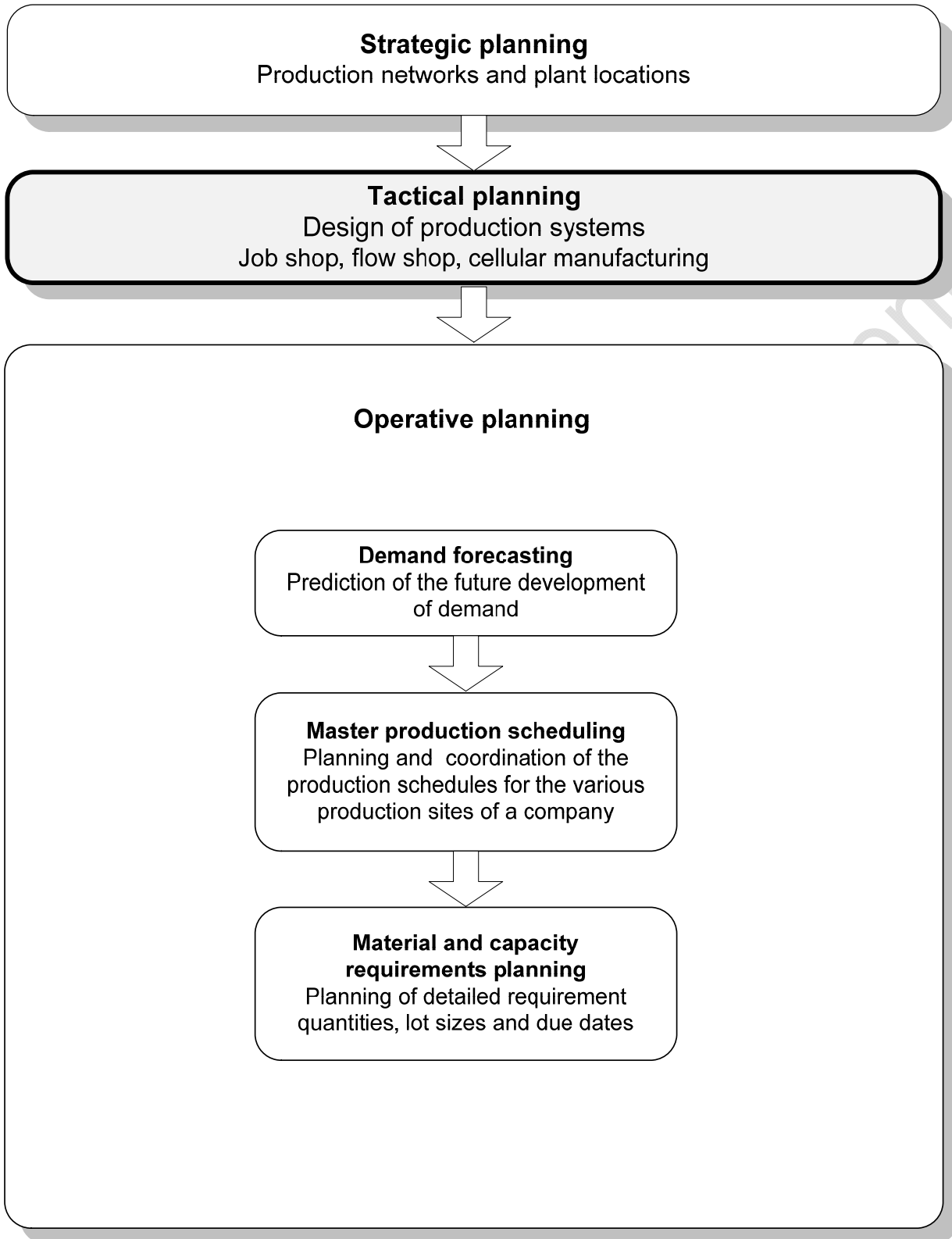


3. Design of production systems

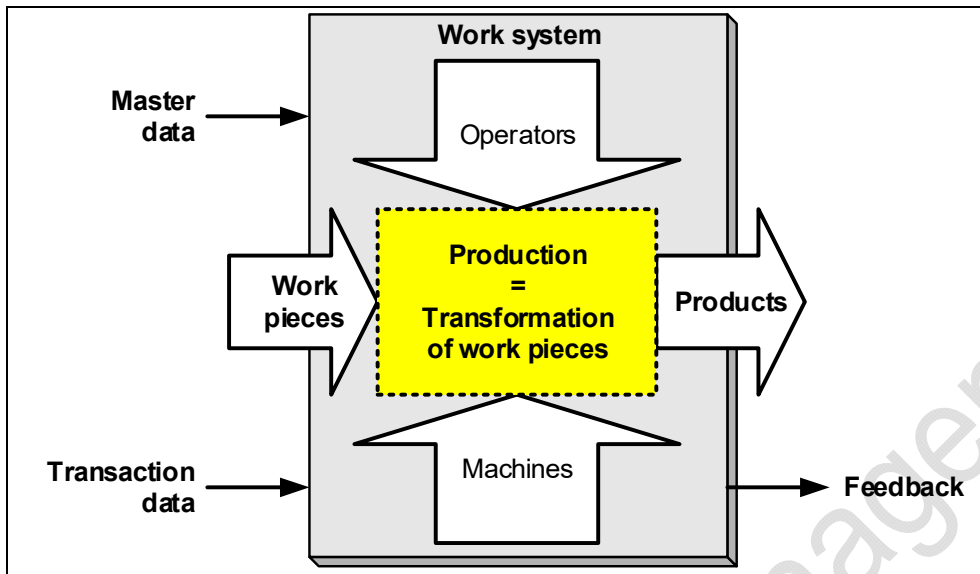
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3.1 The infrastructure of a production system

- **Work system:** *smallest organizational unit of the production system*



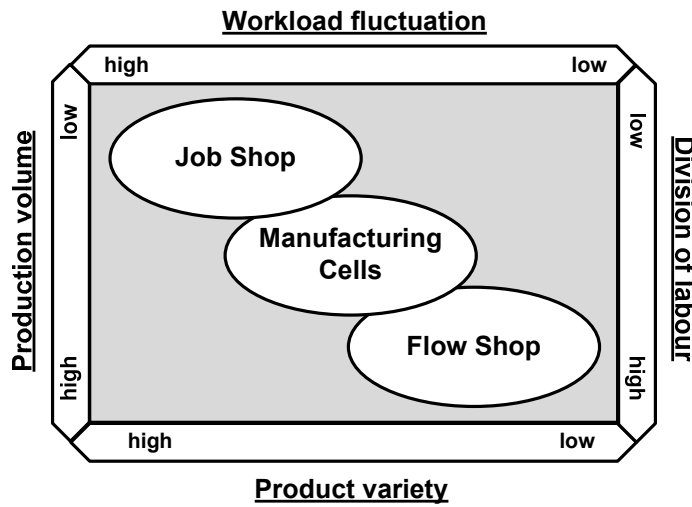
- ◇ Give examples of basic data, planning data and feedback.

Master data:

Transaction data:

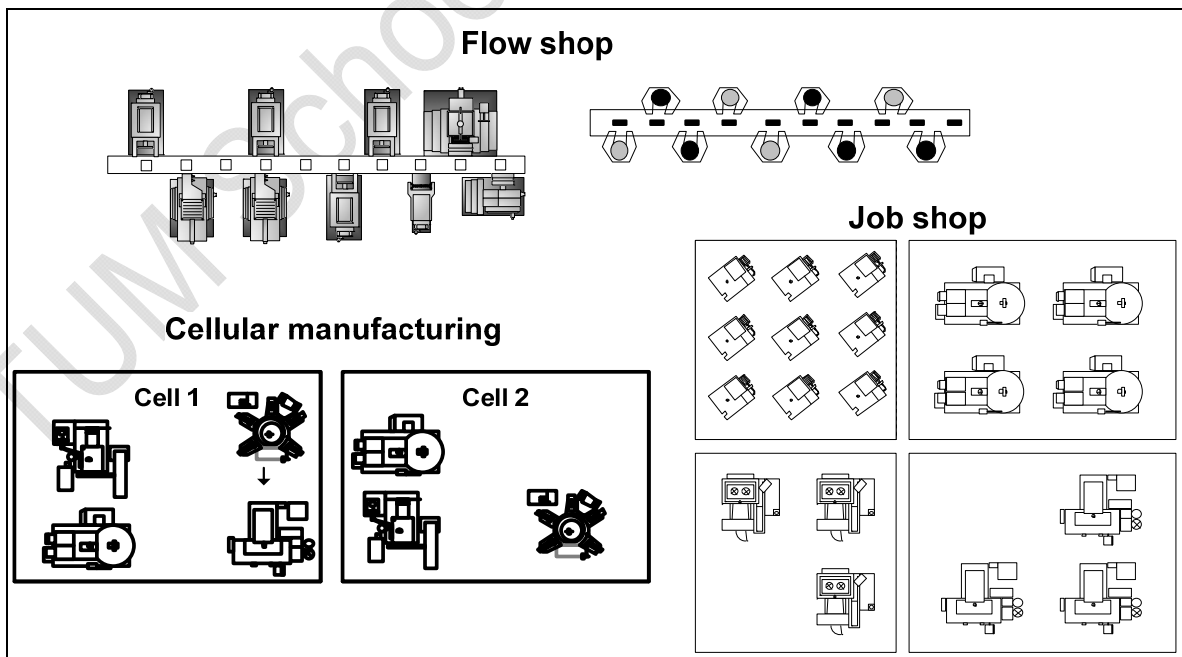
Feedback:

- Layout types of production systems: *indicate the physical arrangement and mode of interaction of the various work units*



- ⇒ **Job shop** (Functional layout):
Spatial concentration of similar work systems
- ⇒ **Flow shop** (Object layout, uniform material flow):
Arrangement of work systems according to the work flow
- ⇒ **Cellular manufacturing** (Object layout, production-dependent material flow):
Assignment of product families to machine groups

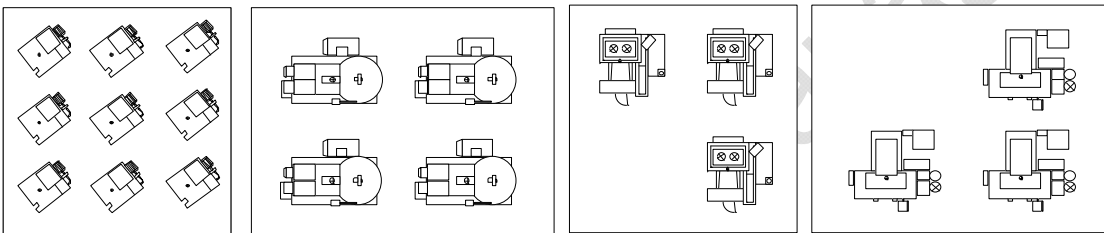
- Production segment:** *Subsystem of the production system that is organized according to a specific layout type*



❖ Characterize the three basic layout types of production systems!

	Job shop	Cellular manuf.	Flow shop
Production volume	Low	Medium	High
Production processes	Manual		Automated
Demand fluctuation	High	Medium	Low
Product types	Various	Some	One/few
Production equipment			

3.2 Job shop production



❖ Which pros and cons do job shops show in comparison to other layout types?

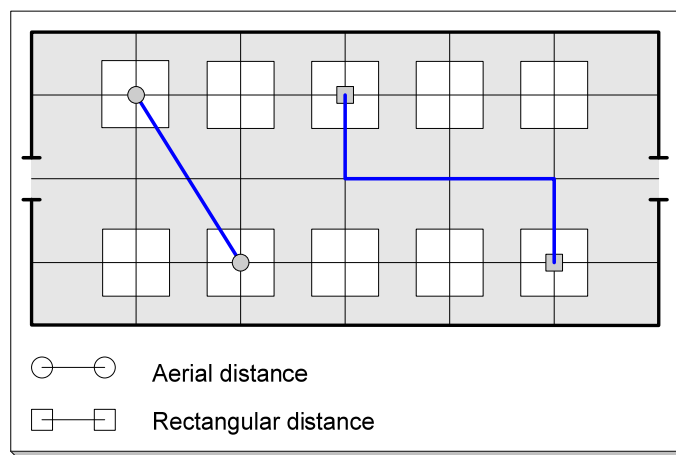
	Pro	Con
Transportation costs		—
Material flow		—
Throughput times		—
Work-in-process		—
Space requirement		—
Production control		—
Visibility of production processes		—
Flexibility	+	
Monotony of work	+	
Investment (automation)	+	

- Job shop production suitable for one-of-a-kind and small series applications

- **Factory layout**

- **Facility layout planning (determining in-plant locations)**

- Determination of the spatial arrangement of objects on a defined floor space
- In-plant locations
 - ⇒ Grid division of the floor space
 - ⇒ Distance measure: mostly **rectangular** along the in-plant traffic lanes



⇒ Aerial distance
$$d_{ij}^e = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

⇒ Rectangular distance
$$d_{ij}^r = |x_i - x_j| + |y_i - y_j|$$

where $(x_i, y_i), (x_j, y_j)$ (gridpoint) coordinates of positions i and j

- **Simplifying assumptions**

- ⇒ Subdivision of the entire floor space into equally-sized *grid squares*.
- ⇒ Each *object* occupies exactly one grid square.
- ⇒ The *orientation* of the objects inside the grid square is not relevant.
- ⇒ *Traffic lanes and storage areas* are included in the grid squares.
- ⇒ The *transport quantities* between the objects are known in advance and do not show seasonal variations.
- ⇒ Objective: Minimization of the entire *proxy criterion* (defined as product of transport quantity and transport distance summed up over all types of goods).

Exercise: Determination of material flows

Four types of products are produced in a manufacturing system. These products differ by daily production rates, machine sequences and pallet requirements. Details are given in the following table.

Product	Daily production rate (pieces)	Pieces per pallet	Machine sequence
1	<u>100</u>	<u>11</u> <u>5</u>	<u>A</u> → <u>B</u> → <u>C</u> →E
2	<u>150</u>	<u>1</u> <u>10</u>	<u>A</u> → <u>C</u> → <u>D</u> →E
3	<u>60</u>	<u>1</u> <u>4</u>	<u>B</u> → <u>C</u> → <u>D</u> →E
4	<u>200</u>	<u>1</u> <u>10</u>	<u>A</u> → <u>D</u> →E

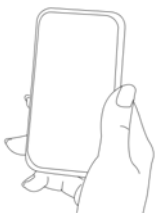
← from process plans

Determine the material flows (in terms of pallets).

Solution

From/to	A	B	C	D	E
A		20	15	20	
B			20+15 35		
C				15+15 30	20
D					15+15+20 50
E	/	/	/	/	/

(1) The total quantity of products to be transported between machines B and C is (in no of pallets):



- a. 15
- b. 20
- c. 25
- d. 35

- Greedy method (construction heuristic)

- (1) Determine the object i^* which shows the most intensive transport relations from/to all other objects.
- (2) Assign i^* to a grid square at the center of the floor space.
- (3) Determine a yet unassigned object i^{**} which shows the strongest transport relations from/to the already assigned objects.
- (4) Assign i^{**} to a grid square closest to the already assigned objects so that the proxy criterion between i^{**} and to the already assigned objects is minimized.
- (5) If all objects are assigned, STOP; otherwise go to (3).

◇ Example

Five objects are to be assigned to nine grid squares shown on the floor space sketched below. Distances are measured rectangularly. Because of structural and safety-related reasons, the feasible assignments of objects to the floor space are limited. The transport intensities between the five objects are given in the table below.

1	2	3
4	5	6
7	8	9

From	To					Σ
	O 1	O 2	O 3	O 4	O 5	
O 1	-	<u>5</u>	<u>8</u>	<u>2</u>	-	15
O 2	<u>12</u>	-	3	7	4	26
O 3	-	-	-	8	13	21
O 4	<u>5</u>	6	10	-	18	39
O 5	<u>4</u>	15	3	3	-	25
Σ	21	26	24	20	35	

Feasible grid squares
4, 6, 9
2, 5, 8
1, 7, 9
1, 2, 3
2, 5, 6

Solution

Step 1

	5	

- O1: $21 + 15 = 56$
- O2: $26 + 26 = 52$
- O3: $21 + 24 = 45$
- O4: $39 + 20 = 59$
- O5: $25 + 35 = 60$ ← Highest throughput

Step 2

- O1: $0 + 4 = 4$
- O2: $15 + 4 = 19$
- O3: $3 + 13 = 16$
- O4: $3 + 18 = 21$ ← Highest correlation with O5

Distance matrix to S

2	1	2
	4	
	5	

- Grid square 1: $21 \cdot 2 = 42$
- Grid square 2: $21 \cdot 1 = 21$ ← lowest cost
- Grid square 3: $21 \cdot 2 = 42$

Step 3

- O1: $4 + 2 + 5 = 11$
- O2: $19 + 6 + 7 = 32$
- O3: $16 + 10 + 8 = 34$ ←

Dist. Matr. to S
Dist. Matr. to h

2		
1	3	4
1		5
2		
2		
3		

- Grid square 1: $16 \cdot 2 + 18 \cdot 1 = 50$ ←
- Grid square 7: $16 \cdot 1 + 18 \cdot 2 = 52$
- Grid square 9: $16 \cdot 2 + 18 \cdot 3 = 86$

Step 4

O1: $11 + 0 + 8 = 19$

O2: $32 + 0 + 3 = 35 \leftarrow$

1	3	4	3
4	5	6	
7	8	2	5

~~Grid square 2~~ \leftarrow occupied

~~Grid square 5:~~ \leftarrow occupied

~~Grid square 8:~~

(see feasible grid sq. column)

Step 5

3	4	
1	5	
	2	

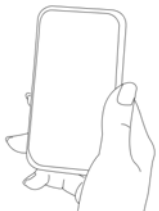
Grid square 4: $17 \cdot 2 + 8 \cdot 1 + 7 \cdot 2 + 4 \cdot 1 = 60 \leftarrow$

Grid square 6: $17 \cdot 2 + 8 \cdot 3 + 7 \cdot 2 + 4 \cdot 1 = 76$

Grid square 9: $17 \cdot 1 + 8 \cdot 4 + 7 \cdot 3 + 4 \cdot 2 = 78$

• Improvement procedure

- (1) For each pair (i,j) of objects determine the change of costs resulting from swapping the location of the objects.
- (2) Determine the pair of objects (i^*,j^*) which achieves the largest cost reduction. If no cost reduction is achieved then STOP; otherwise swap the location of i^* and j^* , then proceed with Step (1).

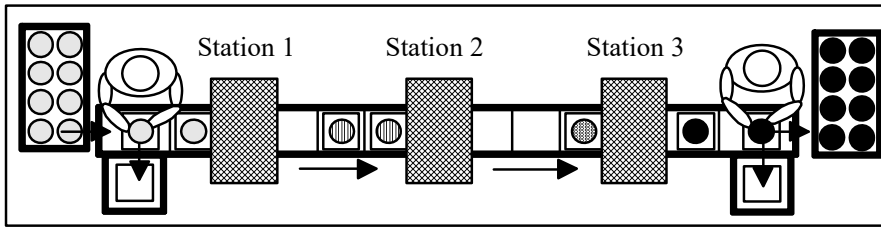


(2) Object 1 is placed in the following position:

- a. Grid square 4
- b. Grid square 6
- c. Grid square 9

3.3 Flow shop production

- **Organization principle**

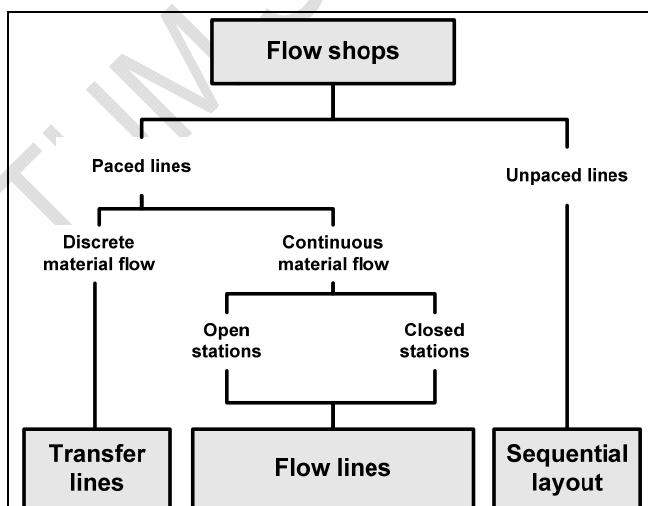


◇ Which pros and cons do flow shops show in comparison to other layout types?

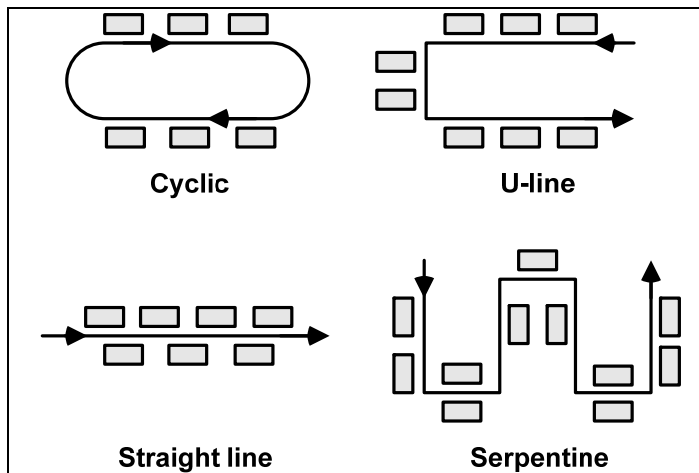
	Pro	Con
Transportation costs	+	
Material flow	+	
Throughput times	+	
Work-in-process	+	
Space requirement	+	
Production control	+	
Visibility of production processes	+	
Flexibility		-
Monotony of work		-
Investment (automation)		-

- **Flow shop production suitable for large series and mass production applications**

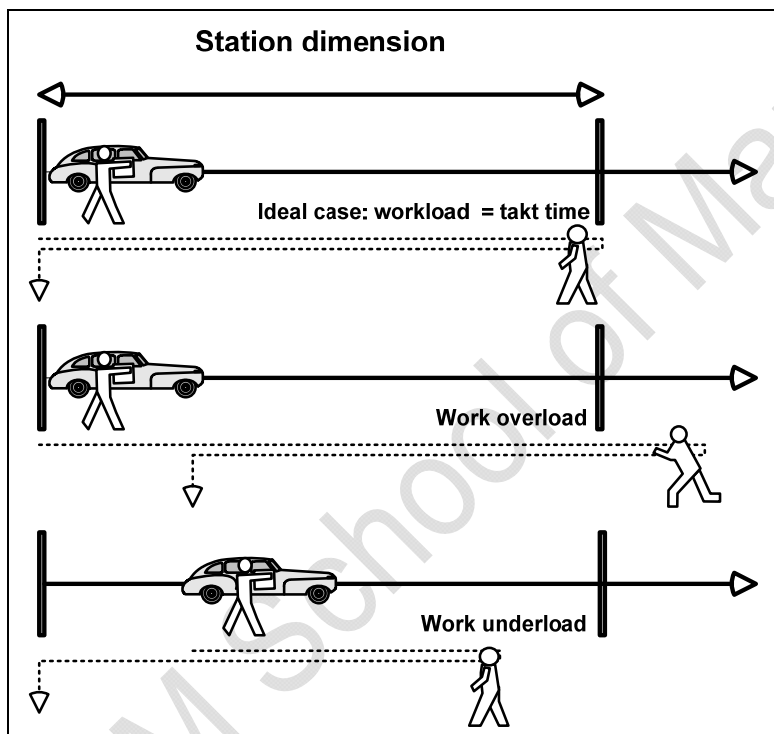
- **Types of line production**



- Geometrical line layout



- Line production with continuous material flow and open stations



- Transportation systems

- ⇒ Continuously moving conveyor (e.g. automotive final assembly lines)
- ⇒ Synchronous transport (e.g. automated transfer lines)
- ⇒ Asynchronous transport (e.g. manual lines)

- **Assembly line balancing for paced assembly lines (given cycle time)**
 - Subdivision of the entire work process into individual **tasks**
 - Definition of **standard time (task times)** for each task
 - Derivation of **technical precedence relationships** for the individual tasks
 - Given **cycle time**, based on desired production volume and operating time of the plant
 - Problem: *Assignment of tasks to work stations within the line*
 - Objective: *Minimize the number of work stations subject to a given cycle time*
- **Scope of the assembly line balancing problem**
 - introduction of a completely new assembly line
 - adaptation of an existing line (e.g. due to model update, reorganization of work, outsourcing of tasks)
- **Assumptions made in the following exercises**
 - (1) 1 product
 - (2) Closed stations
 - (3) Synchronized material flow
 - (4) Deterministic task times
 - (5) No zoning restrictions
 - (6) No parallel lines

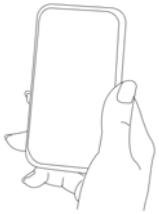
Example

Askin, R.G., Standridge, C.R., *Modeling and Analysis of Manufacturing Systems*. Wiley, New York, 1993

The following table shows details for the assembly of a toy car. In order to produce the car, an assembly line shall be set up. Develop the precedence graph. Which tasks can be assigned to the first work station considering a cycle time of 60 sec?

Task	Standard time (sec)	Task	Immediate predecessor
1	15	Insert mount for rear axle	--
2	30	Install rear axle	1
3	15	Insert mount for front axle	--
4	30	Install front axle	3
5	10	Install first rear wheel	2
6	10	Install second rear wheel	2
7	10	Install first front wheel	4
8	10	Install second front wheel	4
9	20	Install steering	5,6,7,8
10	20	Functional testing	9

Precedence graph:

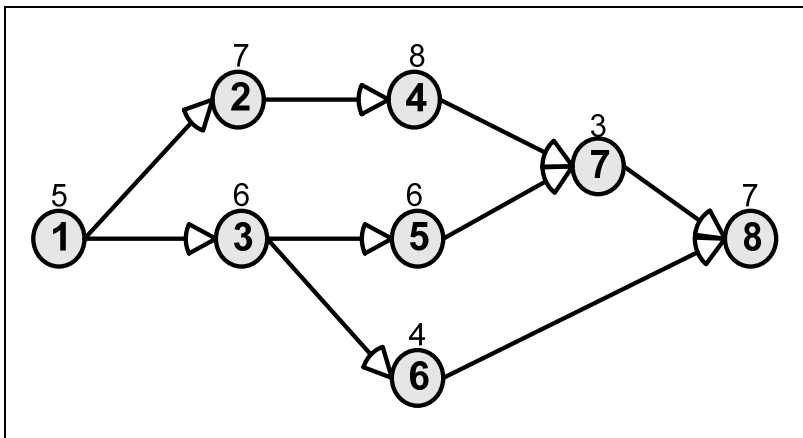


(1) How many different assignments of tasks to station 1 exist, which cannot be improved by adding another task?

- a. 1
- b. 2
- c. 4
- d. 6

3.3.1 Line balancing for a single-product line

◇ Example



- a) What is the cycle time assuming a production volume of $X=30$ pieces per day and effective operation times of $T=360$ min per day?

$$C = \frac{T}{X}$$

- b) Determine the theoretical minimal number of work stations given the total assembly time of τ in minutes?

$$\underline{M} = \left\lceil \frac{\tau}{C} \right\rceil$$

where $\lceil x \rceil =$ smallest integer number $\geq x$

- c) Up to which lower limit could the cycle time be reduced (minimum cycle time)?

$$C_{min} =$$

- d) What is the line utilization if the theoretical minimal number of work stations could be realized?

$$\rho = \frac{\tau}{M \cdot C}$$

- e) What is the line utilization if $M=5$ work stations have to be set up?

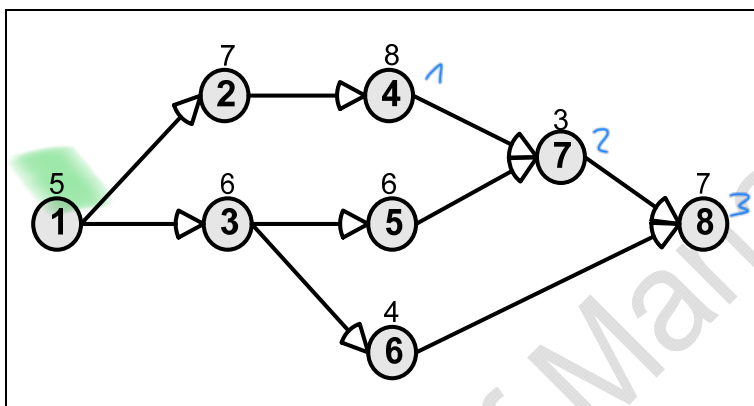
$$\rho = \frac{\tau}{M \cdot C}$$

• **Line balancing by use of a priority rule based heuristic**

- Principle: **successive assignment** of the feasible tasks to stations according to a given priority rule
- **Popular priority rules:** maximum standard time, maximum number of immediate successors, maximum total number of successors, position weight etc.

❖ For the precedence graph shown below complete the assembly line balancing according to the priority rule „maximum total number of successors“. (In case of ties choose the task with the lowest task number.) The cycle time is 12 min.

1. Draw the precedence graph



2. Determine priority values of the tasks

Task	1	2	3	4	5	6	7	8
Priority value	7	3	4	2	2	1	1	0

3. Generate the stations one-by-one

Work station	Feasible tasks	Chosen task	Task time	Remaining cycle time
1	1	1	5	12-5 = 7
	2, 3	3 (higher prio.)	6	1
2	2, 5, 6	2	7	5
	(4), (5), 6	6	4	1
3	4, 5	4	8	4
4	5	5	6	6
	7	7	3	3
5	8	8	7	5

6 exceeds rem. time
task 8 does not fit; new station

Exercise (Quiz)

Eight tasks of an assembly process have to be assigned to stations in a line such that an average output of six product units per hour is achieved. Details are given below.

Task	Task time (min)	Immediate predecessor
1	3	-
2	4	1
3	3	1
4	5	2, 3
5	3	3
6	5	3
7	3	4, 5
8	2	6, 7

- Draw the precedence graph.
- Determine the cycle time which is required to achieve six product units per hour.
- Determine the theoretical minimal number of work stations.
- Carry out the line balancing procedure according to the maximum total number of successors rule.

Solution

a)

b)

c)

d)

Task	1	2	3	4	5	6	7	8
Priority value								

Work station	Feasible tasks	Chosen task	Task time	Remaining cycle time

Quiz: What is the utilization level of the production system?

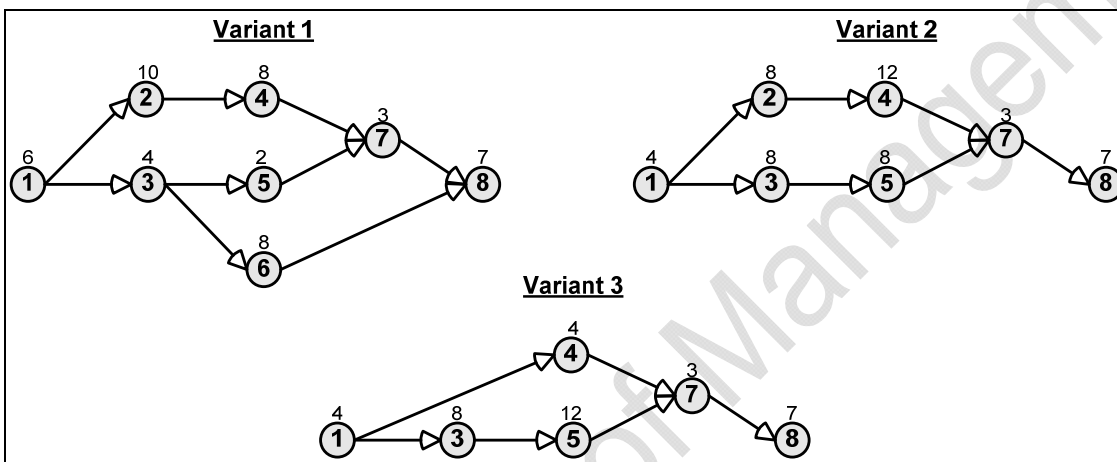
- a. 100 %
- b. 93.33 %
- c. 75 %
- d. 70 %

3.3.2 Line balancing for a mixed model assembly line

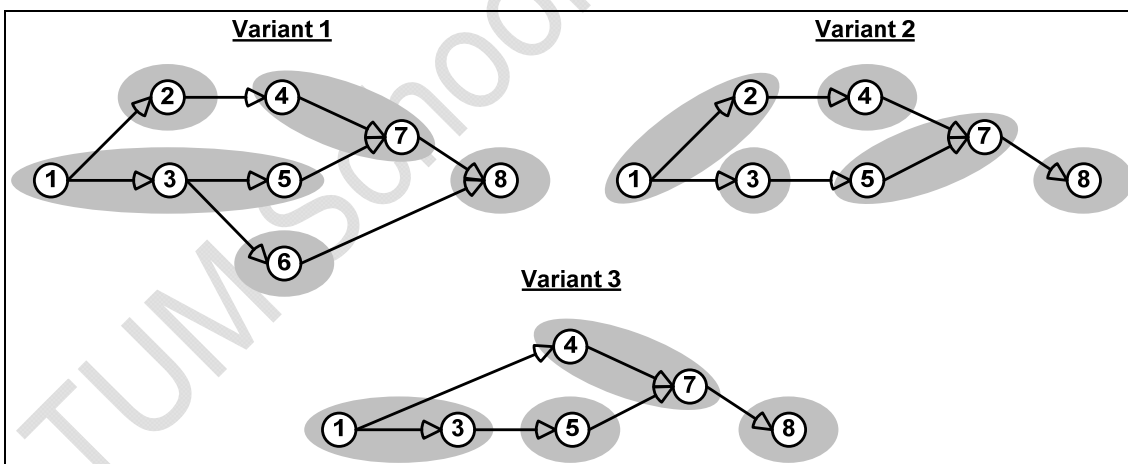
- Variants of basic product types are determined through various characteristics, e.g. optional equipment (automotive), size (clothing), technical performance (electrical devices) or colors.
- Different product variants are manufactured on the same line.
- No changeovers between different product variants are necessary.
- Product variants differ in task sequences and task times.

Example

The precedence graphs for three variants of a basic product type are shown below. The related processes differ by task times and the absence/presence of specific tasks.



- The optimum line balance for each of the product variants (cycle time = 12 min) is shown below.



- The result is infeasible for the entire line configuration.
- Practical procedure: use of a mixed (representative) hybrid represented in a joint precedence graph.

- **Flow lines for the assembly of product variants**

- Lines are designed such that multiple variants of the same basic product type can be produced.
- Generation of a “**hybrid**“ with task times of the “**hybrid**“ corresponding to the variant-specific weighted task times, using the demand ratios of the variants as weighting factors. **Precedence relationships** of each variant are considered, when determining the precedence relations of the “**hybrid**“.



Exercise 1: mixed model assembly line

Generate the “**hybrid**“ and draw the combined precedence graph. Complete the assembly line balancing procedure using the priority rule “maximum total number of all successors“. The cycle time is 13 min.

Task	Task time (min)			Immediate predecessor			Task time (min) Hybrid	Pre-decessor Hybrid
	Product variant (demand ratio)			Product variant				
	1 (25%)	2 (25%)	3 (50%)	1	2	3		
1	-	2	5	-	-	-		
2	-	12	-	-	1	-		
3	-	2	7	-	1	1		
4	8	-	8	-	-	1		
5	5	3	12	-	2	-		
6	3	3	3	4	3	3,4		
7	2	-	3	4	-	4		
8	8	8	2	5	5,6	5		
9	8	-	8	7	-	7		
10	1	1	1	8,9	8	8,9		

(5) The processing time in the hybrid for task 4 is:

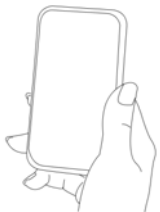
- 0
- 4
- 6
- 8

(6) The processing time in the hybrid for task 5 is:

- 0
- 4
- 6
- 8

(7) The predecessors in the hybrid for process 6 is (are):

- 3
- 4
- 1 and 3
- 3 and 4



Joint precedence graph for the hybrid

Ranked positional weight technique

- Specific priority rule based procedure
- Positional weight: sum of all task times of the (direct and indirect) succeeding tasks and the task itself

$$p_i = t_i + \sum_{k \in N(i)} t_k$$

p_i : positional weight of task $i \in I$

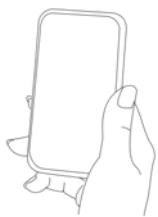
$N(i)$: successors of task $i \in I$

t_i : task time of task $i \in I$

Line balancing

Task	1	2	3	4	5	6	7	8	9	10
Priority value										

(8) Which are the priority values of the work elements based on the ranked positional weight method? The values are sorted in the same order as the elements in the table.



- a. 41,17,13,23,14,9,9,6,7,1
- b. 41,17,13,15,14,9,9,6,7,1
- c. 38,14,9,17,6,6,9,6,7,1
- d. 41,17,13,15,13,9,9,6,7,1

Work station	Feasible task	Chosen task	Task time	Remaining cycle time

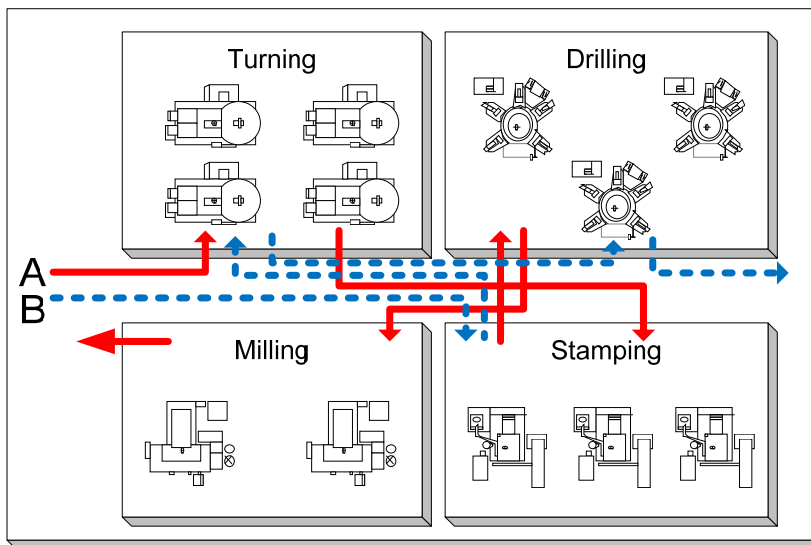
⇒ Work load of the stations:

Product variant	Work station			
	1	2	3	4
1				
2				
3				

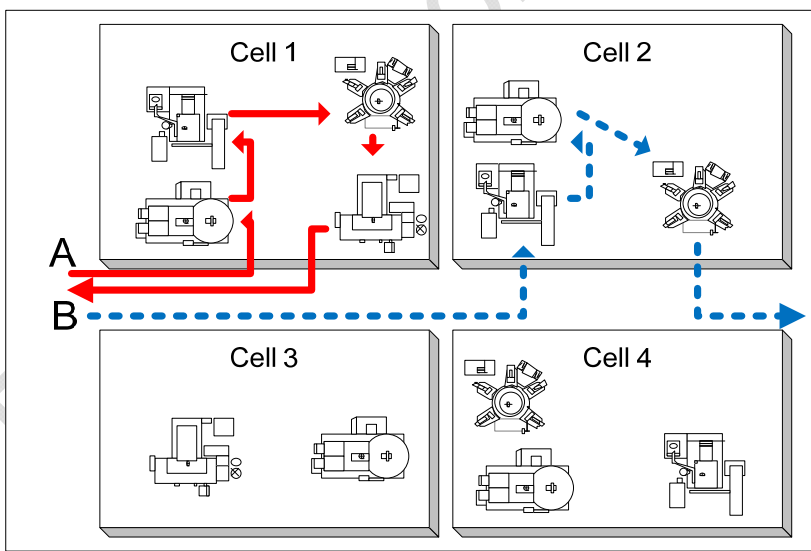
3.4 Cellular manufacturing

- **Manufacturing cells**

- Established through the spatial consolidation of a limited number of working systems or machines
- Generation of **product families** based on the similarity of machine requirements
- Generation of **machine groups** with respect to a specific product family
- Based on: **machine-product incidence matrix**



Material flow in job shop production

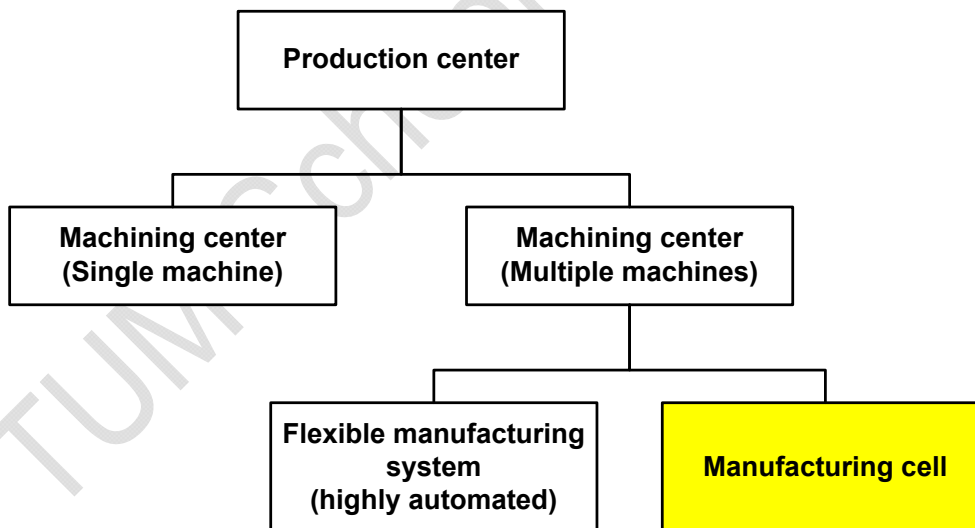


Material flow in cellular manufacturing

- ❖ Which pros and cons does cellular manufacturing show in comparison to other layout types?

	Pro	Con
Transportation costs		
Material flow		
Throughput times		
Work-in-process		
Space requirement		
Production control		
Visibility of production processes		
Flexibility		
Monotony of work		
Investment (automation)		
Generation of product families and machine groups		
Capacity utilization		

- Types of production centers



- **Method for the generation of product families and machine groups**

- **Binary sorting** (Aim: Generation of a block-diagonal-structure)

Machine	Product					
	A	B	C	D	E	F
1			1		1	
2		1	1			
3	1			1		
4		1	1		1	
5	1			1		1

(1) Sorting of rows (machines)

Machine	Product					
	A	B	C	D	E	F

(2) Sorting of columns (products)

Machine	Product					
5						
3						
4						
2						
1						

◇ **Exercise: binary sorting and duplication of machines**

The bike manufacturer Bone Shaker SE produces and assembles a variety of components in a dedicated production area. This portfolio comprises eight components and nine types of processing equipment units. The corresponding incidence matrix is given below.

	Bottle cage (1)	Chain (2)	Rear lamp (3)	Pump peg (4)	Mud gard (5)	Dynamo (6)	Ball bearing (7)	Front lamp (8)
Paint station (P)			1		1			1
Wiring equipment (W)			1			1		1
Bending machine (B)	1			1	1			
Rubber coating machine (R)	1			1				
Surface cleaning station (C)		1					1	
Deburring machine (D)	1			1	1			
Saw (S)	1			1	1			
Oiling station (O)		1				1	1	
Functional test station (F)			1			1		1

Determine equipment groups and component families using binary sorting. Are there any material transfers required between the cells?

The costs per period of additional equipment are shown in the following table:

P	W	B	G	C	D	S	O	F
250	270	200	150	50	225	175	150	260

Production volumes of the components per period are estimated as follows:

1	2	3	4	5	6	7	8
110	125	130	95	150	175	165	250

Transportation costs between cells are 1.25 € per unit of a component (also to and from, if required).

Determine the optimal cellular design!

(9) How many machine groups are defined?

- 2
- 3
- 4
- A number equal to the number of machines.

(10) Is there any material flow between the machine groups? If so, between which groups?

- No material flow between the groups
- Between groups 1 and 2 and groups 2 and 3
- Between groups 1 and 2
- Between groups 1 and 3 and groups 2 and 3

(11) The alternatives for avoiding material flows between groups 2 and 3 need to be evaluated. Which of the following alternatives would lead to minimal overall costs?

- Add a machine O to machine group 3.
- Add machines W and F to machine group 2.
- Keep transporting product 6 between machine groups 2 and 3.
- Add machine O to machine group 3 and machines W and F to machine group 2.

