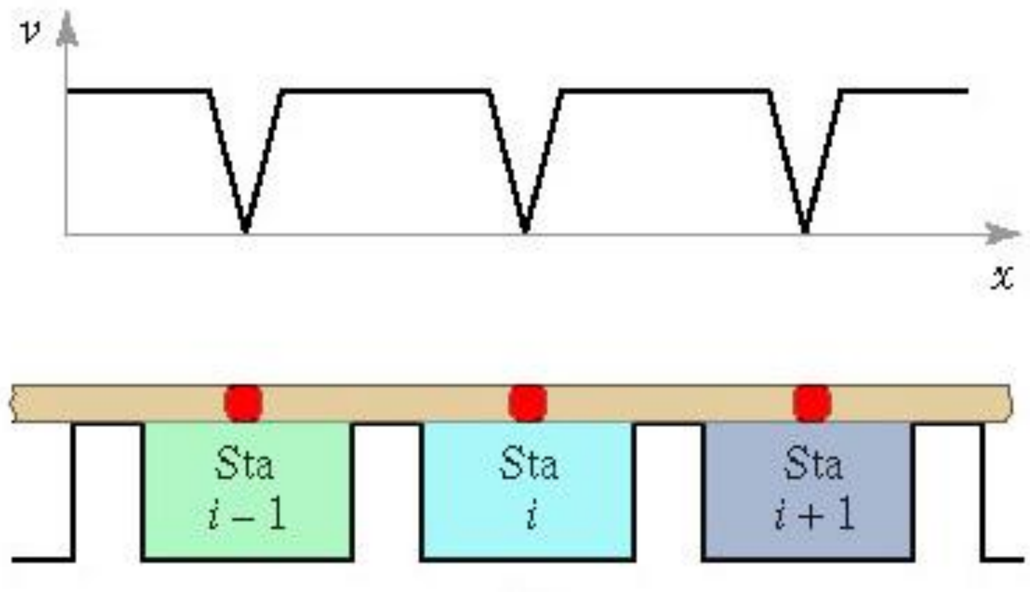
- Continuous transport
  - Conveyor moves at constant speed
- Synchronous transport
  - Work units are moved simultaneously with stop-and-go (intermittent) motion to next stations
- Asynchronous transport
  - Work units are moved independently between workstations
  - Queues of work units can form in front of each station

Continuous Transport



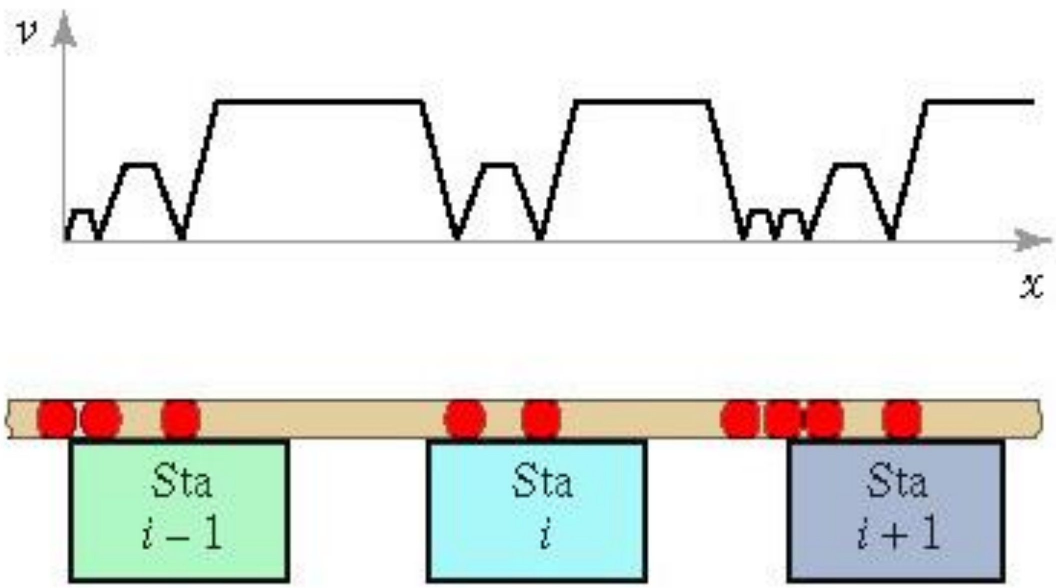
Conveyor moves at constant velocity v_c

Synchronous Transport



All work units are moved simultaneously to their respective next workstations with quick, discontinuous motion

Asynchronous Transport



Work units move independently, not simultaneously. A work unit departs a given station when the worker releases it. Small queues of parts can form at each station.

Material Handling Equipment for Mechanized Work Transport

Continuous transport

- Overhead trolley conveyor
- Belt conveyor
- Drag chain conveyor

Synchronous transport

- Walking beam
- Rotary indexing machine

Asynchronous transport

- Power-and-free conveyor
- Cart-on-track conveyor
- Automated guided vehicles

Line Pacing

- A manual assembly line operates at a certain cycle time - On average, each worker must complete his/her assigned task within this cycle time
- Pacing provides a discipline for the assembly line workers that more or less guarantees a certain production rate for the line
- Several levels of pacing:
    1. Rigid pacing
    2. Pacing with margin
    3. No pacing

Rigid Pacing

Each worker is allowed only a certain fixed time each cycle to complete the assigned task

- Allowed time is set equal to the cycle time less repositioning time
- Synchronous work transport system provides rigid pacing

Undesirable aspects of rigid pacing:

- Incompatible with inherent human variability
- Emotionally and physically stressful to worker
- Incomplete work units if task not completed

Pacing with Margin

Worker is allowed to complete the task within a specified time range, the upper limit of which is greater than the cycle time

On average, the worker's average task time must balance with the cycle time of the line

How to achieve pacing with margin:

- Allow queues of work units between stations
- Provide for tolerance time to be longer than cycle time
- Allow worker to move beyond station boundaries

No Pacing

No time limit within which task must be completed

Each assembly worker works at his/her own pace

No pacing can occur when:

- Manual transport of work units is used
- Work units can be removed from the conveyor to perform the task
- An asynchronous conveyor is used

Coping with Product Variety

Single model assembly line (**SMAL**)

- Every work unit is the same

Batch model assembly line (**BMAL**)

- Hard product variety
- Products must be made in batches

Mixed model assembly line (**MMAL**)

- Soft product variety
- Models can be assembled simultaneously without batching

MMAL vs. BMAL

Advantages of mixed model lines over batch models lines:

- No lost production time between models
- High inventories typical of batch production are avoided
- Production rates of different models can be adjusted as product demand changes

MMAL vs. BMAL

Difficulties with mixed model line compared to batch model line

- Line balancing problem more complex due to differences in work elements among models
- Scheduling the sequence of the different models is a problem
- Logistics is a problem - getting the right parts to each workstation for the model currently there
- Cannot accommodate as wide model variations as BMAL

Line Balancing Problem

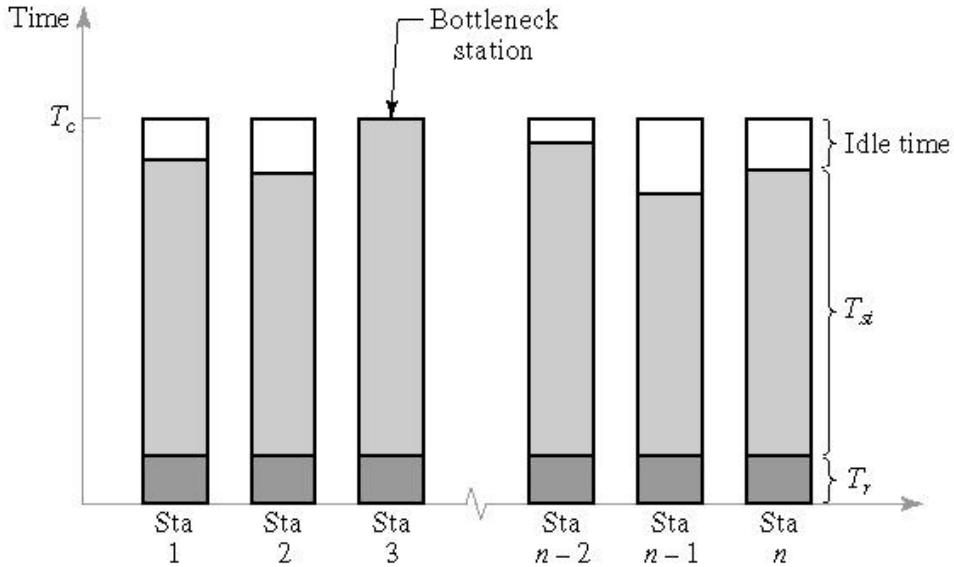
Given:

- 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: There is a production rate needed, i.e. how many products needed per time period

Problem:

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

Components of Cycle Time T_c



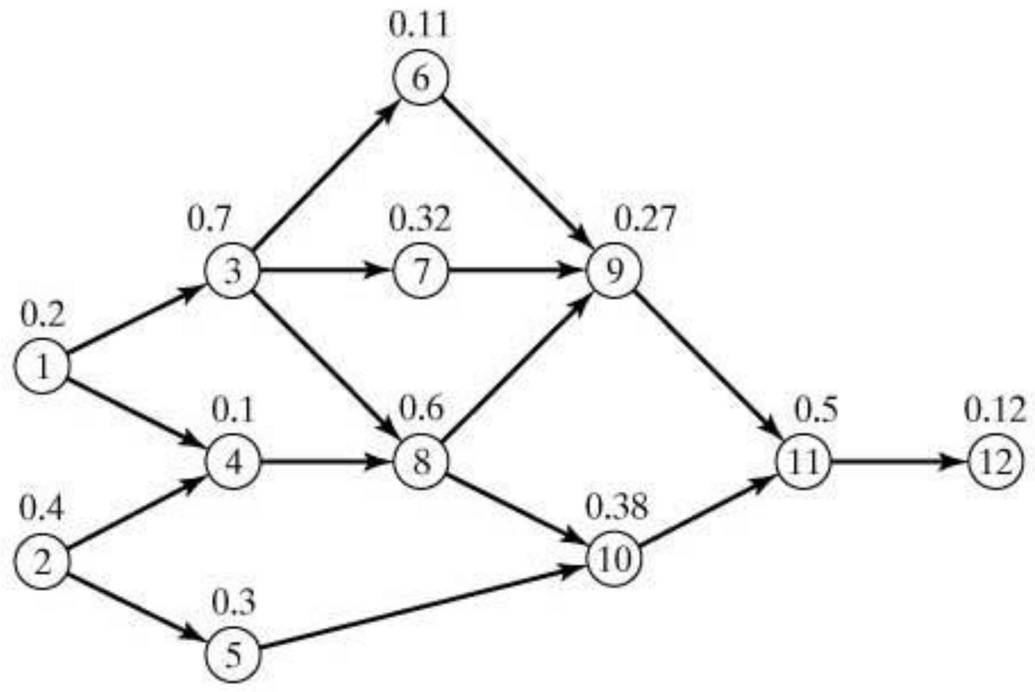
T_{si} = service time
T_r = repositioning time

Components of cycle time at several workstations on a manual assembly line. At the bottleneck station, there is no idle time.

Precedence Constraints

Restrictions on the order in which work elements can be performed

Precedence diagram



Line Balancing Algorithms

Largest Candidate Rule

- Assignment of work elements to stations based on amount of time each work element requires

Kilbridge and Wester Method

- Assignment of work elements to stations based on position in the precedence diagram
- Elements at front of diagram are assigned first

Ranked Positional Weights

- Combines the two preceding approaches by calculating an RPW for each element

Mixed Model Assembly Lines

A manual production line capable of producing a variety of different product models simultaneously and continuously (not in batches)

Problems in designing and operating a MMAL:

- Determining number of workers on the line
- Line balancing - same basic problem as in SMAL except differences in work elements among models must be considered
- Model launching - determining the sequence in which different models will be launched onto the line

Other Considerations in Line Design

Line efficiency

- Management is responsible to maintain line Operation at efficiencies (proportion uptime) close to 100%
  - Implement preventive maintenance
  - Well-trained emergency repair crews to quickly fix breakdowns when they occur
  - Avoid shortages of incoming parts to avoid forced downtime
  - Insist on highest quality components from suppliers to avoid downtime due to poor quality parts

Other Considerations - continued

Methods analysis

- To analyze methods at bottleneck or other troublesome workstations

Subdividing work elements

- It may be technically possible to subdivide some work elements to achieve a better line balance

Sharing work elements between two adjacent stations

- Alternative cycles between two workers

Other Considerations - continued

Utility workers

- To relieve congestion at stations that are temporarily overloaded

Changing workhead speeds at mechanized stations

- Increase power feed or speed to achieve a better line balance

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

Other Considerations - continued

Zoning constraints - limitations on the grouping of work elements and/or their allocation to workstations

- Positive zoning constraints
  - Work elements should be grouped at same station
  - Example: spray painting elements
- Negative zoning constraints
  - Elements that might interfere with each other
  - Separate delicate adjustments from loud noises

Other Considerations - continued

Position constraints

- Encountered in assembly of large products such as trucks and cars, making it difficult for one worker to perform tasks on both sides of the product
- To address, assembly workers are positioned on both sides of the line

Alternative Assembly Systems

- Single-station manual assembly cell
- Worker teams
- Automated assembly systems

Single-Station Manual Cell

A single workstation in which all of the assembly work is accomplished on the product or on some major subassembly

- Common for complex products produced in small quantities, sometimes one-of-a-kind
  - Custom-engineered products
  - Prototypes
  - Industrial equipment (e.g., machine tools)

Assembly by Worker Teams

Multiple workers assigned to a common assembly task

- Workers set their own pace
- Examples
  - Single-station cell with multiple workers
  - Swedish car assembly (job enlargement) - product is moved through multiple workstations by AGVS, but same worker team follows it from station to station

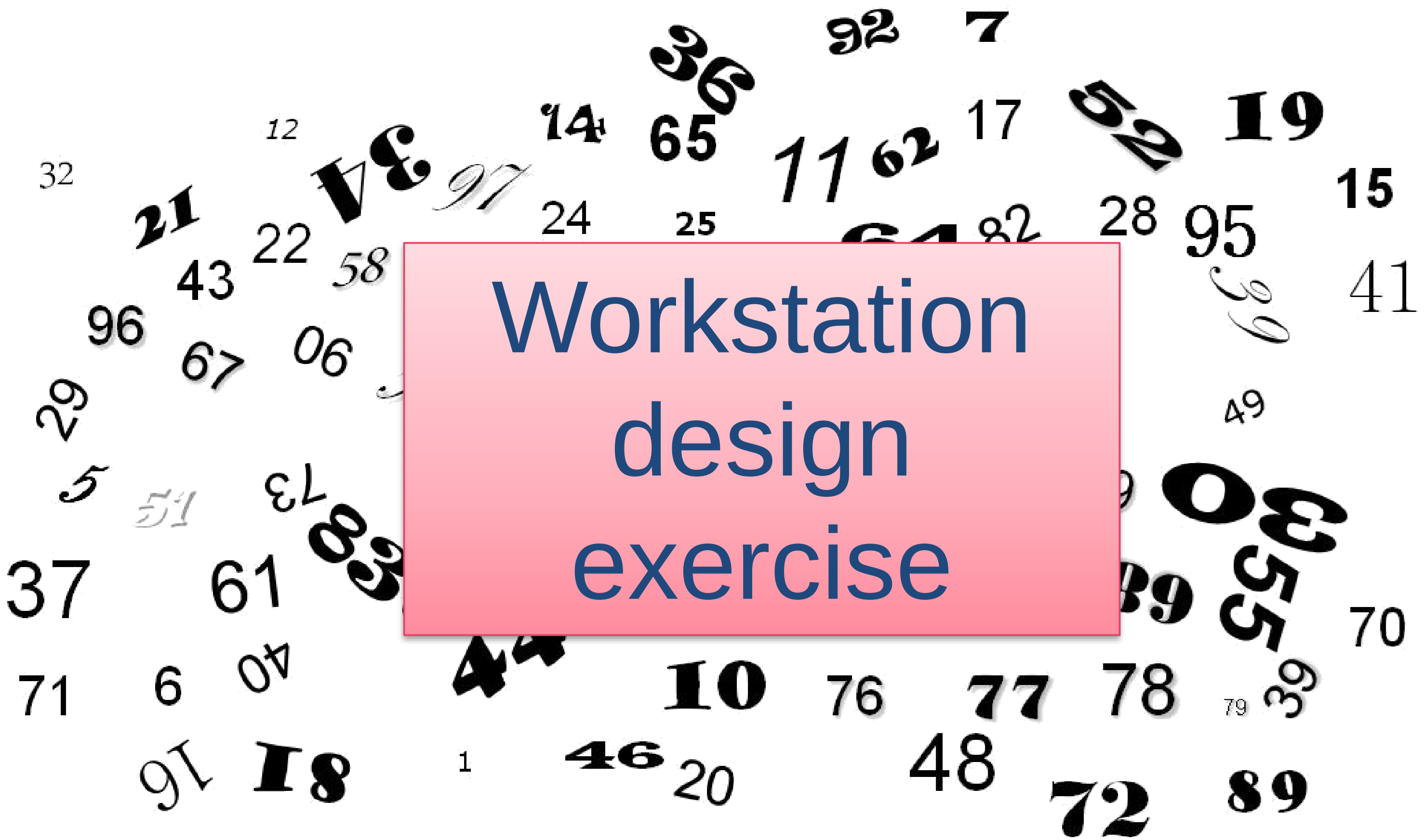
Reported Benefits of Team Assembly

- Greater worker satisfaction
- Better product quality
- Increased capability to cope with model variations
- Greater ability to cope with problems that require more time rather than stopping the entire production line

Disadvantage:

- Team assembly is not capable of the high production rates of a conventional assembly line

Workstation design



Workstation design exercise

3 48 30 87 69 33 45 27 72

75 21 57 9 24 51 78 55 18 6 63 36

12 39 66 84 42 60 15 81 90

29 74 65 2 68 77 86 80 53 62

20 5 56 23 32 41 8 35 44 68 83

38 47 11 14 59 50 26 17 71

28 54 64 49 40 31 61 34 7

10 1 22 58 76 16 88 52

73 46 19 37 82 85 13 4 67 79 43 70 25

3 48 30 33 45 27

21 6 24 18 9 36

12 42 15

39 2

29

5

20 32 41 23 8 44 35

38 47 11 14 26 17

28 49 40 31 16 34 7

10 22

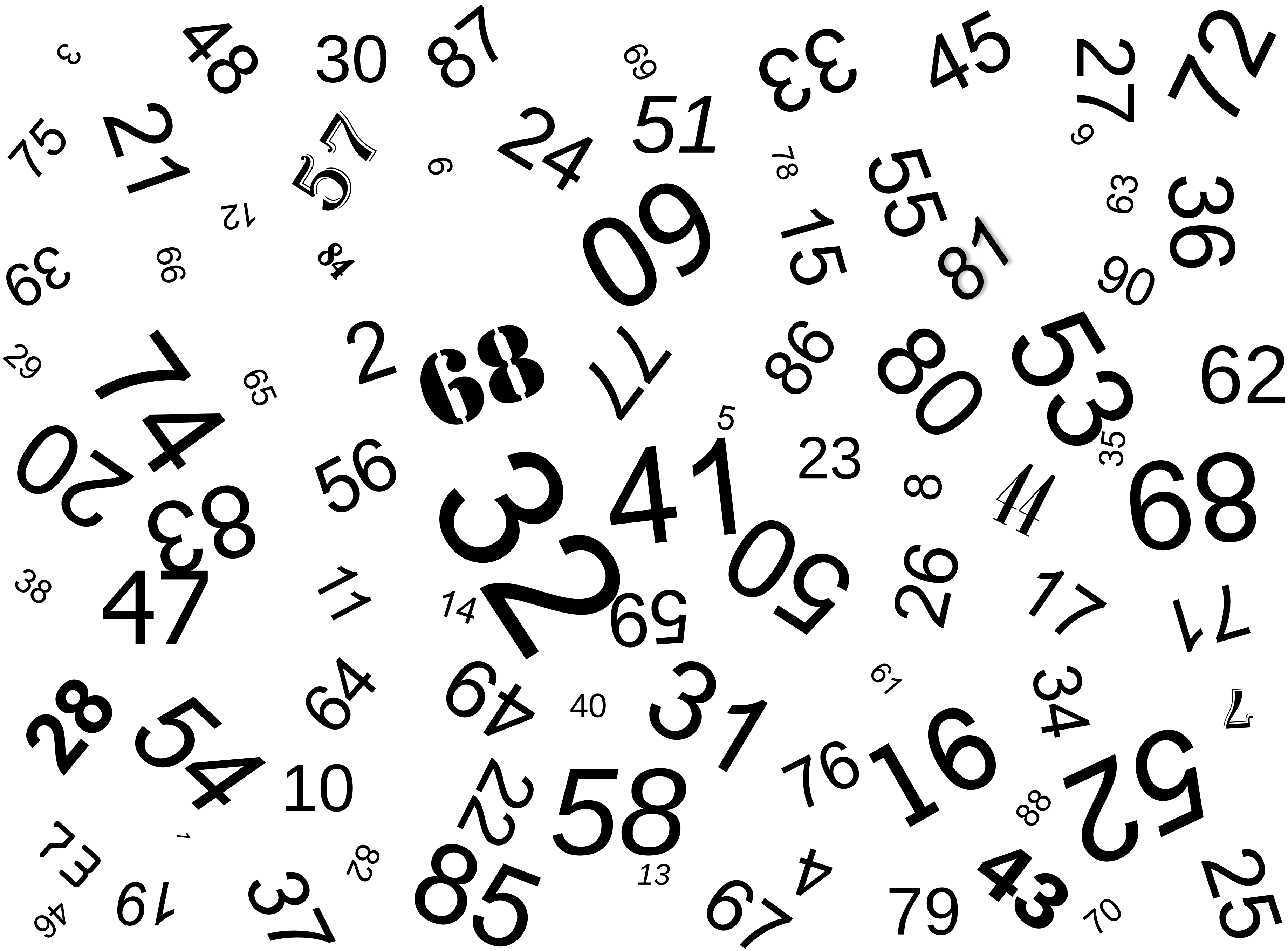
1 13 4 43 25

46 19 37

3 48 30 21 12 39	33 24 6 15 42	45 27 9 18 36
29 2 20 38 47 11	5 41 23 32 14	35 8 44 26 17
28 10 1 46 19 37	49 40 31 22 13 4	34 7 16 43 25

Numbers from 1 to 49

1	2	3	4	5	6	7	8	9	10
11	12	*13*	14	15	**16**	17	*18*	*19*	20
21	22	23	24	25	26	27	**28**	29	30
31	32	33	34	35	36	*37*	38	39	40
41	***42***	**43**	44	45	46	47	48	49	

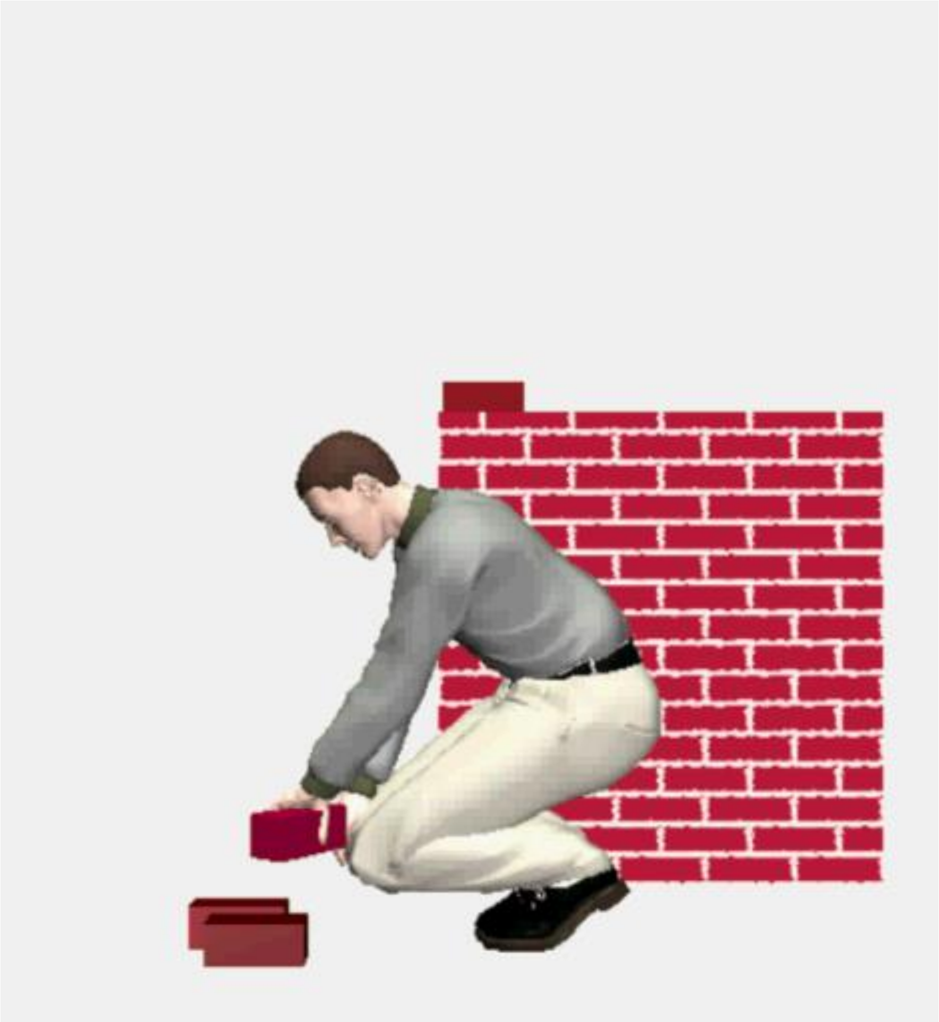

3 48 30 87 69 33 45 27 72
75 21 57 6 24 51 78 9 55
12 60 15 63 36 81 90
39 66 84
29 74 2 68 77 86 80 53 62 65
5 20 56 23 35 8 32 41 44 68 83
38 47 11 14 59 50 26 17 71
61 28 64 49 40 31 34 7
54 10 76 16 52 22 58 88
73 1 82 13 4 43 25 46 19 37 85 67 79 70

Numbers from 1 to 49

1	2	3	4	5	6	7	8	9	10
11	12	*13*	14	15	**16**	17		*19*	20
21	22	23	24	25	26	27	**28**	29	30
31	32	33	34	35	36	37	38	39	40
41		**43**	44	45	46	47	48	49	

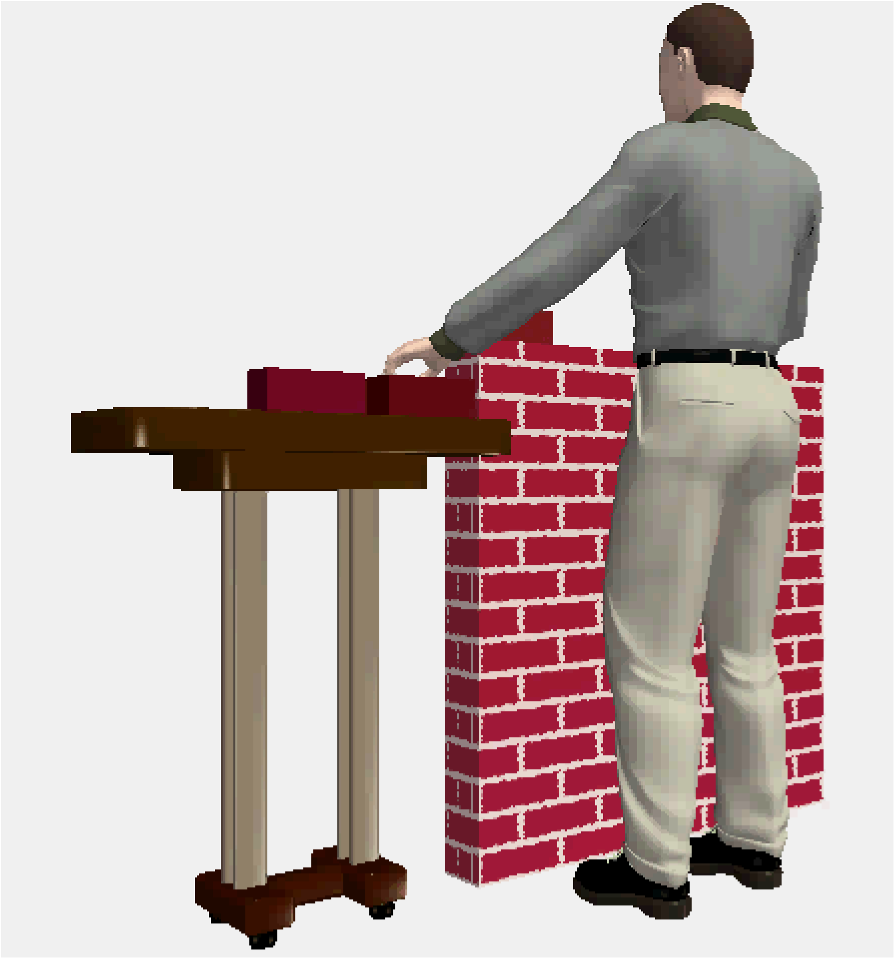
Waste of…?

Waste is often built into jobs



Waste of…?

The solution is obvious but we have to recognize first that we have a problem !



Waste of motion

Waste of motion is any motion of a resource (can be both operator or equipment) that does not add value to the product or service.

Underlying reasons might be

- Ergonomically poor conditioned workstations (excessive walking, bending, reaching etc.)
- Poor method design – transferring parts from one hand to the other
- Poor workplace organization
- Reorientation of materials

Recap on line balancing problem and example

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.
- Demand rate → production rate → cycle time
- Annual demand D_a must be reduced to an hourly production rate Rp

$$R_p = \frac{D_a}{52 S_w H_{sh}}$$

Where:

D_a = annual demand

R_p = hourly production rate

S_w = number of shifts/week

H_{sh} = number of hours/shif

52 = W_y weeks in one year

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.

$$T_c = \frac{60E}{R_p}$$

where production rate, R_p, is converted to a cycle time, T_c, accounting for line efficiency, E

Number of station required

- Work content time (T_p): The total time of all work elements that must be performed to produce one unit of the work unit.
- The theoretical minimum number of stations that will be required to on the line to produce one unit of the work unit,

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

where

Twc = work content time, min; Twc = $\sum T_{ek}$

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

$T_{max} = T_c – T_r$

Where T_r = time of repositioning

Line balancing problem (imperfect balancing):

It is not possible to divide the work content time 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 some 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 unit just completed to the upstream unit entering the station
- In conveyor systems, time is required to remove work units from the conveyor and position it at the station for worker to perform his task.

Repositioning losses

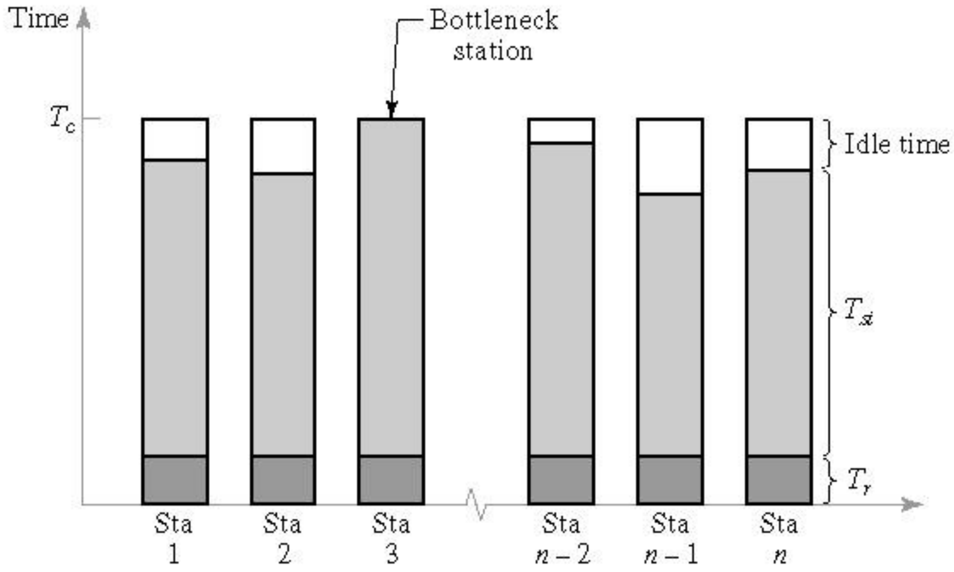
- Repositioning time = time available each cycle for the worker to position = T_r
- Service time = time available each cycle for the worker to work on the product = T_s

- Service time $T_s = Max\{T_{si}\} \leq T_c - T_r$

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

- Repositioning efficiency $\eta_r = \frac{T_{max}}{T_c}$

Components of Cycle Time T_c



T_{si} = service time
T_r = repositioning time

Components of cycle time at several workstations on a manual assembly line. At the bottleneck station, there is no idle time.

Accounting of other losses

Efficiency of balancing

$$\eta_b = \frac{T_p}{N\, T_{max}}$$

Overal efficiency is given by

- $\eta = \eta_L$ (line efficiency) * η_R (repositioning efficiency) * η_B (balancing efficiency)

So the final number of station required is given by:

$W = R_p\, T_p / 60\, \eta$

Line Balancing Problem

Given:

- 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: There is a production rate needed, i.e. how many products needed per time period

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

- Total work content time T_{wc}

$$T_{wc} = \sum_{k=1}^{n_e} T_{ek}$$

where T_{ek} = work element time for element k

- Work elements are assigned to station i that add up to the service time for that station

$$T_{si} = \sum_{k \in i} T_{ek}$$

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

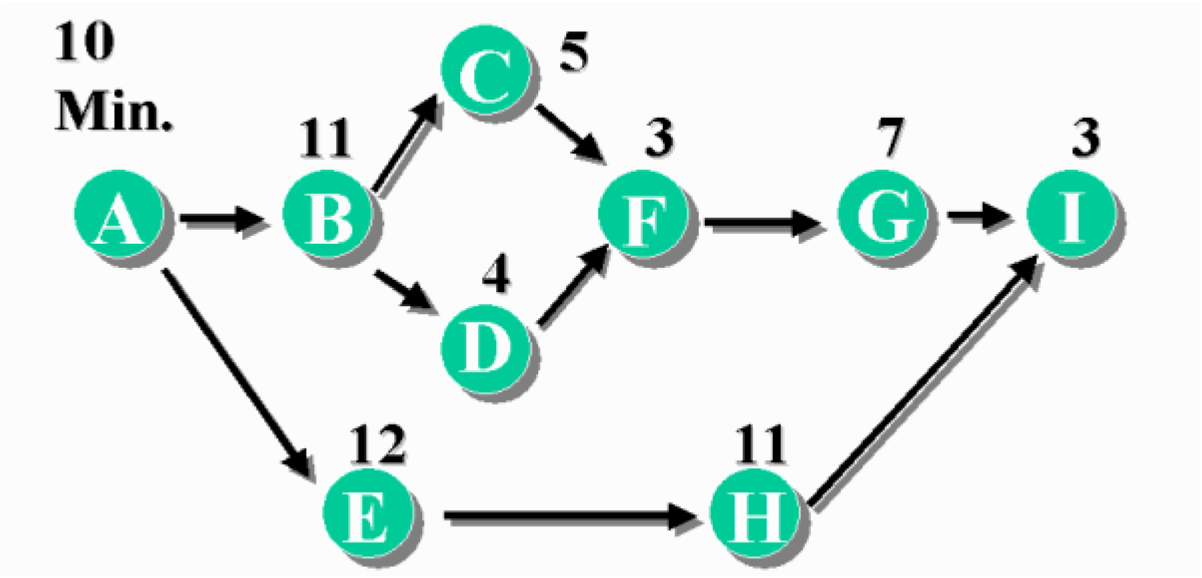
$$T_{wc} = \sum_{i=1}^{n} T_{si}$$

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_{si}, 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

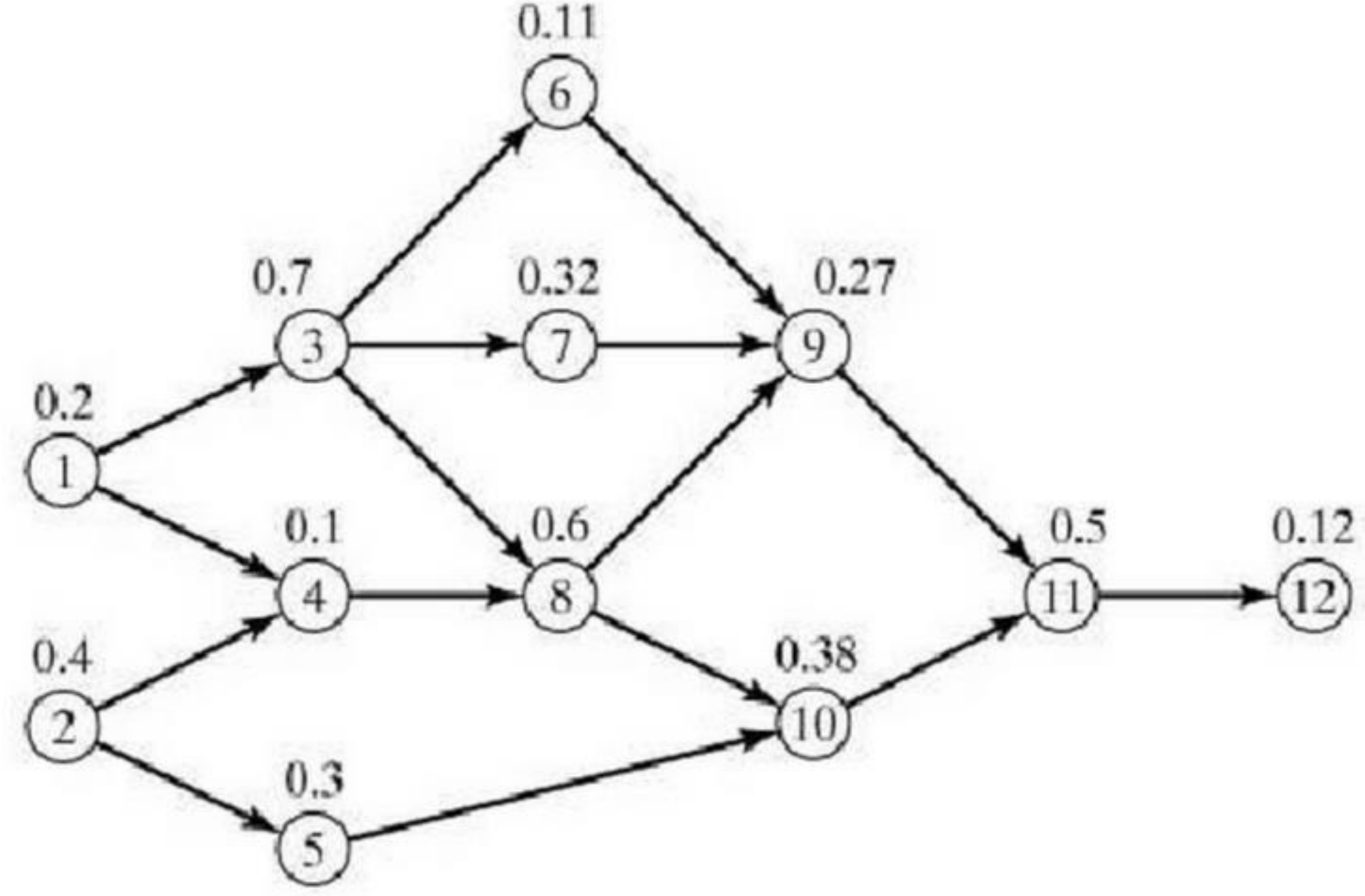
- Some elements must be done before the others.
- Restrictions on the order in which work elements can be performed
- Can be represented graphically (precedence diagram)



Example

No.	Work Element Description	T_{ek} (min)	Must Be Preceded by
1	Place frame in workholder and clamp	0.2	—
2	Assemble plug, grommet to power cord	0.4	—
3	Assemble brackets to frame	0.7	1
4	Wire power cord to motor	0.1	1,2
5	Wire power cord to switch	0.3	2
6	Assemble mechanism plate to bracket	0.11	3
7	Assemble blade to bracket	0.32	3
8	Assemble motor to brackets	0.6	3,4
9	Align blade and attach to motor	0.27	6,7,8
10	Assemble switch to motor bracket	0.38	5,8
11	Attach cover, inspect, and test	0.5	9,10
12	Place in tote pan for packing	0.12	11

Example



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 lost=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: solutions

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

$$T_{wc}=4.0 \text{ min}$$

$$T_{wc} = \sum_{k=1}^{n_e} T_{ek}$$

(b) The hourly production rate

$$R_p = \frac{100{,}000}{50(5)(7.5)} = 53.33 \text{ units/hr}$$

$$R_p = \frac{D_a}{50 S_w H_{sh}}$$

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

$$T_c = \frac{60(0.96)}{53.33} = 1.08 \text{ min}$$

$$T_c = \frac{60E}{R_p}$$

(d) The minimum number of workers:

w^* = (Minimum Integer ≥ 4.0 /1.08=3.7)=4 workers $w^* = \frac{T_{wc}}{T_c}$

(e) The available service time

$$T_s=1.08-0.08=1.00 \text{ min}$$

$$T_s = T_c - T_r$$

Line balancing objectives

- To distribute the total work content on the assembly lines evenly as possible among the workers
- Minimize (wTs – Twc)

or

- Minimize $\sum_{i=1}^{w}\left(T_s - T_{si}\right)$

Subject to:

(1) $\sum_{k \in i} T_{ek} \leq T_s$

(2) all precedence requirements are obeyed

Line Balancing Algorithms

Largest Candidate Rule

- Assignment of work elements to stations based on amount of time each work element requires

Kilbridge and Wester Method

- Assignment of work elements to stations based on position in the precedence diagram
- Elements at front of diagram are assigned first

Ranked Positional Weights

- Combines the two preceding approaches by calculating an RPW for each element

Largest Candidate Rule

List all work elements in descending order based on their T_{ek} values; then,

1. Start at the top of the list and selecting the first element that satisfies precedence requirements and does not cause the total sum of T_{ek} to exceed the allowable T_s 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

TABLE 4.4 Work Elements Arranged According to T_{ek} Value for the Largest Candidate Rule

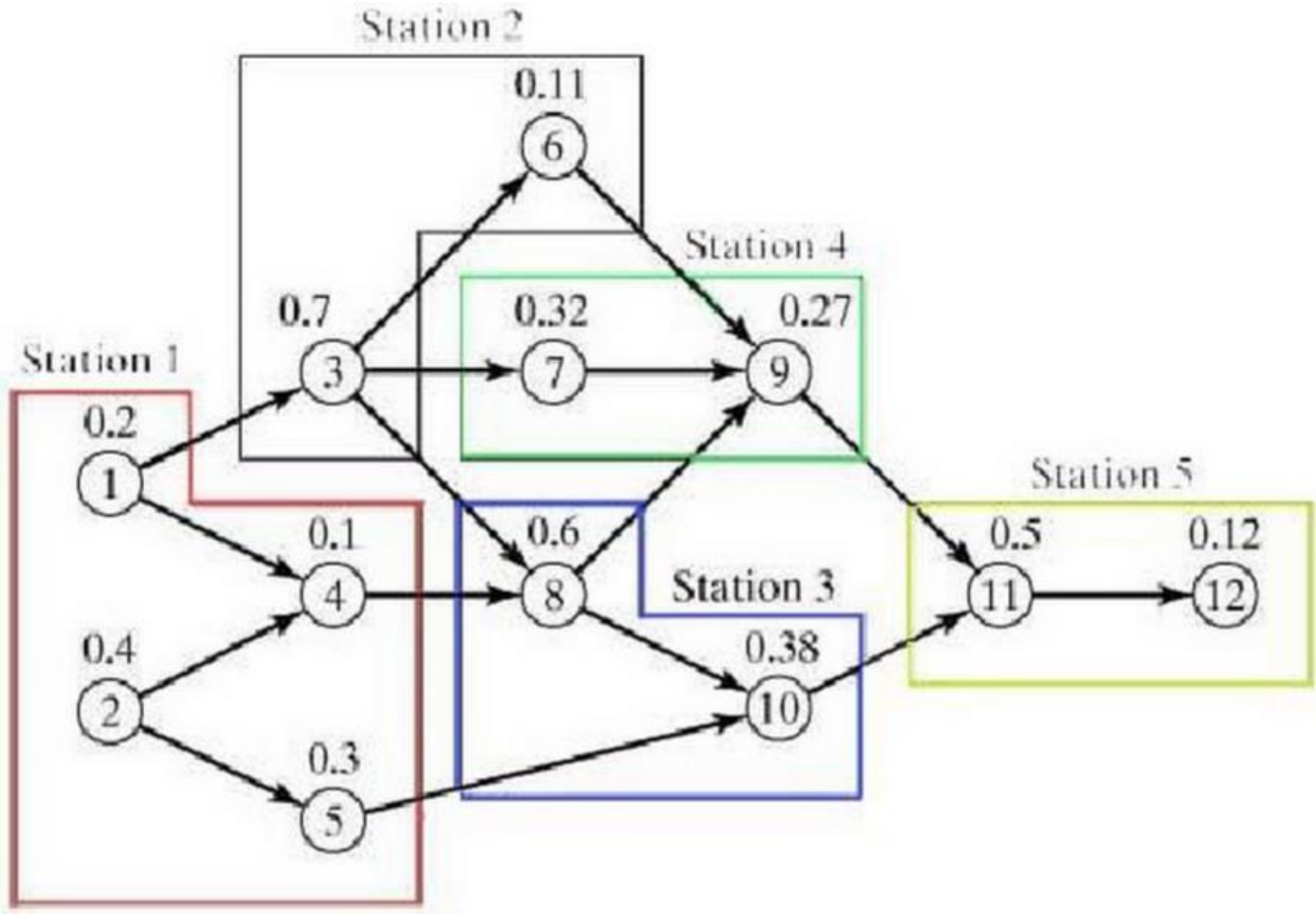
Work Element	T_{ek} (min)	Preceded by
3	0.7	1
8	0.6	3,4
11	0.5	9,10
2	0.4	—
10	0.38	5,8
7	0.32	3
5	0.3	2
9	0.27	6,7,8
1	0.2	—
12	0.12	11
6	0.11	3
4	0.1	1,2

Solution for Largest Candidate Rule

TABLE 4.5 Work Elements Assigned to Stations According to the Largest Candidate Rule

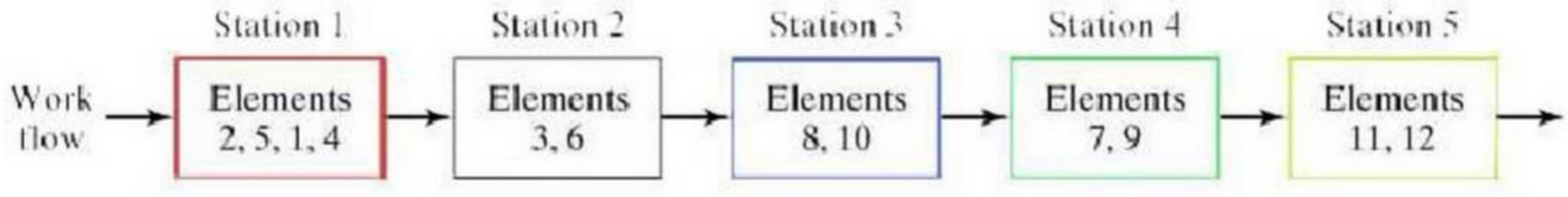
Station	Work Element	T_{ek} (min)	Station Time (min)
1	2	0.4	
	5	0.3	
	1	0.2	
	4	0.1	1.0
2	3	0.7	
	6	0.11	0.81
3	8	0.6	
	10	0.38	0.98
4	7	0.32	
	9	0.27	0.59
5	11	0.5	
	12	0.12	0.62

Solution for Largest Candidate Rule



Solution for Largest Candidate Rule

Physical layout of workstations and assignment of elements to stations using the largest candidate rule

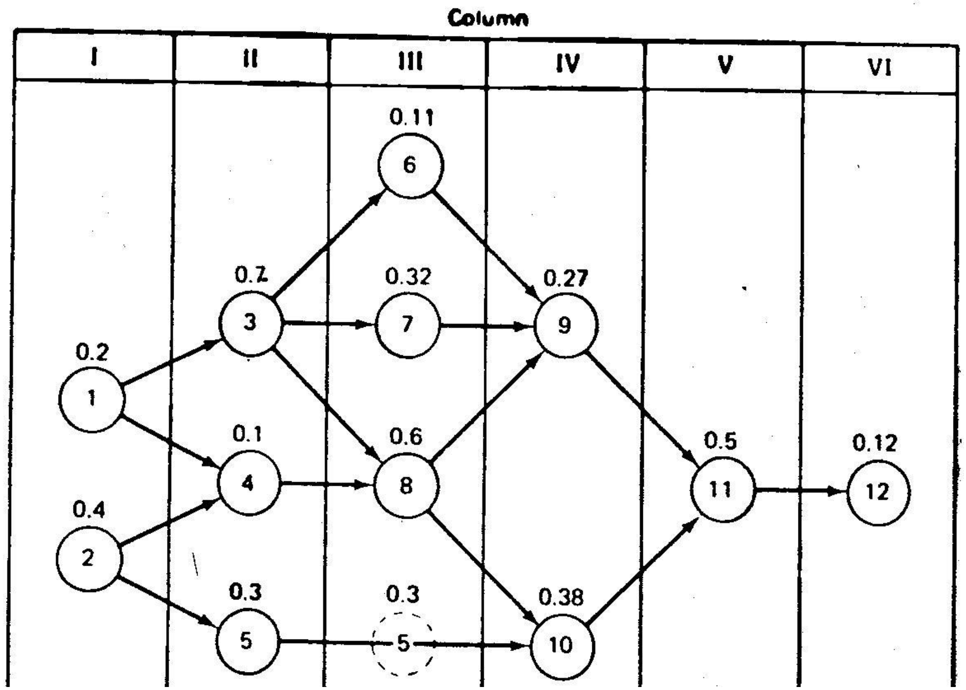


Kilbridge and Wester’s method

- It is a heuristic procedure which selects work elements for assignment to stations according to their position in the precedence diagram.
  - The elements at the front of the diagram are selected first for entry into the solution.
  - This overcomes one of the difficulties with the largest candidate rule, with which elements at the end of the precedence diagram might be the first candidates to be considered, simply because their T, values are large.
- We demonstrate Kilbridge and Wester’s method on our sample problem. However, our problem is elementary enough that many of the difficulties which the procedure is designed to solve are missing.

Kilbridge and Wester's method

Step 1. Constraint the precedence diagram so that nodes representing work elements of identical precedence are arranged vertically in columns.



Note that element 5 could be located in either column II or III without disrupting precedence constraints

Kilbridge and Wester's method

Step 2. List the elements in order of their columns, column I at the top of the list. If an element can be located in more than one column, list all the columns by the element to show the transferability of the element.

TABLE 6.4 Work Elements Arranged According to Columns from Figure 6.3 in the Kilbridge and Wester Method

Work element	*Column*	T_e	*Sum of column* T_e*s*
1	I	0.2	
2	I	0.4	0.6
3	II	0.7	
4	II	0.1	
5	II,III	0.3	1.1
6	III	0.11	
7	III	0.32	
8	III	0.6	1.03
9	IV	0.27	
10	IV	0.38	0.65
11	V	0.5	0.5
12	VI	0.12	0.12

Kilbridge and Wester's method

TABLE 6.5 Work Elements Assigned to Stations According to Kilbridge and Wester's Method

Station	Element	T_e	ΣT_e at station
1	1	0.2	
	2	0.4	
	4	0.1	
	5	0.3	1.00
2	3	0.7	
	6	0.11	0.81
3	7	0.32	
	8	0.6	0.92
4	9	0.27	
	10	0.38	0.65
5	11	0.5-	
	12	0.12	0.62

Step 3. To assign elements to workstations, start with the column I elements. Continue the assignment procedure in order of column number until the cycle time is reached.

In general, the Kilbridge and Wester method will provide a superior line balancing solution when compared with the largest-candidate rule. However, this is not always true, as demonstrated by our sample problem.

Ranked Positional Weight (RPW)

- 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_{ek} 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

Solution for RPW

TABLE 4.8 Elements and Their Ranked Positional Weight (*RPW*)

Work Element	*RPW*	T_{ek} (min)	Preceded by
1	3.30	0.2	—
3	3.00	0.7	1
2	2.67	0.4	—
4	1.97	0.1	1, 2
8	1.87	0.6	3, 4
5	1.30	0.3	2
7	1.21	0.32	3
6	1.00	0.11	3
10	1.00	0.38	5, 8
9	0.89	0.27	6, 7, 8
11	0.62	0.5	9, 10
12	0.12	0.12	11

Solution for RPW

TABLE 4.9 Work Elements Assigned to Stations According to *RPW* Method

Station	Work Element	T_{ek} (min)	Station Time (min)
1	1	0.2	
	3	0.7	0.90
2	2	0.4	
	4	0.1	
	5	0.3	
	6	0.11	0.91
3	8	0.6	
	7	0.32	0.92
4	10	0.38	
	9	0.27	0.65
5	11	0.5	
	12	0.12	0.62

Other Considerations in Line Design (1)

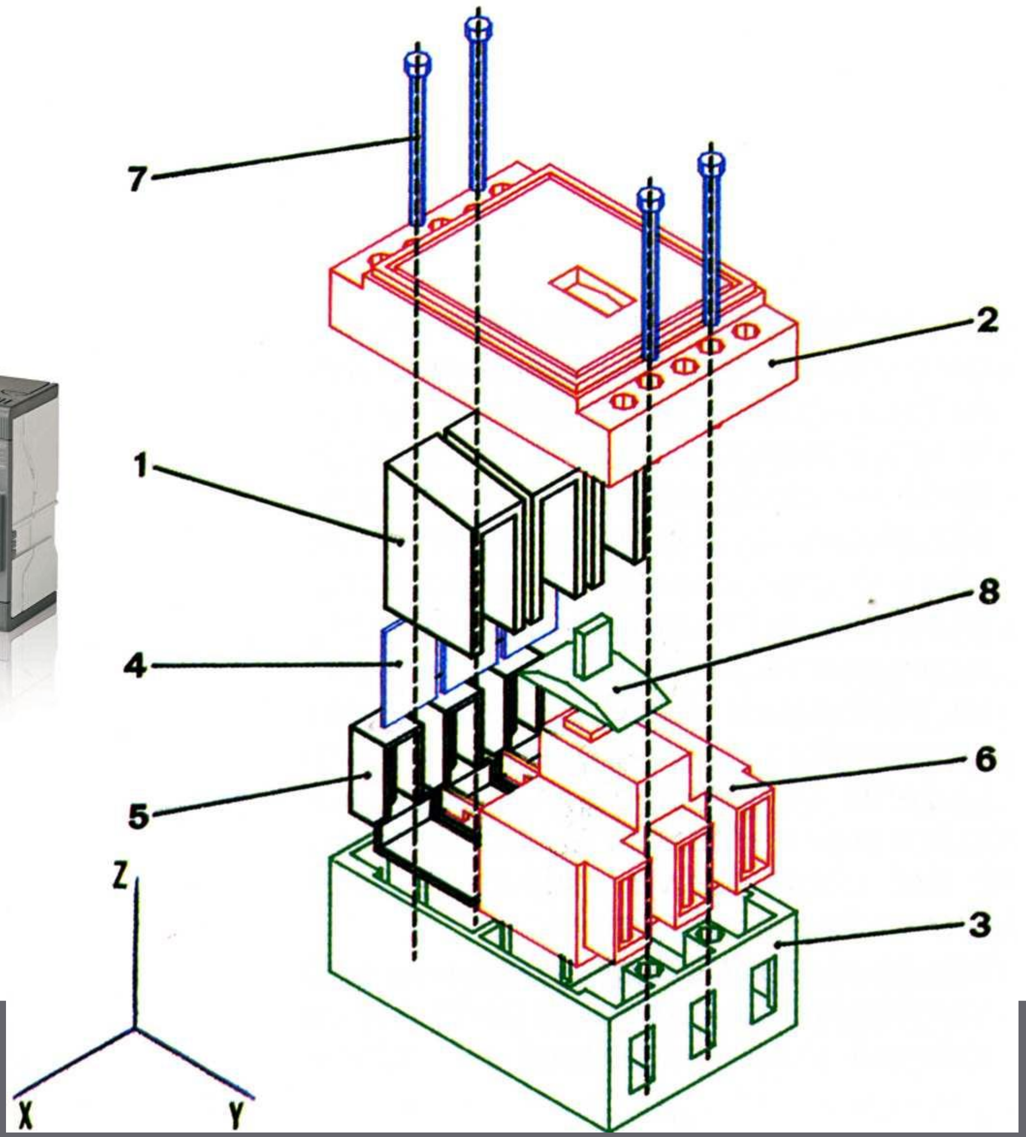
- Methods analysis
  - To analyze methods at bottleneck or other troublesome workstations:
    - improved motions,
    - better workplace layout,
    - special tools to facilitate manual work elements
    - product design
- Utility workers
  - To relieve congestion at stations that are temporarily overloaded
- Preassembly of components
  - Prepare certain subassemblies off-line to reduce work content time on the final assembly line

Other Considerations in Line Design (2)

- 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 toreduce subassembly stocks

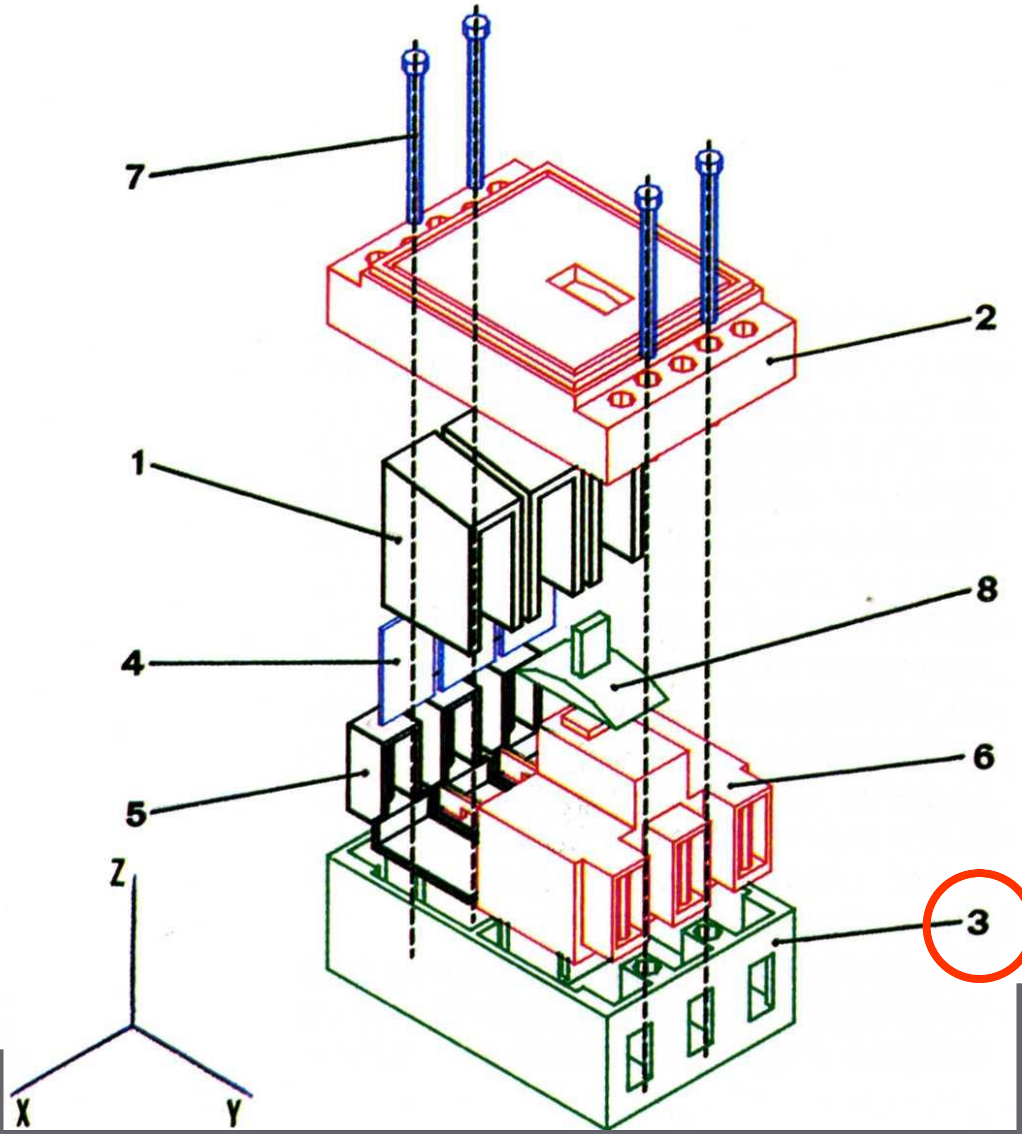
Example of product assembly:

tripolar switch



Example of product assembly:

tripolar switch



Operation 1:

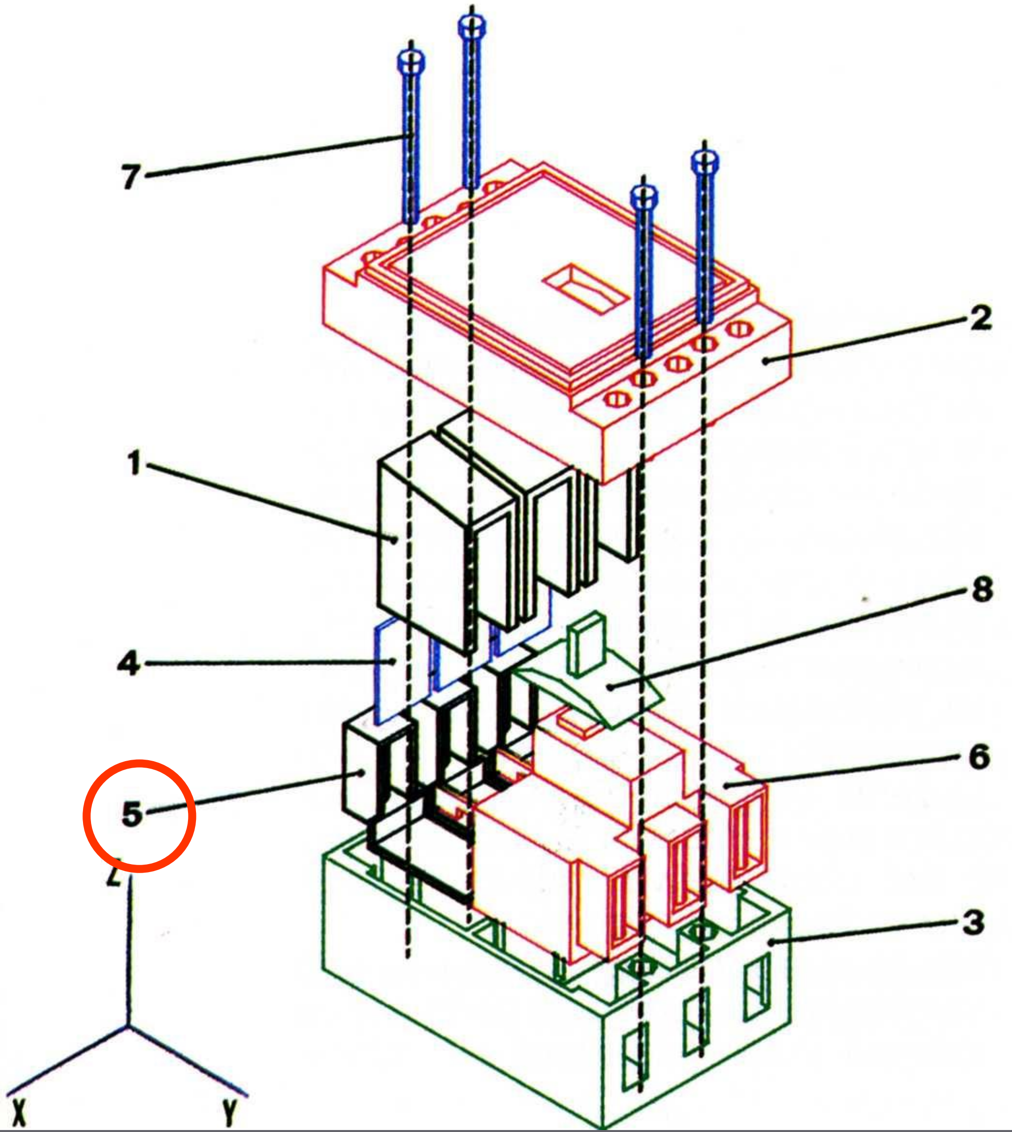
Put the base object in the assembly fixture

T_{e1}: 0,18 min

Precedence: -

Example of product assembly:

tripolar switch



Operation 2:

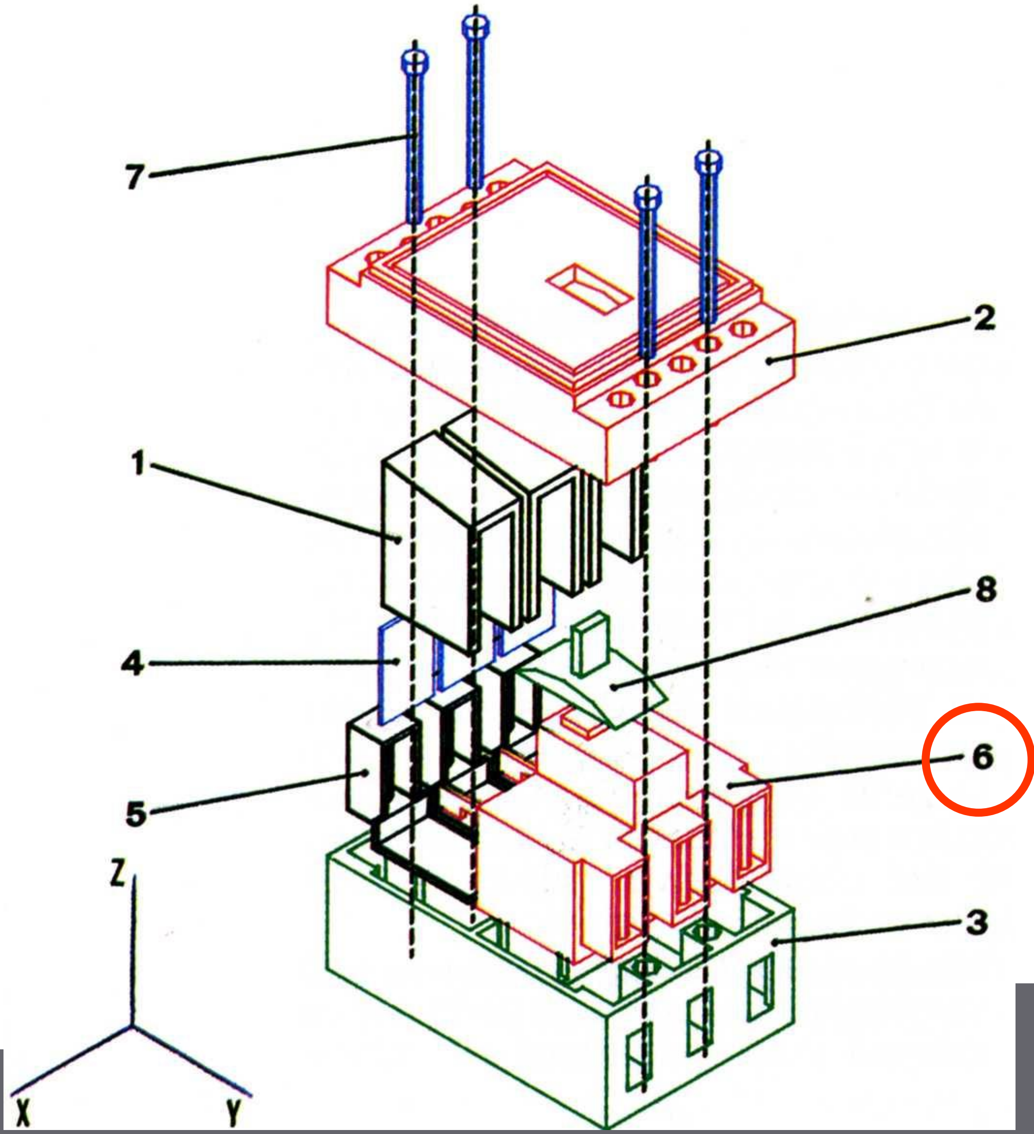
Insert the terminal 5 in the base object

T_{e2}: 0,58 min

Precedence: 1

Example of product assembly:

tripolar switch



Operation 3:

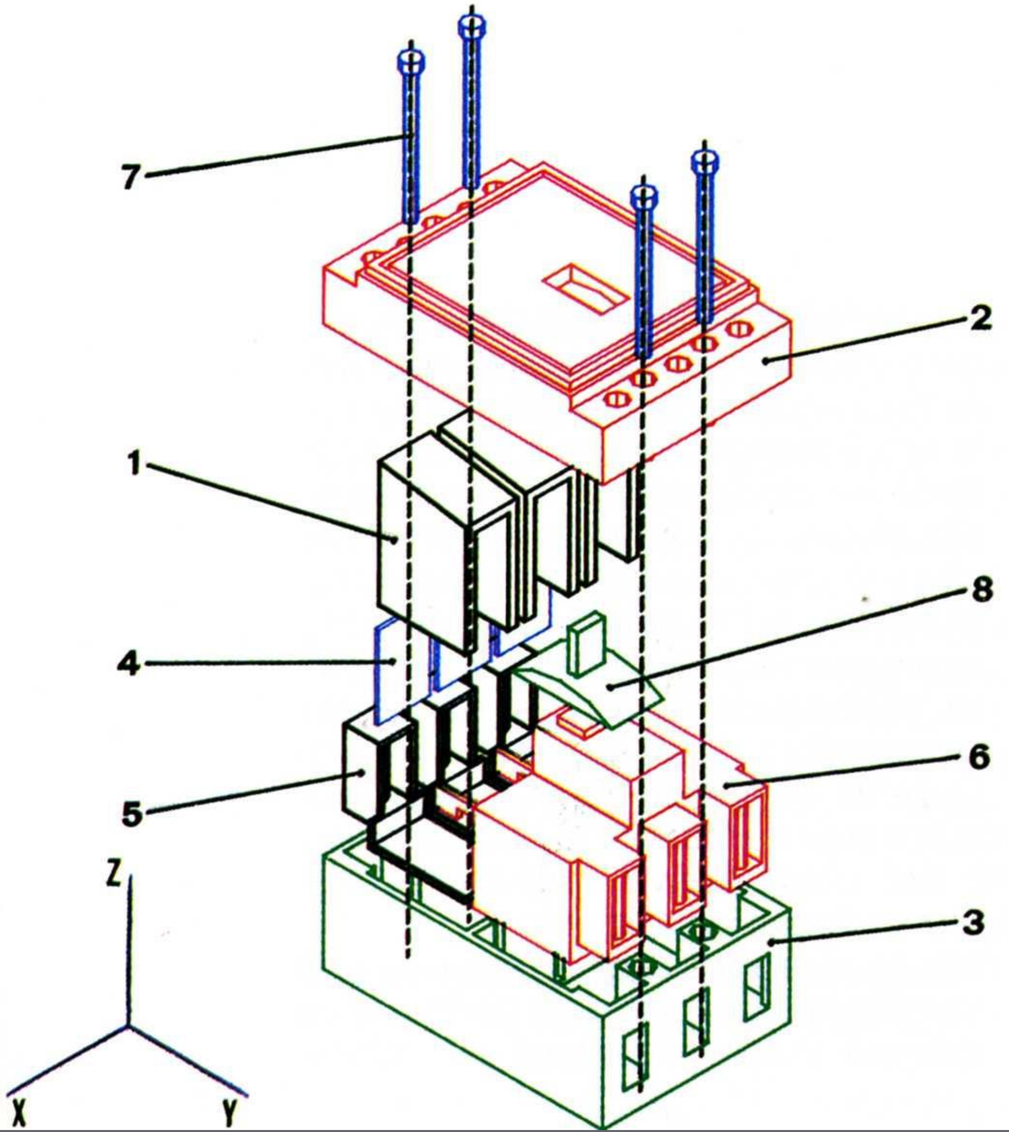
Insert the main body 6 in the base object

T_{e3}: 0,33 min

Precedence: 1

Example of product assembly:

tripolar switch



Operation 4:

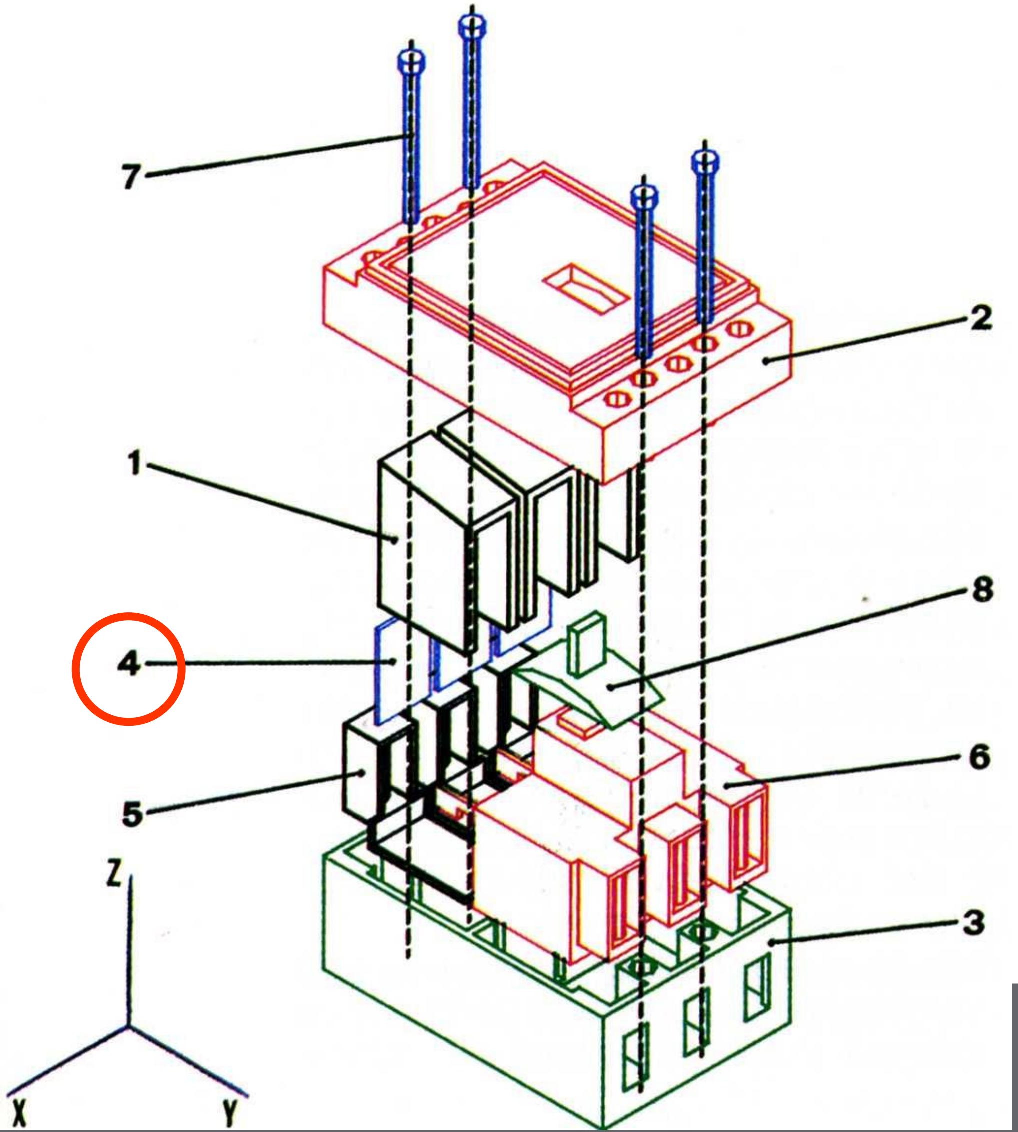
Test and calibration of the switch

T_{e4}: 0,93 min

Precedence: 2 e 3

Example of product assembly:

tripolar switch



Operation 5:

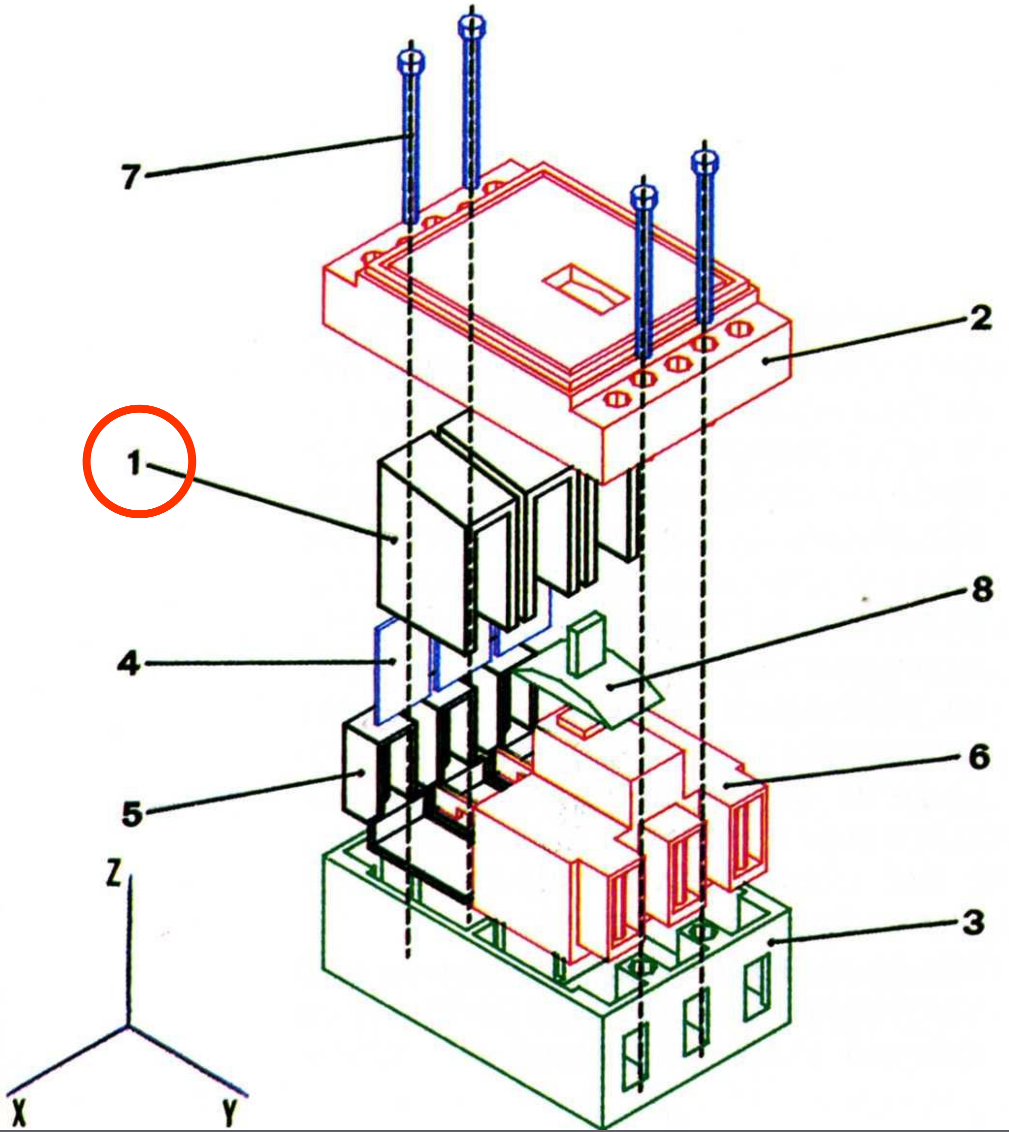
Mount the isolators 4 in the base object

T_{e5}: 0,51 min

Precedence: 4

Example of product assembly:

tripolar switch



Operation 6:

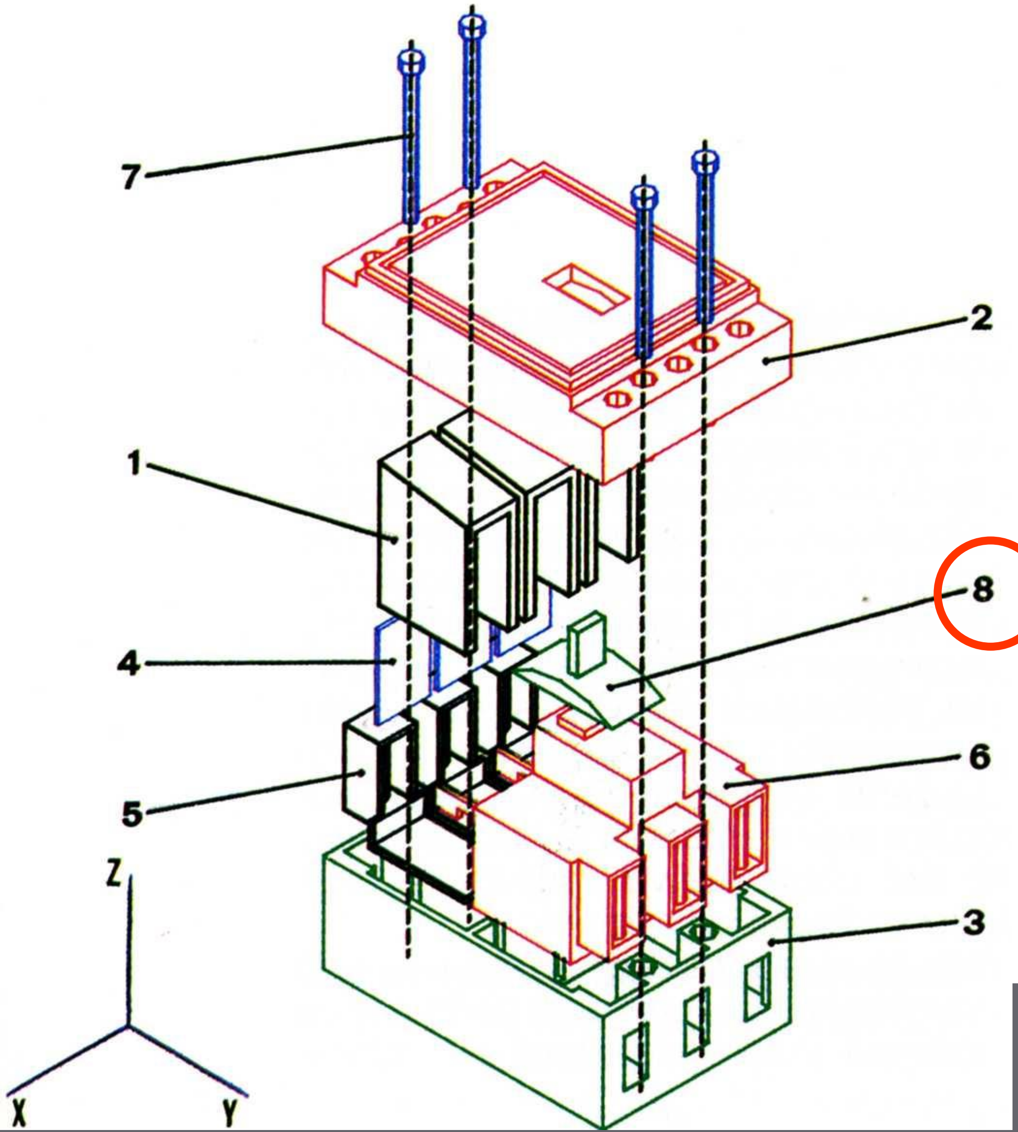
Mount the covers 1 on the terminals

T_{e6}: 0,34 min

Precedence: 4

Example of product assembly:

tripolar switch



Operation 7:

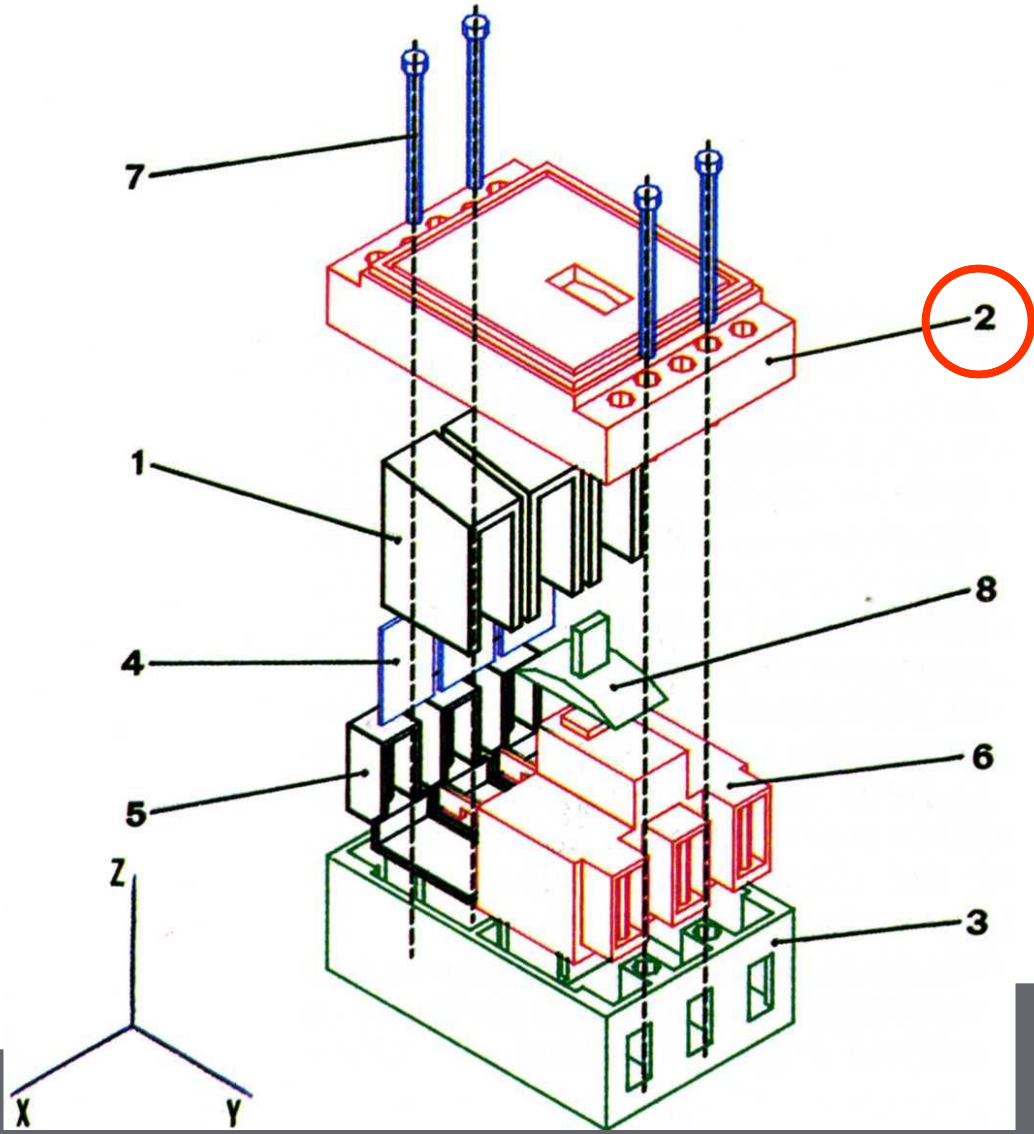
Mount the lever 8 on the main body

T_{e7}: 0,18 min

Precedence: 4

Example of product assembly:

tripolar switch



Operation 8:

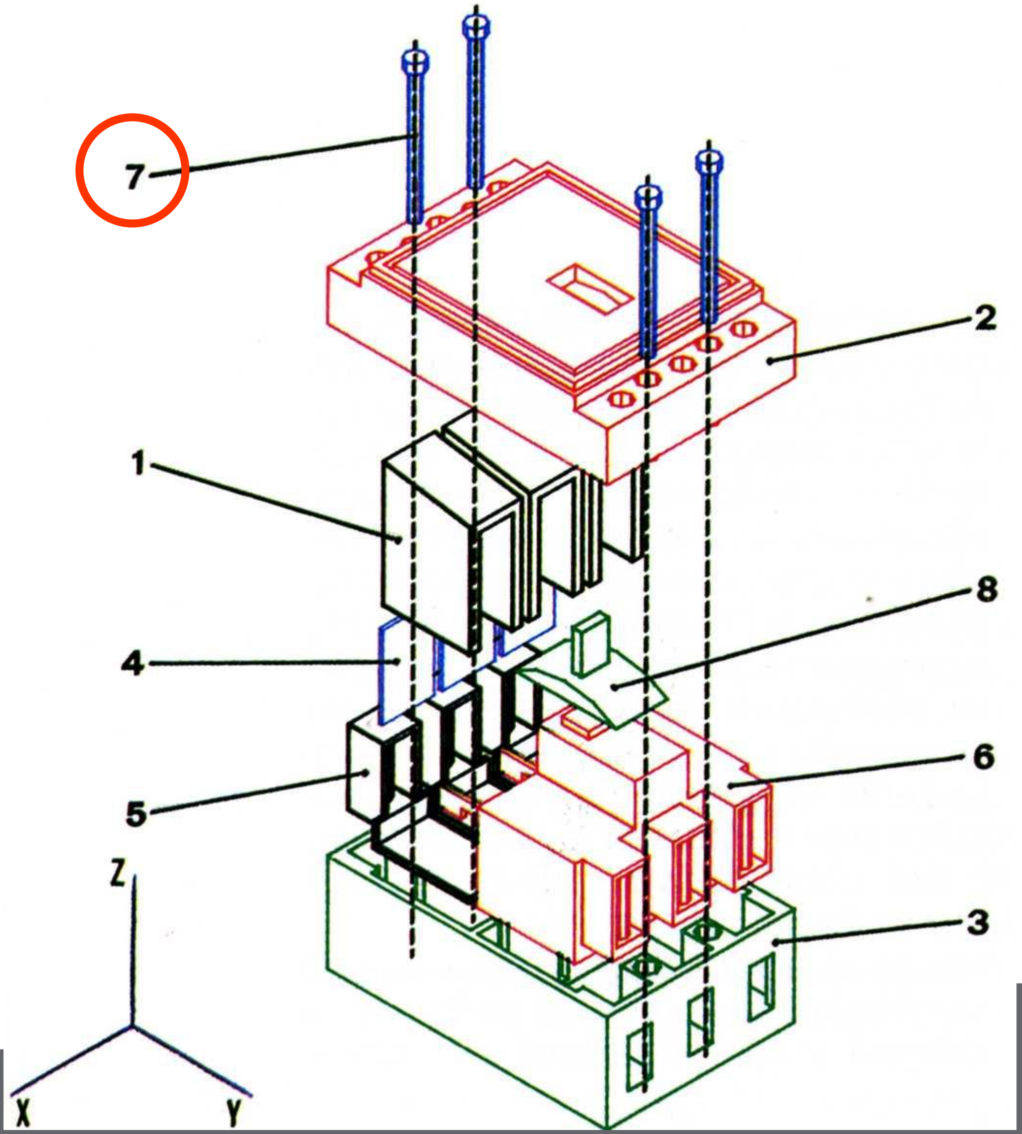
Mount the upper cover 2 on the base object

T_{e8}: 0,33 min

Precedence: 5, 6 e 7

Example of product assembly:

tripolar switch



Operation 9:

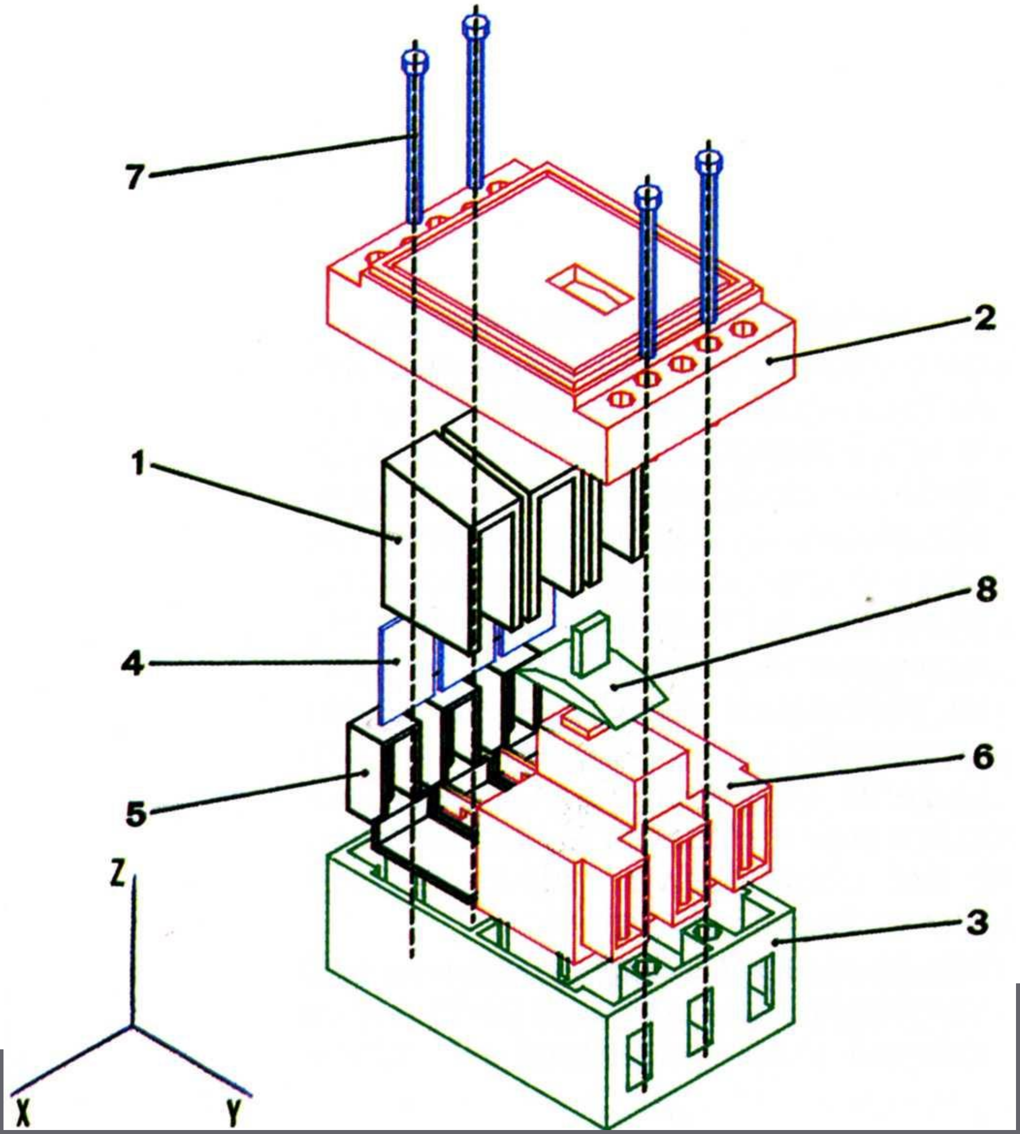
Screw 7 on the upper cover

T_{e9}: 0,74 min

Precedence: 8

Example of product assembly:

tripolar switch



Operation 10:

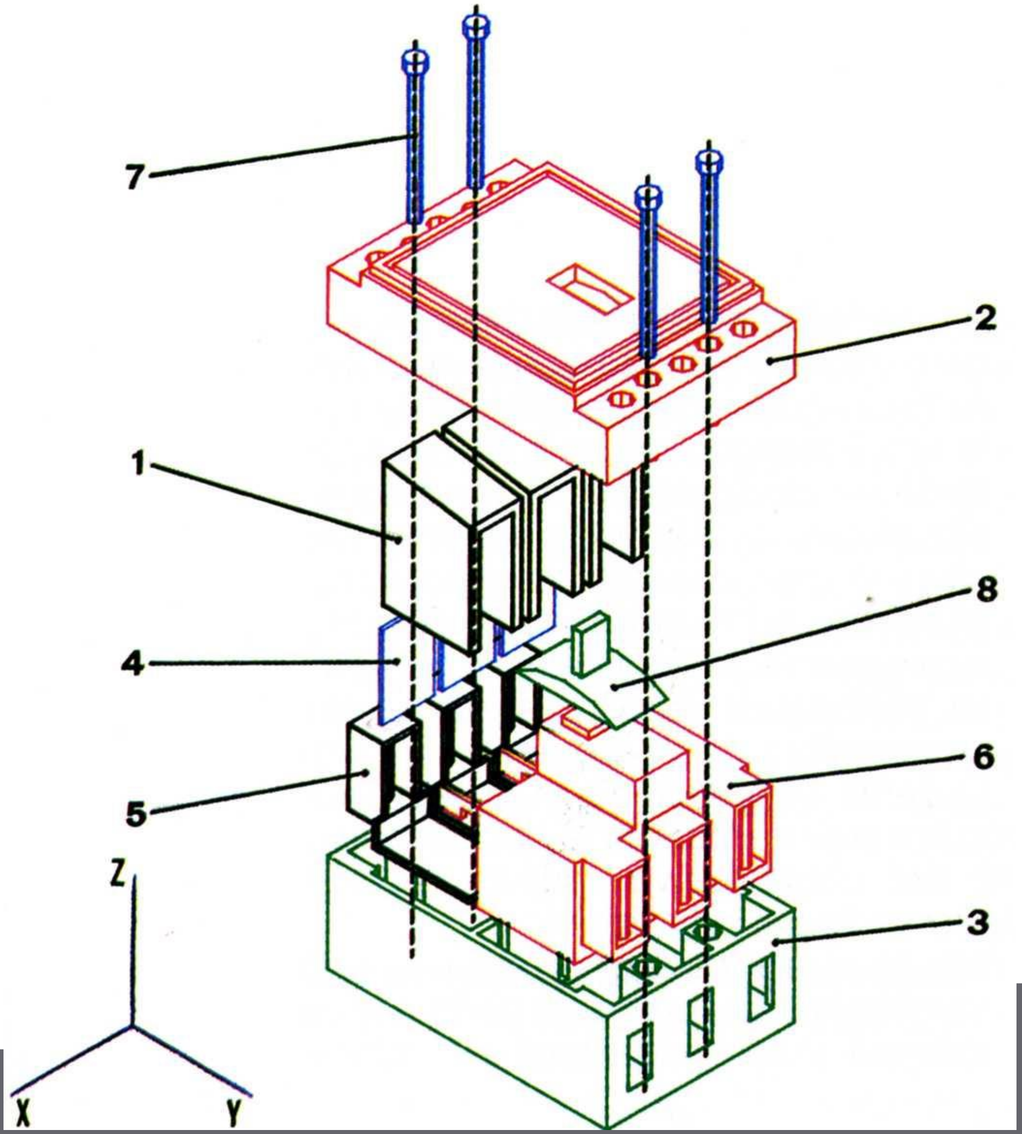
Final test

T_{e10}: 0,70 min

Precedence: 9

Example of product assembly:

tripolar switch



Operation 11:

Remove the switch and put the assembly in the box

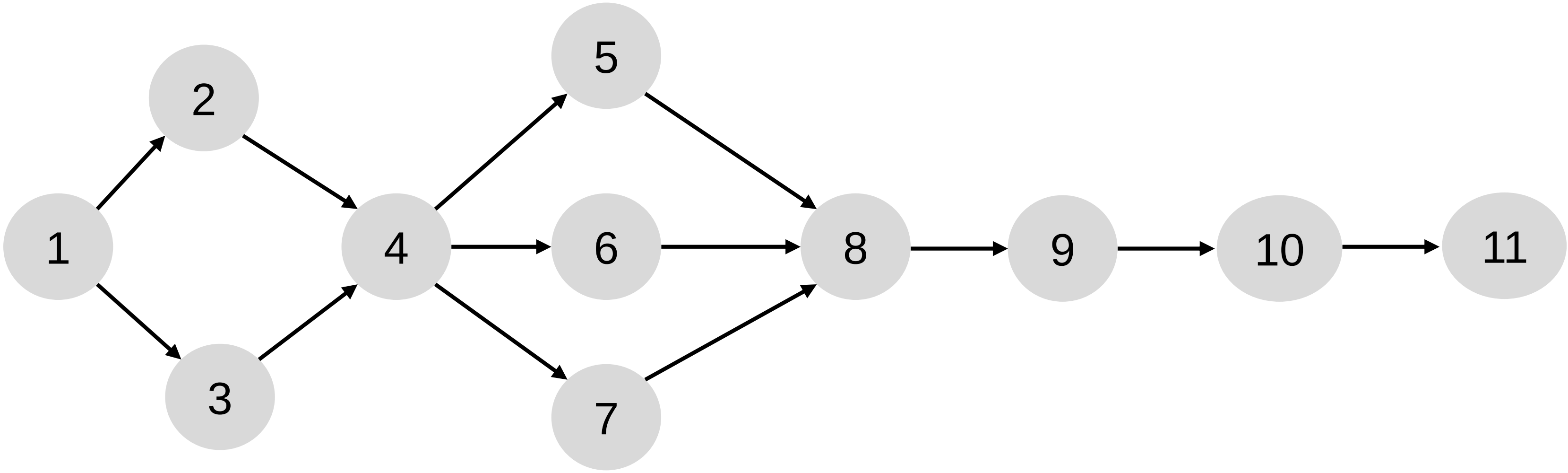
T_{e11}: 0,16 min

Precedence: 10

Summary

No.	Operation elementare	Tek [min]	Precedence
1	Put the base object in the assembly fixture	0,18	
2	Insert the terminal 5 in the base object	0,58	1
3	Insert the main body 6 in the base object	0,33	1
4	Test and calibration of the switch	0,93	2 e 3
5	Mount the isolators 4 in the base object	0,51	4
6	Mount the covers 1 on the terminals	0,34	4
7	Mount the lever 8 on the main body	0,18	4
8	Mount the upper cover 2 on the base object	0,33	5, 6 e 7
9	Screw 7 on the upper cover	0,74	8
10	Final test	0,70	9
11	Remove the switch and put the assembly in the box	0,16	10

Precedence Diagram



Cycle time 1.2 minutes

Method "Largest Candidate Rule"

No.	Operation elementare	Tek [min]	Precedence
4	Test and calibration of the switch	0,93	2 e 3
9	Screw 7 on the upper cover	0,74	8
10	Final test	0,70	9
2	Insert the terminal 5 in the base object	0,58	1
5	Mount the isolators 4 in the base object	0,51	4
6	Mount the covers 1 on the terminals	0,34	4
3	Insert the main body 6 in the base object	0,33	1
8	Mount the upper cover 2 on the base object	0,33	5, 6 e 7
1	Put the base object in the assembly fixture	0,18	
7	Mount the lever 8 on the main body	0,18	4
11	Remove the switch and put the assembly in the box	0,16	10

Method “Largest Candidate Rule”

No.	Operation elementare	Tek [min]	Precedence
4	Test and calibration of the switch	0,93	2 e 3
9	Screw 7 on the upper cover	0,74	8
10	Final test	0,70	9
2	Insert the terminal 5 in the base object	0,58	1
5	Mount the isolators 4 in the base object	0,51	4
6	Mount the covers 1 on the terminals	0,34	4
3	Insert the main body 6 in the base object	0,33	1
8	Mount the upper cover 2 on the base object	0,33	5, 6 e 7
1	Put the base object in the assembly fixture	0,18	
7	Mount the lever 8 on the main body	0,18	4
11	Remove the switch and put the assembly in the box	0,16	10

Method “Largest Candidate Rule”

No.	Operation elementare	Tek [min]	Precedence
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9	Screw 7 on the upper cover	0,74	8
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2	Insert the terminal 5 in the base object	0,58	1
5	Mount the isolators 4 in the base object	0,51	4
6	Mount the covers 1 on the terminals	0,34	4
3	Insert the main body 6 in the base object	0,33	1
8	Mount the upper cover 2 on the base object	0,33	5, 6 e 7
1	Put the base object in the assembly fixture	0,18	
7	Mount the lever 8 on the main body	0,18	4
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8	Mount the upper cover 2 on the base object	0,33	5, 6 e 7
1	Put the base object in the assembly fixture	0,18	
7	Mount the lever 8 on the main body	0,18	4
11	Remove the switch and put the assembly in the box	0,16	10

Method “Largest Candidate Rule”

No.	Operation elementare	Tek [min]	Precedence
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Method “Largest Candidate Rule”

No.	Operation elementare	Tek [min]	Precedence
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5	Mount the isolators 4 in the base object	0,51	4
6	Mount the covers 1 on the terminals	0,34	4
8	Mount the upper cover 2 on the base object	0,33	5, 6 e 7
7	Mount the lever 8 on the main body	0,18	4
11	Remove the switch and put the assembly in the box	0,16	10

Method “Largest Candidate Rule”

No.	Operation elementare	Tek [min]	Precedence
4	Test and calibration of the switch	0,93	2 e 3
9	Screw 7 on the upper cover	0,74	8
10	Final test	0,70	9
5	Mount the isolators 4 in the base object	0,51	4
6	Mount the covers 1 on the terminals	0,34	4
8	Mount the upper cover 2 on the base object	0,33	5, 6 e 7
7	Mount the lever 8 on the main body	0,18	4
11	Remove the switch and put the assembly in the box	0,16	10

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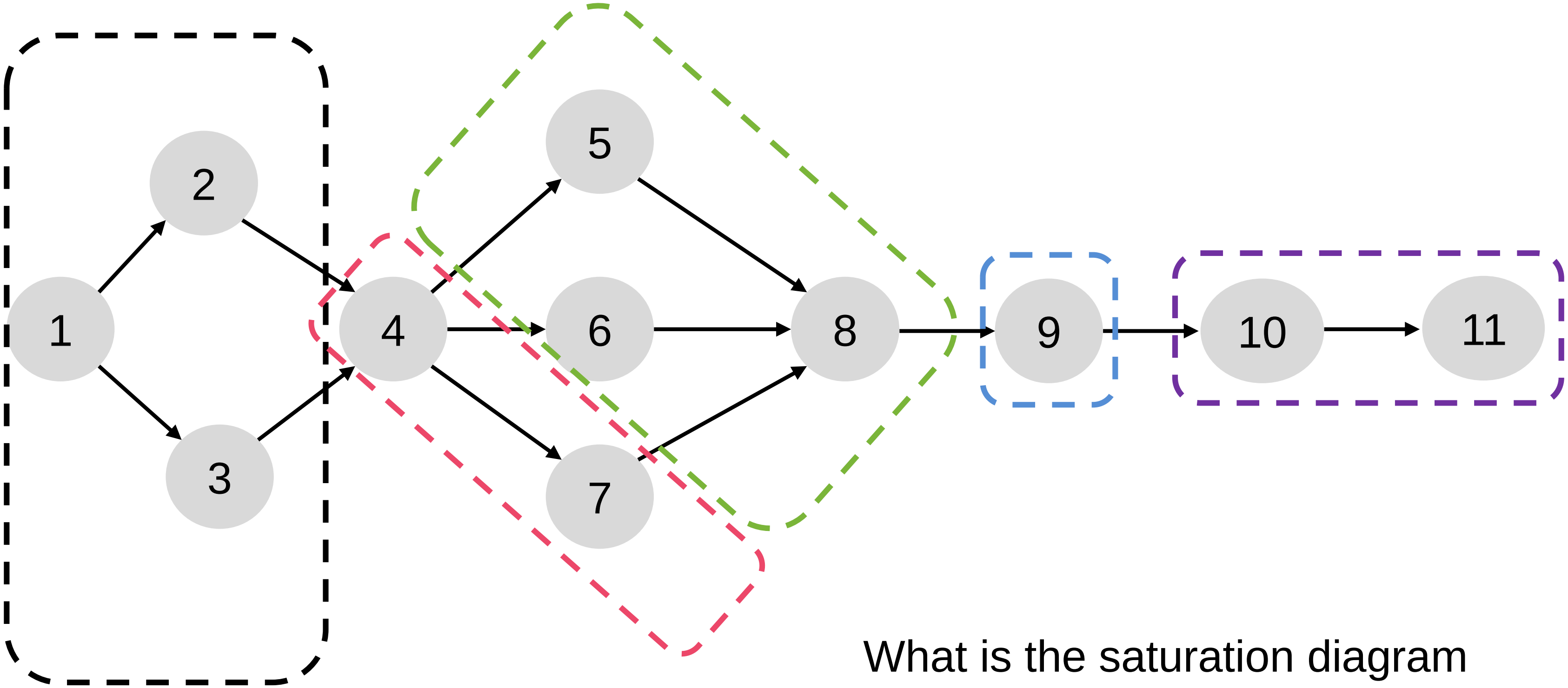
11	Remove the switch and put the assembly in the box	0,16	10

Method “Largest Candidate Rule”

No.	Operation elementare	Tek [min]	Precedence
10	Final test	0,70	9
11	Remove the switch and put the assembly in the box	0,16	10

Precedence Diagram

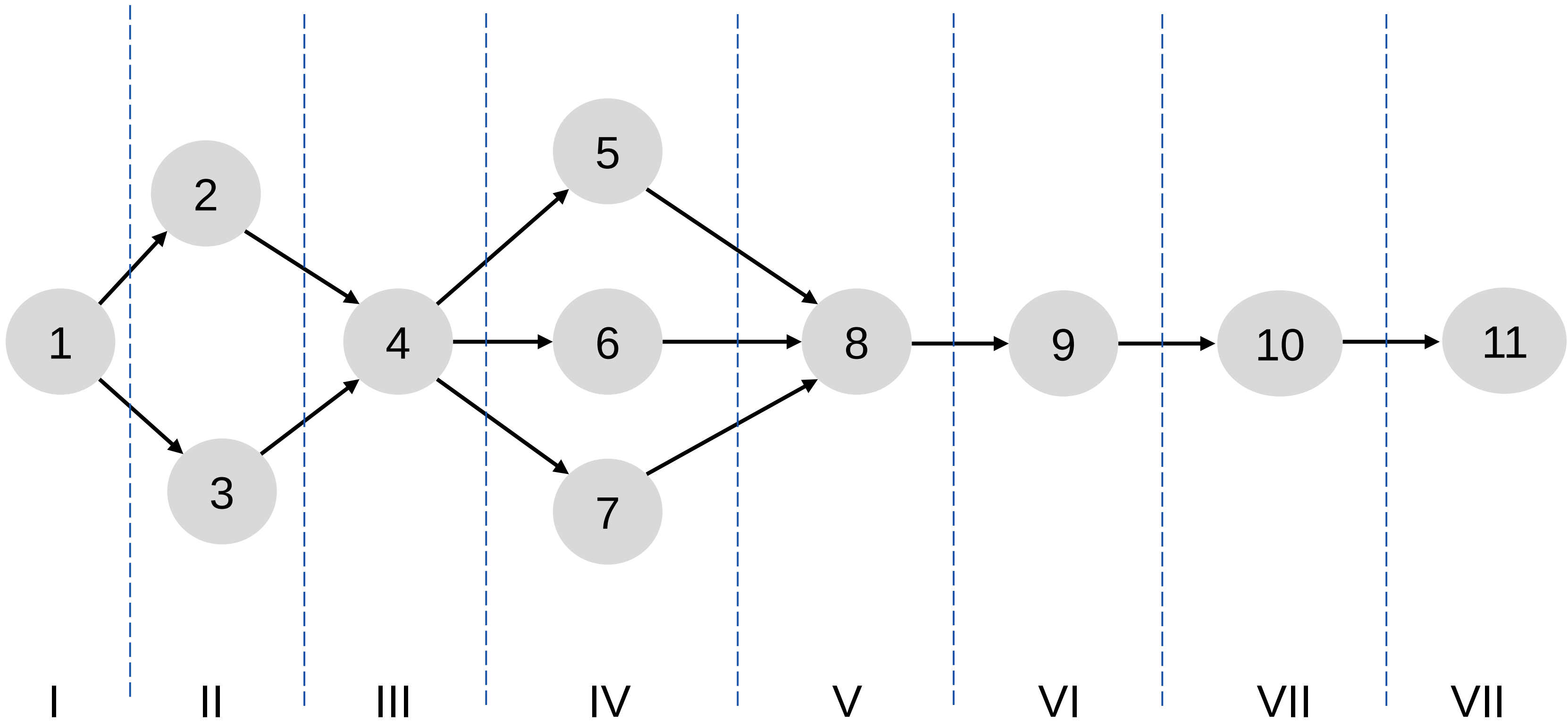


What is the saturation diagram going to look like?

Method Kilbridge and Wester

No.	Operation elementare	Tek [min]	Column
1	Put the base object in the assembly fixture	0,18	I
2	Insert the terminal 5 in the base object	0,58	II
3	Insert the main body 6 in the base object	0,33	II
4	Test and calibration of the switch	0,93	III
5	Mount the isolators 4 in the base object	0,51	IV
6	Mount the covers 1 on the terminals	0,34	IV
7	Mount the lever 8 on the main body	0,18	IV
8	Mount the upper cover 2 on the base object	0,33	V
9	Screw 7 on the upper cover	0,74	VI
10	Final test	0,70	VII
11	Remove the switch and put the assembly in the box	0,16	VIII

Column



Method Ranked Positional Weight

No.	Operation elementare	Tek [min]	RPW
1	Put the base object in the assembly fixture	0,18	4,98
2	Insert the terminal 5 in the base object	0,58	4,47
3	Insert the main body 6 in the base object	0,33	4,22
4	Test and calibration of the switch	0,93	3,89
5	Mount the isolators 4 in the base object	0,51	2,44
6	Mount the covers 1 on the terminals	0,34	2,27
7	Mount the lever 8 on the main body	0,18	2,11
8	Mount the upper cover 2 on the base object	0,33	1,93
9	Screw 7 on the upper cover	0,74	1,60
10	Final test	0,70	0,86
11	Remove the switch and put the assembly in the box	0,16	0,16

Video

- Automotive Assembly Line (7:27)
- Goodbye Assembly Line, Hello D-Shop (2:23)
- Manual assembly work at 100% performance rating (6:38)
- Manual Front Air Deflector Assembly Stations (2:03)

Question for the formative assessment

1. Which are the factors favoring the use of assembly lines?
2. Which are the possible approaches to design a manual assembly station? Classify them according to the use and list some of the operation performed at manual assembly stations.
3. Define a manual assembly line and list some of the typical products assembled with this approach. Characterize the manual assembly process in sub-processes and influencing factors
4. Which are the kinds of mechanized transport systems used in assembly lines? Provide a graphical description of the speed profile and some example of industrial systems.
5. What are SMAL, BMAL, MMAL and how do they relate to each other?
6. List and provide a short description of some of the element that must be considered when design a manual line (except layout and balancing)
7. List and describe the assembly line balancing algorithms you know.