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Production

Control in Practice

A Situation-Dependent Decisions Approach

Exercises and Answers

**Introduction**

In this book, you can find several exercises and answers for the different chapters in the book “Production Control in Practice – A Situation Dependent Decisions Approach. There is also a separate book that contains the derivations/calculations for the exercises where these are relevant. That document is meant for the instructor/teacher.

**How to use the exercises**

- The section with "Key Concepts" is there for you to check on whether you know what the main theoretical concepts are of this chapter of the book.

- The "Theory"-questions are for you to check whether you understand the basic theoretical concepts in such a way that you can use them in discussions on related topics. For some of these questions, the answers can be found directly in the text of the book, for others some relevant text needs to be used and interpreted.

- The "Basic Exercises" give a nice step-by-step introduction to the type of approach and calculations needed for the issues discussed in this chapter of the book. Understanding these types of approaches and calculations is a prerequisite to solving the more realistic questions.

- The "Complex Exercises" are on a more realistic level. Usually, these exercises are related to a case description, from which both the data needed and the calculations or steps to take have to be derived. Solving these exercises requires a higher level of insight into the concepts discussed in the related chapter of the book.

1. **Production Control - a logistic control**

**function**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

*- Production control*

*- Logistics*

*- Logistic planning and control (LPC)*

*- Transformation process*

*- Planning*

*- Control*

*- Control cycle*

*- Basic decision elements LPC: planning, acceptance, release, progress monitoring*

*- Work in progress (WIP)*

*- Process, Control, Organization, Information (PCOI)*

- *Logistic performance*

- *Delivery time*

*- Delivery performance*

- *Delivery reliability*

- *Delivery flexibility*

*- Logistic costs*

- *Logistic concept*

- *Work centers*

*- Routing*

*- Job*

*- Order*

*- Processing time*

*- Service time*

*- Throughput time*

*- Lead time*

*- Due date*

*- Completion date*

*- Lateness*

*- Tardiness*

*- Earliness*

*- Complexity*

*- Uncertainty*

*- Flexibility*

**Theory**

**Question 1.1.1**

a What is the difference between planning and control?

b What are the four essential decisions in Logistics Planning and Control?

c Explain how Work In Progress is related to the Release Decision.

d LPC combines four different types of elements to allow a transformation process to start … which four types of elements are these?

e What are the four basic aspects to be considered when describing a production system?

f What are the four elements usually considered when determining the logistic performance?

g What is the difference between delivery time and lead time?

h Besides ‘delivery performance’ two other aspects should be considered as well when discussing the overall performance of a transformation process. What are the other two?

i Is the following statement correct or incorrect: "Logistics in a production company consists entirely of external transport and storage of goods in warehouses".

j Is the following statement correct or incorrect: "Often logistic tasks are performed by operators from production departments as well".

k Is the following statement correct or incorrect: "Logistic planning and control is only relevant in case of physical good flows".

l Explain the relation between lateness, completion date, and due date.

m What is the relation between tardiness and lateness?

n What is the difference between throughput time and lead time?

**Question 1.1.2**

a Give an example of a goal relevant to flexibility in logistics.

b Give an example of a goal relevant to delivery reliability.

c Is the goal to achieve a high capacity utilization an internal goal or an external goal? Explain.

**Question 1.1.3**

a Under which aspect of the PCOI model is described the way a message is sent from one person to another in an Engineering department (the P, the C, the O, or the I)?

b Under which aspect of the PCOI model is described the routing of a production order through a production process?

c Under which aspect of the PCOI model is described who is responsible for the picking of materials in a warehouse?

d Under which aspect of the PCOI model is described what sequencing rule is used by an operator when choosing the next job to start with?

**Question 1.1.4**

a Give an example of the input (‘material’), output (‘product’), a ‘capacity resource’, and ‘supporting information’ in case of a curing process in a hospital.

b Give an example of the input (‘material’), output (‘product’), a ‘capacity resource’, and ‘supporting information’ in case of the storage process in a warehouse.

c Give an example of the input (‘material’), output (‘product’), a ‘capacity resource’, and ‘supporting information’ in case of the administrative process used to enroll students in a university.

**Question 1.1.5**

a A complex situation for control does not need to have uncertainty as well. Explain.

b Short lead times of purchased components improve the flexibility of a production process. Explain.

c Explain how the decomposition of a control problem may reduce the complexity of that control problem.

d Name two forms of flexibility related to the logistics of an amusement park.

**Question 1.1.6**

a Give two examples of characteristics of a production situation that add to the *complexity* of the situation.

b Give two examples of characteristics of a production situation that add to the *uncertainty* of the situation.

c Give two examples of characteristics of a production situation that add to the *flexibility* of the situation.

d Give an example of uncertainty for LPC coming from the demand side, one for material supply, and one for the availability of resources.

**Basic Exercise**

**Exercise 1.2.1**

Consider the data and registrations of customer orders finished and delivered in the week from 11 to 17 December as given in Table 1.1.

a What would be the average lateness of these orders?

b What is the average tardiness of these orders?

c What is the maximum earliness of these orders?

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Order | A | B | C | D | E | F | G | H |
| Due date | 9 Dec | 11 Dec | 11 Dec | 12 Dec | 14 Dec | 15 Dec | 17 Dec | 18 Dec |
| Delivery date | 11 Dec | 11 Dec | 12 Dec | 13 Dec | 13 Dec | 14 Dec | 16 Dec | 17 Dec |

**Table 1.1** Different data of several customer orders.

**Answers (or pages where answers can be found)**

**Theory**

**Question 1.1.1**

a p6

b p6 (planning, acceptance, release, progress control)

c WIP increases when new jobs are released

d p7 (jobs, materials, capacity resources, and information)

e p7 (Process, Control, Organization, Information)

f p8/9 (Delivery reliability, Delivery Time, Delivery Flexibility and Logistic Costs)

g p11

h p9 (Quality, Costs)

i Incorrect

j Correct

k Incorrect

l p11

m p11

n p11

**Question 1.1.2**

a At least 10% of requests on a change in due date for accepted orders are accepted

b At least 95% of orders accepted are delivered on or before the due date

c internal: focus on costs and/or productivity

**Question 1.1.3**

a I

b P

c O

d C

**Question 1.1.4**

a Material: patient; product: cured patient; resource: bed; information: list of medicines

b Material: items to be stored; product: picked items; resource: forklift truck; information: picking list

c Material: data on a student; product: registration; resource: administrator; information: rules to be followed

**Question 1.1.5**

a p12

b Short lead times shorten the possible reaction time

c p12

d Multi-skilled operators, overcapacity

**Question 1.1.6**

a High diversity routings, a large number of operations in a routing

b Unannounced changes in demand, uncertainty in yield of a process

c Multipurpose machines with short change-over times, option for overtime

d Change in customer order, delay in delivery, breakdown machine

**Answers**

**Basic exercise**

**Exercise 1.2.1**

a 0 day

b 0.50 day

c 1 day

**2 Horizontal and Vertical Decomposition**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

*- Production unit*

*- Production unit control (PUC)*

*- Decoupling point control (DPC)*

*- Horizontal decomposition*

*- Vertical decomposition*

*- Acceptance decision*

*- Release decision*

*- Sequencing decision*

*- Supply logistics*

*- Production logistics*

*- Distribution logistics*

*- Decoupling point (DP)*

*- Customer order decoupling point (CODP)*

*- Distribute to Stock (DtS)*

*- Make to Stock (MtS)*

*- Assemble to Order (AtO)*

*- Make to Order (MtO)*

*- Purchase to Order (PtO)*

*- Downstream*

*- Upstream*

*- Customer order delivery time*

*- Floating decoupling point*

*- Controlled stock point*

*- Buffer*

*- Just in Time (JIT)*

*- Just in Case (JIC)*

*- Push-based trigger*

*- Pull-based trigger*

*- Plan-based trigger*

*- On order*

*- On stock*

- *Lead time*

- *Delivery time*

*- Throughput time*

**Theory**

**Question 2.1.1**

a Decoupling points are not only relevant for the material flow but also for the flow of capacities. Explain.

b Decoupling points are not only relevant for the material flow but also for the flow of information. Explain.

c Explain why a CODP can be considered as a special decoupling point (so: why would it be a decoupling point, and what is so special about it?).

d In what way does a Customer Order Decoupling Point divide a transformation process into a set of planning-based activities and a set of customer-order-based activities?

e Name and describe the five CODPs.

f Do all parts of a product require the same position of the CODP? Explain.

g Explain the difference between MtS and AtO.

h The logistic function for a production situation, can be split up into three subfunctions. Name them.

i What two decisions need to be made at each decoupling point?

j Name one advantage of having a CODP far downstream and one advantage of having a CODP far upstream.

k CODP is also known as a Push-Pull Point. Explain.

l What is the difference between horizontal decomposition and vertical decomposition for the LPC problem?

m Is a Production Unit also necessarily an organizational unit?

n Why could creating a JIT situation be difficult in the case of a Make-to-Order CODP?

0 Can there be more than one CODP in a company?

**Question 2.1.2**

Consider the process diagram as given in Figure 2.1.

|  |
| --- |
| 1  2 |

**Figure 2.1** The process diagram for the process in question 1.2.

a Which process is upstream from the stock point?

b Which process is downstream from the stock point?

**Question 2.1.3**

a Why would a change in batch size be a good point for a decoupling point (DP)?

b Why would a DP after a process with unreliable yield be useful?

c Why would a DP after a process with a long throughput time be useful?

**Question 2.1.4**

a Explain the basic difference between pull-based production and plan-based production.

b If push-based production is based on accurate forecasts, then this may result in a “just-in-time” situation. Explain.

**Basic Exercises**

**Exercise 2.2.1**

Consider the process diagram as given in Figure 2.2.

|  |
| --- |
| Production unit 1  Production unit 2  **CODP**  order  intake  2 days  3 days  4 days |

**Figure 2.2** The process diagram for a certain process**.**

What is the expected customer order delivery time?

**Exercise 2.2.2**

Consider the maintenance of machinery on a large chemical plant (230 ha.). The first-line maintenance is done right at the location of the machines themselves (also called "factories": on the plant, there are six interrelated but different factories). Second-line maintenance is done at the plant's central repair shop. Third-line maintenance is done elsewhere, usually at a repair shop of the manufacturer of the asset. The maintenance manager is thinking about two possible locations of a decoupling point for the capacity resources, i.e. only one at a central location (all mechanics are positioned at the central repair shop, and will be sent to the local factories when required) or also decoupling points at each factory (so each factory has one dedicated mechanic).

a Give two (logistical) reasons why a decoupling point for capacity resources at each factory could be useful.

b What would be the drawback of having factory decoupling points with dedicated capacity resources?

**Exercise 2.2.3**

Consider the production of plastic buckets, using an injection molding machine for producing the bucket (in different colors), manual assembly for attaching the handle, adding a sticker, and packing the bucket in a box.

a In a make-to-stock situation, when would it be useful to have a decoupling point between the injection molding and manual assembly?

b In a make-to-stock situation, when would it not be useful to have a decoupling point (not a CODP) between injection molding and manual assembly?

c When would it be useful to position the CODP between the injection molding process and the manual assembly?

**Exercise 2.2.4**

A company assembles complex machines in a limited number of special assembly docks. The large number of components used are partly bought from external suppliers, and partly produced by the component manufacturing departments of the company.

a Explain why positioning a decoupling point in front of the assembly docks would be a good decision.

b When would it be a good idea to position the CODP at the decoupling point in front of the assembly docks, and when would it be a better choice to put the CODP earlier in the process?

**Complex Exercises**

**Exercise 2.3.1**

Furniture Factory A-Design (FFAD) makes dining chairs. The following materials are stored in the raw materials warehouse:

* Steel tubes of a single diameter
* MDF boards with identical dimensions
* 10 different colors of metallic paint
* Fasteners (nuts and bolts)
* Plastic chair-leg caps (one version)

The production of a chair involves five production departments, each with a head who is responsible for his department. The following is a brief description of each department:

- Department 1:

From the raw materials warehouse steel tubes go to department 1 where they are cut and welded into seat frames. After department 1 the frames are put in stock. The seat frames are made so that they are easy to store (nested/fit together). The lead time is 2 days.

- Department 2:

From the raw materials warehouse MDF boards go to department 2 where they are made into either seats or backrests (these are made from the same raw material). The produced seats or backrests are stored in large crates. The lead time is 3 days.

- Department 3:

From stock, the frames go to department 3 (paint shop). Here they are given their color through the application of metallic paint (choice of 10 colors).

The metallic paint is supplied from the raw materials warehouse. The spray painting is done by hand, which makes it very quick; no time is lost when switching between colors, and the paint is dry in a few minutes. After painting, the frames are placed in stock. Here they can no longer be stacked, due to the risk of paint damage. The lead time is 2 days.

- Department 4:

The seats and backrests come to Department 4 from the storage after department 2.

Leather is also supplied directly to Department 4 by a local company (no stock); this company can deliver fast: when an order is placed by 17:00, the required types of leather in the desired colors are present in Department 4 at the start of the next working day.

There are 10 different colors of leather. Department 4 upholsters the seats and backrests with leather.

Compared to the other materials which are used in a chair, leather is very expensive. The products from Department 4 then go into a storage area. This contains special racks that take up a relatively large amount of space. The lead time for this department is 2 days.

- Department 5:

Department 5 is the assembly department. This department receives fasteners and chair-leg caps from the raw materials warehouse. The painted frames, upholstered seats, and backrests come from the storage locations. Department 5 makes complete chairs from the various components and packages them, after which they go to the finished product warehouse. The lead time is 1 day.

The chairs are sold through a number of retailers (furniture stores) in the Netherlands and Belgium. Each retailer has a few demonstration models in the showroom. The customers can choose their desired color using color swatches. The customer's final choice can be any combination of:

* The color of the frame
* The color of the leather for the seats
* The color of the leather for the backrest

After the choice has been made, the retailer places the order with FFAD, which supplies the chairs from stock within a week. The administrative process needed to turn the customer order into production orders takes 3 days.

a Draw the basic logistic structure for this situation.

b What could be a good reason for a decoupling point of "frames"?

c What could be a good reason for a decoupling point of "backrests"?

d Where is/are the Customer Order Decoupling Point(s) (CODP) located?

e What is de the delivery time that can be promised to a customer?

f What would be the total lead time from raw materials to finished product?

g What is the downside of the location of the CODP for FFAD?

h What are the advantages for retailers of this/these CODP location(s)?

i How would it benefit FFAD to locate the CODP directly after departments 3 and 4?

j What would be the delivery time that can be promised to customers if the CODP is located directly after departments 3 and 4?

k If delivery times would permit it, what would be the advantages for FFAD of locating the CODP just before departments 3 and 4?

**Exercise 2.3.2**

One of the products manufactured by Fred & Co. is outside mirrors for truck and bus manufacturer Codema. Figure 2.3 shows the product build-up.

**Production process**

* Plastic granules are made into mirror housings (2) through an injection molding process.
* In a hot forming process the plastic ring (4) is created by forming sheet material (PVC with plasticizers) in a (simple) mold.

|  |  |
| --- | --- |
| A diagram of a device  AI-generated content may be incorrect. | Product drawing / BOM   1. the finished product, a heated black side mirror (available in ten versions, 5 electric and 5 mechanical) 2. plastic mirror housing (injection molded) 3. heating film (purchased part) 4. plastic ring (PVC) (hot forming) 5. fasteners including motor (purchased parts) |

**Figure 2.3** The product build-up of the outside mirror.

* The raw materials/purchasing warehouse supplies plastic granules (for injection molding), plastic sheet material (for hot forming), fasteners (5), and heating film (for assembly) from stock.
* From assembly, the finished products (1) go into storage.

**Supply chain**

General:

* The total demand from Codema is nearly constant every week. The demand for each type can vary greatly per week.

Supplier:

* The supplier can deliver any desired quantity at any desired time for the same price.

Fred & Co.: (current working method)

* Raw materials. A two-day safety stock is maintained for each purchased item. This is in addition to the materials needed for the (ordered) weekly production volume.
* Injection molding*.* In connection with the very long changeover time for the injection molding, only two versions can be produced in any given week (more changeovers would mean a too great loss of capacity). Each type is therefore produced once every five weeks.
* Hot forming*.* The quantity required for assembly of each type is produced every week. Each type is produced once a week.
* Assembly. Units are assembled for stock. On average, sufficient stock of each type is held for about two weeks. There is sufficient production capacity to meet the daily demand.

Codema: (current ordering method)

* Codema accepts a delivery time of one week.
* Codema maintains a two-day safety stock for the items it purchases from Fred & Co. in its purchasing warehouse. The weekly deliveries from Fred & Co. correspond to the actual need (LFL) for their weekly production planning.

a Draw the basic logistic structure for this situation.

b Specify where the CODP(s) is/are.

c Which of the five described situations regarding ‘order fulfillment’ (DtS, MtS, AtO, MtO, PtO) is applicable in this situation?

d What would be a better place for the CODP(s) in this production process? Why there?

e How many different types of production orders would this company use?

f What could be a good reason for a decoupling point of "fasteners"?

**Exercise 2.3.3**

Company Vis-à-Vis designs and produces diving masks, both for snorkeling and for professional diving. The masks consist of the following parts (see Figure 2.4):

- Silicon skirt ('facepiece’)

- Silicon strap

- Plastic frame

|  |
| --- |
| A close-up of a scuba mask  Description automatically generated |

**Figure 2.4** The product structure of a diving mask.

- Lenses (safety glass or plexiglass), one or two (depending on design).

The frame is produced from plastic granules via injection molding. Pigments can be added to the granules to give the frame a color to your liking. The amount of pigment used depends on the weight of the frame. If desired, the frames are provided with a special customer-specific logo (via silkscreen printing).

Customers can choose from different standard shapes and standard colors of the glasses. The company produces diving masks in 8 different frame shapes and uses 6 standard colors (a total of 48 variants). The company uses a fixed range of silkscreen inks.

Both the skirts and the straps are made of silicone (standard material, two options in terms of color: black or transparent), also via injection molding. Skirts and straps are specific to the frame shape (so 8 variants each).

After that, the masks are assembled (purchased lenses are inserted; the lenses to be used depending on the chosen frame). Finally, the masks are tested and packed for shipment.

Customer orders first go through an intake process. If a customer asks for a customer-specific logo via silkscreen printing, the product design is done during the order intake process.

Table 2.1 contains the lead times of each of the processes. These lead times form the basis of the production planning.

Figure 2.5 shows the logistic basic structure, including 12 connecting arrows between the processes, but without the indication of decoupling points. At 11 of the 12 connecting arrows, a decoupling point could be added (on the position of the number on the arrow).

|  |  |  |  |
| --- | --- | --- | --- |
| *Process* | *lead time* | *Process* | *lead time* |
| Shipment | 1 | Supply lenses | 10 |
| Testing and packing | 1 | Supply plastic granulate | 15 |
| Assembly | 3 | Supply silicone | 10 |
| Molding frame | 5 | Supply pigment | 20 |
| Silkscreen printing frame | 4 | Supply silkscreen ink | 15 |
| Molding skirt | 6 | Order intake process | 3 |
| Molding strap | 4 |  |  |

**Table 2.1** Lead times (in days) of the processes.

a If a diving mask is provided with a customer-specific logo (which is only known after the receipt of the customer order), which connection arrow(s) should contain a customer order decoupling point so that the customer order delivery time is as short as possible? Be complete and explain your answer.

|  |
| --- |
| A diagram of a machine  Description automatically generated |

**Figure 2.5** Logistic basic structure.

b Assume the company has placed customer order decoupling points at points 1, 2, 3, 4, and 5 in the basic logistic structure so that one knows the customer's choices for frame, color, skirt, and strap before producing. What is the minimum delivery time that can be promised then to customers who want diving masks without a specific logo, given the lead times of the processes?

Explain your answer.

c In which situation for testing and packing would a decoupling point on arrow 10 be required, and in which situation is there no need for such a decoupling point? Explain your answer.

**Answers (or pages where answers can be found):**

**Theory**

**Question 2.1.1**

a Only when an order is released at a decoupling point, the required (flexible) capacity resources should be assigned as well.

b Only when an order is released at a decoupling point, the relevant information should be provided as well.

c It decouples the process in sub-processes just like all other DP’s; special: split up between planning-based processes and customer-order-based processes.

d Before CODP: planning-based; after CODP: customer-order based

e p19

f No. The position of the CODP depends (a.o.) on the lead times of the supplies.

g p19

h p16

i p17 (acceptance and release)

j p20 (short delivery time vs no inventory)

k Push = plan based; pull = customer order based

l p15

m No (see remark p21/22)

n Then the delivery time will be dependent on the throughput times of the processes still to be done, which is not necessarily the same as “in time” from a customer perspective

0 No, there can be multiple CODPs in a company. Some products can be MTS while other products are MTO. This depends on the characteristics of the product and/or the characteristics of the customer (for instance: what lead time do they expect?).

**Question 2.1.2**

a 1 is upstream

b 2 is downstream

**Question 2.1.3**

a Gives DPC the option of creation and/or allocation of controlled stock.

b Inventory could be used to compensate, and decisions could be adapted (like the allocation of capacity resources and priorities between orders).

c Requirements (demand) and other characteristics (like availability of capacity resources) may have changed in the meantime

**Question 2.1.4**

a p29/30

b If both the throughput time and the demand at time t are forecasted accurately, and the production is started at t-TPT, then exactly on time t the correct amount of the product wanted will be available.

**Answers**

**Basic Exercises**

**Exercise 2.2.1**

5 days

**Exercise 2.2.2**

a - Reaction time is much shorter (esp. for corrective maintenance)

- In the situation where we have dedicated resources (or: specialized knowledge/

experience)

b - No easy way to organize flexibility (exchange of resources)

- In total more capacity (1 for each factory) is needed than necessary (each factory

needs "own" extra capacity to cover peaks in demand)

**Exercise 2.2.3**

a When assembly is done in different batch sizes and is based on for instance the availability of the different assembled buckets in stock

b When assembly is done plan-based in large batch sizes (so not on "pull-base" taking into account the assembled buckets in stock)

c When the assembled items are customer-specific

**Exercise 2.2.4**

a To make sure no jobs are started if not all parts are available

b Depends on required delivery time versus specificity (and variety) of the parts used

**Answers**

**Complex Exercises**

**Exercise 2.3.1**

a (see also Figure 2.6).

S = suppler, C = customerA diagram of a flowchart

AI-generated content may be incorrect.

**Figure 2.6** The basic logistic structure.

b Combining frames for the same color

c Waiting for the availability of the right leather

d Stock point "chair"

e 3 days

f 6 days

g Many different variants in stock

h Short delivery time

i Less inventory needed

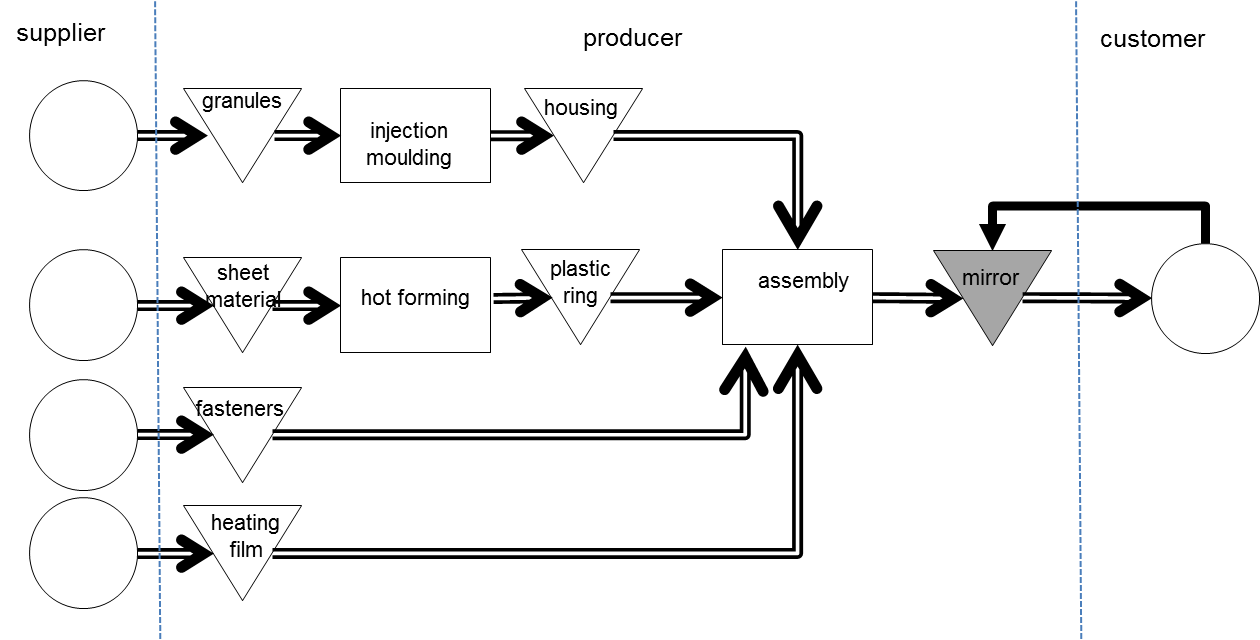
j 4 days

k Reduction inventory and risk

**Exercise 2.3.2**

a See Figure 2.7

b Stock point "mirror"



mirror

**Figure 2.7** The basic logistic structure.

c MTS

d Stock points directly before assembly: less diversity in items to store and thus lower total stock

e 3

f Long lead time of supply

**Exercise 2.3.3**

a At 1, 6, 7, 8, and 5

b 3+max(5,6,4)+3+1+1 = 14 days

c Yes: testing and packing done customer-specific

No: if only standard tests and packing

**3 Planning and Control in Production Units**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *Material complexity*

*- Capacity complexity*

*- Bill of Materials*

*- Routing*

*- Job shop*

*- Project-wise production*

*- Process wise production*

*- Mass assembly/flow production*

*- Dock production*

*- Decoupling point*

*- Batch operation time*

*- Item processing time*

*- Setup time*

*- Takt time (required, actual)*

*- Batching time*

*- Deterministic problem*

*- Stochastic problem*

**Theory**

**Question 3.1.1**

a What are the two dimensions used in the logistic typology of Bertrand/ Wortmann/Wijngaard for production units?

b What three characteristics of the products produced in a production unit determine the material complexity of that unit?

c What three characteristics of the products produced in a production unit determine the capacity complexity of that unit?

**Question 3.1.2**

a Give an example of a project-based production situation.

b Give an example of a one-step process situation.

c Give an example of a job shop.

d Give an example of a line production situation.

e Name two logistic issues typically for a job shop.

f Name two logistic issues typically for line production.

g Name two logistic issues typically for a process-based situation.

h Name two logistic issues typically for a project-based situation.

i A strong convergent material flow and a high repeating rate of demand per product, are typical characteristics of which of the following types of production units:

I Job shop production

II Process production

III Line assembly

IV Project-based production

j A non-convergent material flow and production orders with long and varying routings with a low repeating rate of demand, are typical characteristics of which of the following types of production units:

I Job shop production

II Process production

III Line assembly

IV Project-based production

k Consider the following two statements:

I The complexity of material planning and control for a production unit is low for line assembly situations.

II The complexity of capacity planning and control for a production unit is high for a project-based situation.

Choose one of the following options:

1 I and II are both true

2 Only I is true

3 Only II is true

1. I and II are both wrong

l Name two advantages of a production unit designed as a job shop.

**Question 3.1.3**

In case products are produced in batches, the batching operation time differs from the item processing time due to setup time and so-called *batching* time. Explain why these two times can be regarded as a special kind of 'non-value adding' queuing time.

**Basic Exercises**

**Exercise 3.2.1**

A product X consists of two components, i.e. A and B. In each X one A is used and two B's. Draw the Bill of Materials for this product.

**Exercise 3.2.2**

To produce a table, the following activities are required:

- turning the legs (4x)

- drawing holes (4x) in the table blade

- gluing the legs in the table blade

- filling up any cracks or spaces with silicon-based wood splinters.

These activities are all done in the same production unit. Each of these activities is done on a different workstation.

a How many production orders will be used for producing such a table?

b How many operations would be included in the routing of these production orders?

**Exercise 3.2.3**

a If demand on average requires 20 products to be produced per hour, what would be the required takt time for this situation?

b If the actual takt time of a production line is 6 seconds, what would be the takt of this line per hour?

**Exercise 3.2.4**

A production batch consists of 20 products. The setup time for this batch is 15 minutes, while the item processing time is 2 minutes.

a Determine the batch operation time.

b What is the batching time per item?

**Exercise 3.2.5**

The processing time of a product is stochastic by nature because the operation is done totally by hand (no mechanical or automatic support). The average processing time is 30 minutes, while the variance of the processing time is 100 min2.

a Determine the standard deviation of the processing time.

b Determine the variation coefficient of the processing time.

**Complex Exercises**

**Exercise 3.3.1**

A certain company is a manufacturer of stoves in all shapes and sizes. The company buys most of the parts of the stoves and focuses mainly on assembling the stoves and painting the end product.

The Stove Assembly Department consists of twelve processing stations, with the heaters passing through these stations in the same order (starting at station A, then to B, and so on up to and including station L). One or more parts are added per station, depending on the type of heater.

The Paint Department consists of a semi-automated paint line. The mounted heaters are attached to a running chain by an operator and are then automatically painted in the set color. The paint line works in batches, where every week the three different colors (white - metallic gray - black) are finished successively. A batch therefore consists of various types of stoves that must all have the same color.

a What type of situation as given in the production unit typology of Bertrand/ Wortmann/ Wijngaard would apply to the Stove Assembly Department? Explain your answer.

b For such a type of production unit, what are two of the crucial logistic decisions to be taken?

c Name two valid reasons why a decoupling point between the Stove Assembly Department and the Paint Department would be a good idea.

**Exercise 3.3.2**

A company is a producer of garden gnomes in all shapes and sizes. Starting from a mixture of anhydrous calcium sulfate in powder form, pure groundwater, and some other raw materials (including pigments), the basic shape of the gnomes is poured into the Foundry. These cast products (about 20 variants) are then painted in various colors on the Painting workstation. The products then go to the Finishing workstation, where the painted product is supplemented with an accessory, namely a bucket, a wheelbarrow, or a fishing rod, and then packed in a box.

Characterize the process based on the material and capacity complexity. Indicate which standard type from that typology best suits this department (as in the typology of production departments of Bertrand et al.).

**Exercise 3.3.3**

PLAMPRO is a producer of various plastic materials and products. The company has four production departments:

- Three production departments are specially equipped for a certain group of plastics. Each of these departments has a capital-intensive production line that produces plastic granules. The starting material differs between the departments, but within each department the variation is limited. Each production line has all the characteristics of a "real" line.

- One production department where so-called *Specials* are produced. This department's main process is the injection molding of products, using the various plastic granules from the other three production departments. In addition, sometimes, if the customer so wishes, other plastic materials are also used. The number of starting materials is therefore quite large. In addition, the department also can perform a manual end operation, usually an assembly operation in which small parts are added to the product.

The maintenance of the machines and production lines is largely done in-house. To this end, the company has its maintenance workshop, where in particular a variety of metalworking machines are located in a functional arrangement. This workshop is mainly used to repair all kinds of parts of the machines or production lines; the routings are therefore very diverse.

a Characterize the Maintenance Workshop based on the material and capacity complexity and substructure this characterization. Indicate which standard type from that typology best suits this department.

b According to the Head of Maintenance, the software that is also used in the Specials department is very suitable for the (logistical) control of the production of the Maintenance Workshop. After all, maintenance is also a kind of "special". Indicate if you agree with him (and explain why!).

**Exercise 3.3.4**

ChocMe is a company that makes all kinds of chocolate products, such as Easter eggs, chocolates, chocolate letters, and Christmas wreaths, specifically for supermarket-related brands. The raw materials arrive at the raw material warehouse. Most of the raw materials are pumped directly from the trucks into the silos. Before the raw materials from the silos enter production, the right quantities are weighed and dosed.

*Mixing department*

In the mixers, the right combination of raw materials is created and mixed into a paste. An average of 3 flavors of pasta are mixed per day. After the mixing process, the pasta could be stored in large tanks.

*Shaping department*

In the shaping department, the pasta is poured into molds so that the chocolate gets the right shape. There is a diversity of standard shapes that a customer can choose. Then the shaped chocolates are cooled, removed from the mold, and transported to the coating department.

*Coating department*

In the coating department, a shiny layer is created around the chocolate products. This is done in five large coating machines. When this process step is complete, a quality check is performed. After that, the chocolate products are stored in a cooled warehouse before being picked and transported to the decorating department or the packaging department.

*Decorating department*

12% of the chocolate products receive an additional decoration. Think of nuts, marzipan figures, sugar pickles, etc. This depends on the customer's specifications and is done both mechanically and manually. Multiple workplaces have been set up in a row for this purpose, each adding one or more decorations. The remaining 88% of the products skip this process step and go directly to the packaging department.

Packing department

There are 8 different packing machines. Here the products are packed in cellophane, cardboard boxes, or both. Since the packaging must contain customer-specific information, name, and logo, for example, there are 48 different packaging variants.

a Characterize the process in the mixing department of ChocMe based on the typology of production departments of Bertrand c.s.. Please explain your answer briefly.

b Characterize the process in ChocMe's decorating department based on the typology of production departments of Bertrand et al.. Please explain your answer briefly.

**Answers**

**Theory**

**Question 3.1.1**

a Material complexity and capacity complexity

b Nr. of items in a BOM, nr. or layers in a BOM, nr. of different BOM's

c Nr. of operations in a routing, nr. of different sequences of operations in a routing, nr. of different routings

**Question 3.1.2**

a Yacht production in docks; assembly cells for complex machines

b Production of plastic buckets; painting cell

c Tool manufacturer; general machining shop

d Car assembly line; sandwich preparation line

e Waiting times, utilization rates of workstations

f Material availability at workstations, order release versus takt time

g Set-up times needed, batch sizes

h Capacity planning, material planning

i Line assembly

j Job shop

k Only II is true

l Flexibility in routings and types of products

**Question 3.1.3**

Both during setup time and batching time the item considered is waiting without any value being added to the item itself.

**Answers**

**Basic Exercises**

**Exercise 3.2.1**

See Figure 3.1.

A computer screen shot of a diagram

AI-generated content may be incorrect.

**Figure 3.1** The B.O.M. for product X.

**Exercise 3.2.2**

a 1

b 4

**Exercise 3.2.3**

a 3 min

b 600 products/hr

**Exercise 3.2.4**

a 55 min

b 38 min

**Exercise 3.2.5**

a 10 min

b 0.33

**Answers**

**Complex Exercises**

**Exercise 3.3.1**

a Line assembly

b Material availability(supply) at work stations, order release cf. the line takt time

c Batches differ (processing batches are needed at painting);

set-up times are different

**Exercise 3.3.2**

Material complexity: reasonably small (only choice in color and supplements);

capacity complexity: small (identical routings, some differences in operations);

type: process-based

**Exercise 3.3.3**

a Job shop:

- high capacity complexity depending on what needs to be done

- low materials complexity (assuming not too many spare parts are needed))

b No: Specials are more process-based, so a different type of unit

**Exercise 3.3.4**

a Process-based

b Line-assembly

**4 Framework for LPC in Production Systems**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *Logistic Planning and Control*

- *Reaction time*

*- Plan horizon*

*- Time bucket*

*- Vertical decomposition*

*- Aggregate planning*

*- MRP-I (Material Requirements Planning)*

*- MRP-II (Manufacturing Resources Planning)*

*- BWW Framework*

*- Resource planning (capacity planning)*

*- Material planning*

*- Workload planning*

*- Aggregate level (Aggregate Planning)*

*- Factory level (Decoupling Point Level)*

*- Production unit unit level (Shop Floor Control)*

*- Work order acceptance (workload acceptance)*

*- Work order release*

*- Order sequencing*

**Theory**

**Question 4.1.1**

a Explain how required reaction time influences the time horizon of a planning decision.

b Explain the differences between aggregate planning and daily planning in terms of planning frequency, planning horizon, time buckets used, and units used.

**Question 4.1.2**

a What does MRP-II add what is missing in MRP-I?

b In the "MRP-II framework" a distinction is made between "aggregate production planning" and "master production schedule". Name three characteristics where an aggregated plan differs from a more detailed plan.

**Question 4.1.3**

a What is the purpose of checking the Aggregate Production Plan in a supply chain (as is the idea of the Aggregate Procurement Plan and Aggregate Sales Plan)?

b What are the four levels of planning distinguished in the BWW framework? Explain for each level the resulting output.

c Explain what is meant by the statement that "workload takes a central position" in the BWW framework.

d Work orders need to be accepted, released, and sequenced. Explain the differences between these three decisions.

e In the BWW framework, workload planning is also referred to as "utilization planning". Explain why.

f What extra options could be considered for work orders that not have been released yet to a production unit?

**Basic Exercises**

**Exercise 4.2.1**

A company specialized in printing books prints all sorts of books, like novels, study books, books for hobbies, etc. The printing process consists of several steps, including the printing itself, folding and arranging of pages, binding, trimming, and cover attaching. And of course in the end: the packing.

a What would be the aggregated unit used for these products in the aggregate production plan?

b Why would for this company an aggregate production plan be needed?

c Explain what will be decided on the second level, third level, and fourth level of the BWW framework for this company.

**Exercise 4.2.2.**

Indicate for each of the following decisions on which of the four levels of planning and control in the BWW framework these are taken.

a Release of work orders;

b Selection of work order to process next on a workstation;

c Determining work order due dates;

d Assigning operator capacity to workstations;

e Determining the number of shifts to be used next quarter;

f Setting norms for stock levels;

g Assigning operator capacity to production units;

h Release of high-priority orders;

i Ordering materials from suppliers by releasing procurement orders.

**Answers**

**Theory**

**Question 4.1.1**

a Longer reaction time requires a longer time horizon.

b Aggregated: lower frequency, longer horizon, larger time bucket, more aggregated units.

**Question 4.1.2**

a Resources used

b Units used, time horizon, time bucket

**Question 4.1.3**

a To check whether partners in the supply chain follow the planned changes

b p.45/46

c Based on workload vs. capacity orders will be released to a production unit or not (yet)

d Accepted: by a unit to produce the order;

Released: the moment of the actual hand-over of the order to the unit;

sequenced: choice of next order on a workstation

e Workload versus available capacity determines the utilization of the related capacity resource

f Delay the release (and/or change the sequence of release), re-allocate to a different production unit, outsource the order

**Answers**

**Basic Exercises**

**Exercise 4.2.1**

a Printed books

b To align with the planning of the supplier of paper, and to plan the operator capacity needed

c 2nd: customer order acceptance and work order planning

3rd: release of work orders to the production units

4th: sequencing of orders inside production units

**Exercise 4.2.2**

a 3

b 4

c 2

d 4

e 1

f 1

g 3

h 3

i 3

**5 Decoupling Point Control**

Note: In the book, we use the average amount ordered (which equals the average demand in the order cycle) to calculate the P2 service measure; this gives a normative measure that can be used to evaluate the quality of the order policy. For the actual measure we of course have to use the actual demand in a certain period and the number of back orders in that period.

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

For the sections on Decoupling Point Control and Performance Measures:

- *Decoupling Point Control*

*- Production Unit Control*

- *On Order*

*- On Stock*

*- Release decision*

*- Ordering decision*

*- Controlled stock point*

*- Lead time*

*- Delivery time (promised, planned, actual)*

*- Deterministic situation versus stochastic situation*

*- Dependent demand versus independent demand*

*- Program-controlled versus stock-controlled*

*- Time-phased versus non-time-phased*

*- Local stock versus echelon stock (or global stock)*

*- Re-order point control*

*- Echelon stock control*

*- Material requirements planning*

*- Line requirements planning*

*- Internal service level (cycle service level (P1), fill rate (P2), ready rate (P3))*

*- External service level (On Time In Full, CLIP)*

*- Order cycle*

For the section on forecasting:

*- Forecast error*

*- Mean error (ME)*

*- Mean squared error (MSE)*

*- Mean absolute deviation (MAD)*

*- Causal models for forecasting*

*- Time series models for forecasting*

*- Moving average*

*- Weighted moving average*

*- Exponential smoothing (single, double)*

*- Linear regression*

For the section on order size:

*- Holding costs*

*- Ordering costs*

*- Item value (item costs)*

*- Inventory turnover ratio*

*- Demand components (level, trend, seasonality, and randomness)*

*- Economical order quantity (EOQ)*

*- Holding costs*

*- Order-related costs*

*- Period order quantity (POQ)*

*- Silver-Meal and Wagner-Within algorithms*

*- Quantity discount*

*- Minimum order quantity*

*- Single period order problem (news vendor problem)*

**Theory**

**Question 5.1.1**

Answer the following questions related to basic methods for Decoupling Point Control:

a What two decisions determine the stock level at a decoupling point?

b What is for the ordering decision the difference between an "on-stock policy" and an "on-order policy"?

c Name the basic three variables that should be taken into account when making decisions about ordering.

d What is the difference between the promised delivery time, the planned delivery time, and the actual delivery time?

e What are the four basic methods of ordering when looking at the use of stock information on the one side (local vs. global) and the use of a time-phased program versus non-time-phased stock information on the other?

**Question 5.1.2**

Answer the following questions related to performance measures for DCP:

a What is the difference between demand and actual sales?

b Explain the differences between the P1, P2 and P3 service level definitions.

c Explain why the P1, P2, and P3 service levels are considered to be "internal service levels".

d Customer service levels (CSL) focus on how well customer orders are met. Two examples are CLIP and OTIF. Explain these two.

e Why is the Inventory Turnover Rate important from a financial point of view?

f Why does it make sense to focus on the balance between service levels and costs (instead of trying to find a single-dimensional economic optimum)?

**Question 5.1.3**

Answer the following questions related to demand and forecasting:

a Give an example of a product with a demand pattern that is based on "level demand with randomness" (also known as "stationary demand").

b Give an example of a product with a demand pattern that is based on "seasonal demand with randomness".

c Give an example of a product with a demand pattern that is based on "trend demand with randomness".

d What is the difference between a forecast of demand based on a causal model and a forecast based on a time series model?

e Explain the statement that a 'normal moving average model' is a special kind of 'weighted moving average model'.

f Explain the statement that an 'exponential smoothing model' is a special kind of 'weighted moving average model'.

g Name three ways to calculate the quality of a forecast.

h Double exponential smoothing is called that way because exponential smoothing is used twice to create the forecast. Explain.

**Question 5.1.4**

Answer the following questions related to the determination of order sizes:

a. What are the two cost components used to determine the Economical Order Quantity?

b. Give three examples of costs belonging to holding costs.

c. Give three examples of order-related costs.

d. What is the reason that the total costs per period are hardly affected by small changes in the order size chosen around the EOQ?

e. In what way is the POQ related to the EOQ?

f. In what situation would an algorithm like the Silver-Meal algorithm give a better result than the EOQ approach?

g. The holding costs of an item are often considered to be at least partly a function of the purchasing price of that item. Explain.

h. In the case of quantity discount, the EOQ cannot be used straightforwardly. Explain why not.

i. Explain why it makes sense to create interdependencies between order sizes for items that have a BOM relationship.

j. Explain when it might make sense to create interdependencies between order sizes of items that do not have a BOM relationship.

**Basic Exercises**

*Performance Measures:*

**Exercise 5.2.1**

To assess the performance of the inventory control for a purchased part X, a company is considering using either the P1 or the P2 service level. The following data are available for the past year:

- Demand for part X: 2300

- Order size for X: 100

- Number of times the supplier has been called for an urgent delivery due to a shortage: 3

- Total number of pieces X that were missing ('backorders') when they were required to be used in production: 40

For part X, determine each of these two service levels for the past year.

**Exercise 5.2.2**

Table 5.1 shows data from the last 10 order cycles.

|  |  |  |
| --- | --- | --- |
| *Order Cycle* | Demand | Nr. out of Stock |
| *1* | 15 | 0 |
| *2* | 20 | 0 |
| *3* | 15 | 0 |
| *4* | 20 | 5 |
| *5* | 30 | 10 |
| *6* | 25 | 0 |
| *7* | 30 | 5 |
| *8* | 15 | 0 |
| *9* | 20 | 0 |
| *10* | 25 | 0 |
| *Total* | 200 | 20 |

**Table 5.1** Some data for the last 10 order cycles.

Determine the P1 and P2 service levels for this period of 10 order cycles.

**Exercise 5.2.3**

Consider demand and the deliveries in the 6 review periods as given in Table 5.2.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Review period | 1 | 2 | 3 | 4 | 5 | 6 |
| demanded | 50 | 60 | 55 | 46 | 48 | 52 |
| delivered | 50 | 50 | 55 | 40 | 48 | 52 |

**Table 5.2** Demand and the deliveries in 6 review periods.

a What would be the P1-service level for these 6 review periods?

b What would be the P2-service level for these 6 review periods?

c If a year would consist of 12 review periods, what would be the expected number of times a delivery problem might occur assuming the calculated service levels?

**Exercise 5.2.4**

If the average demand for an item is 5000 per year, and the average inventory level for that item is 600, what is the inventory turnover rate for that item?

*Forecasting:*

**Exercise 5.2.5**

Some more theoretical questions on forecasting, going into more detail:

a What is the basic parameter to be used in a forecasting model based on moving averages?

b What is the impact of that parameter (i.e.: what is the difference between using a high value for that parameter and using a small value)?

c Explain the difference between a "normal" moving average and a weighted moving average.

d When are these two forecasting methods the same?

e When could it be worthwhile to use a model based on the weighted moving average instead of a model based on the "normal" moving average?

f What are the essential differences in forecasting between a model based on linear regression and a model based on moving average?

g What are the basic differences between a forecasting model based on linear regression and a forecasting model based on double exponential smoothing?

h Why are often measures like MAD and MSE used to determine the performance of a forecasting model instead of a more simple measure like "the average forecasting error"?

**Exercise 5.2.6**

Consider the demand and forecast data as given in Table 5.3.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Period* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| Demand | 10 | 10 | 9 | 7 | 8 | 6 | 7 | 5 |
| Forecast | 9.5 | 9.8 | 10.0 | 9.8 | 9.0 | 8.5 | 8.0 | 7.5 |

**Table 5.3** Demand and forecast in 8 periods.

a Calculate the Mean Error.

b What is the MAD for these forecasts?

c Determine the MSE for these forecasts.

*Order Sizes:*

**Exercise 5.2.7**

Often inventory holding costs are calculated as a percentage of the item value.

a. Determine the holding cost per year for 1 item if the interest rate is 20% per year and the item value is €150.

b. Determine for that same item the holding costs per month.

**Exercise 5.2.8**

Determine the cost-optimal order size if:

- item value = €200

- holding costs item/year = €32

- average demand/year = 5000

- ordering costs = €50

**Exercise 5.2.9**

If the order quantity for purchasing is 30 and the demand in a year (on average) is 160, how many orders are sent to the supplier in a year (on average)?

**Exercise 5.2.10**

If the order quantity is 50 and demand is randomly spread over time, what would be the average stock level assuming a new order arrives the moment that stock level is 0?

**Exercise 5.2.11**

A company delivers vacuum cleaners from a central stock point somewhere in the country. The average demand is 60 vacuum cleaners per week (there are 50 weeks in 1 year). The cost per order at the supplier is € 50.- and the delivery time is 2 weeks. The interest rate for holding stock is 25% of the purchasing price; the purchase price of a vacuum cleaner is € 120.-.

a How much is the yearly demand (D)?

b What is the cost-optimal order quantity (EOQ)?

c What is the order frequency per year?

d What are the ordering costs per year?

e What are the inventory holding costs per year?

**Exercise 5.2.12**

SHS examines its ordering pattern. A typical product is a small hydraulic fitting. At present SHS orders this part from their supplier in lots of 1000 pieces. The demand for this product is 52000 pieces per year, the purchasing price of one item is €8, the ordering costs are €45 per order and the inventory holding costs (to keep one piece in stock for one year) are €1.25.

a What is the cost-optimal order quantity?

b How much money can the purchaser save per year if he orders following answer a?

**Exercise 5.2.13**

Ximaxi Hospital uses about 3500 boxes of sterile bandages per month. It costs €2.90 to keep one box in stock for a year. The purchase price is €14.50. The order costs are €25 per order, regardless of the order size. There is storage space for up to 1500 boxes. The hospital operates 365 days per year. The Ximaxi Hospital would like to begin using the EOQ.

a How many boxes must be ordered at one time when using the EOQ?

b How many orders will be placed per year?

c What are the expected total costs per year?

d How long, on average, will it take before you need to reorder again?

**Exercise 5.2.14**

The Koeki bakes its cookies every morning before opening. It costs the store €1.5 to bake each cookie, and each cookie is sold for €3.5. At the end of the day, leftover cookies may be sold to a thrift bakery for €0.5 per cookie. The unsatisfied demand does not lead to any penalty (loss of goodwill) cost. The number of cookies sold each day is described by the discrete random variable (X) and it is given in Table 5.4.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| X=x | 0 | 5 | 10 | 15 | 20 |
| P(X=x) | 0.10 | 0.20 | 0.30 | 0.25 | 0.15 |

**Table 5.4** Distribution of the demand for cookies.

a Based on the discrete distribution above, how many cookies should be baked each day before the store opens?

b What is the expected amount of unsatisfied demand under the optimal ordering quantity?

c What is the expected proﬁt under the optimal ordering quantity?

d (pretty difficult)

If you were to approximate the discrete demand distribution with a normal distribution, using a mean of 11 and a variance of 36, what would be the number of cookies that should be baked each day before the store opens?

**Complex Exercises**

*Performance Measures:*

**Exercise 5.3.1**

This exercise shows why choosing a logistic performance indicator requires careful thinking. Consider the following situation for a company delivering products to customers during the time day 1 till 40. In this time the company has to fulfill eleven customer orders (a - k). At the end of day 40 the data on the delivery of these orders as given in Table 5.5 has been collected:

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| order | dd | qty | del1 | qty1 | del2 | qty2 | del3 | qty3 |
| a | 5 | 20 | 6 | 5 |  |  |  |  |
| b | 6 | 100 | 6 | 50 | 8 | 50 |  |  |
| c | 12 | 4 | 11 | 4 |  |  |  |  |
| d | 12 | 30 | 12 | 30 |  |  |  |  |
| e | 15 | 45 | 14 | 15 | 18 | 30 |  |  |
| f | 20 | 10 | 15 | 5 | 20 | 5 |  |  |
| g | 21 | 2 | 25 | 2 |  |  |  |  |
| h | 25 | 80 | 22 | 50 | 25 | 20 | 30 | 10 |
| i | 28 | 50 | 28 | 50 |  |  |  |  |
| j | 31 | 20 | 30 | 10 | 34 | 10 |  |  |
| k | 32 | 15 | 35 | 15 |  |  |  |  |

**Table 5.5** Due date, quantity and delivery dates of several orders; dd: due date (required delivery date), qty: quantity, del1,del2,del3: actual moment of 1st delivery ('del1'), 2nd delivery ('del2') or 3rd delivery ('del3'), qty1,qty2,qty3: quantities delivered in delivery part 1, delivery part 2 and delivery part 3. Note that order a has not completely delivered yet.

As can be seen, some of the customer orders are not delivered in one delivery but require two or even three deliveries.

a Determine the overall delivery performance in these 40 days if the performance indicator chosen is the fraction of customer orders that have been delivered completely on time.

b Determine the overall performance in these 40 days if the performance indicator chosen is the fraction of the number of products that have been delivered on time.

c Determine the delivery performance in the first 10 days (1-10) if the performance indicator chosen is the fraction of customer orders that have been delivered completely on time in that time frame. Repeat this calculation for the time frames 11-20, 21-30 and 31-40.

d Determine the delivery performance in the first 10 days (1-10) if the performance indicator chosen is the fraction of the number of products that have been delivered on time in that time frame. Repeat this calculation for the time frames 11-20, 21-30 and 31-40.

*Forecasting:*

**Exercise 5.3.2**

Consider the observations from maintenance jobs from the past as given in Table 5.6.

|  |  |
| --- | --- |
| *Day* | *Nr. Spare Part X* |
| 5 | 30 |
| 7 | 35 |
| 13 | 40 |
| 25 | 49 |
| 33 | 59 |
| 36 | 69 |

**Table 5.6** The days that maintenance took place and the number of spare parts X that have been used.

There seems to be a relation between the time and the number of items X that have been used in the job. Create a linear regression model for this relation that optimizes the MSE.

**Exercise 5.3.3**

Consider the list of data concerning the amount of part "X1203c1" used each month, given in Table 5.7.

a Make a forecast for the number of parts to be used starting at month t-8 until and including next month (month t) using a regular moving average forecasting model with N=2.

b Repeat question a, now for N=4 (start at month t-6).

c Repeat question b, now using a weighted moving average model with the following relations between the weights:

wt-i-1:wt-i-2:wt-i-3:wt-i-4 = 1:3:6:10

d If you would repeat question c, now with: wt-i-1:wt-i-2:wt-i-3:wt-i-4 = 10:6:3:1, would the forecast improve or get worse? Explain.

|  |  |
| --- | --- |
| Month | Amount used |
| t | pieces |
| t-1 | 23 |
| t-2 | 22 |
| t-3 | 19 |
| t-4 | 18 |
| t-5 | 20 |
| t-6 | 16 |
| t-7 | 19 |
| t-8 | 18 |
| t-9 | 16 |
| t-10 | 14 |

**Table 5.7** The number of pieces of part X1203c1 used in the last 10 months.

e Make a forecast for the amount of spare parts to be used starting at month t-8 until and including next month (month t) using an exponential smoothing model with α=0.1. You may assume F(t-9)=D(t-9).

f Repeat question e, now with α=0.9.

g Calculate the MSE for the model of question e and also for the model of question f. Explain the difference.

h Repeat question g, now using the MAD.

**Exercise 5.3.4**

Consider the demand data from the past as given in Table 5.8.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Demand | 34 | 35 | 32 | 34 | 36 | 30 | 34 | 38 | 42 | 40 | 43 | 42 | 44 | 46 | 47 | 47 | 48 | 45 | 49 | 50 |

**Table 5.8** The demand for the last 20 months.

a Determine the forecast that would have been calculated in the periods 15 till 20 when using the moving average with N=2.

b Repeat the previous question, now with N=6.

c Which one performs best, moving average with N=2 or with N=6? Explain your answer.

d If you would use a forecasting model based on exponential smoothing, would you prefer a small alpha or a large alpha? Explain.

e Assume we're at the beginning of period 10. Make a forecast for the demand in this period based on a linear regression model of the demand using the data from periods 1 to 9.

f If you would repeat the forecasting method used in the previous question for periods 11 to 20, would the MSE of this forecasting method be higher, lower, or equal to the MSE in case we used (single) exponential smoothing?

g If you may assume that Fb(17)=0.75 and Fa(17)=47.25 then determine the forecast for the demand in periods 18, 19, and 20 using double exponential smoothing with alpha = 0.20 and beta = 0.25.

**Exercise 5.3.5**

Table 5.9 gives the demand data for the last 8 periods.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Period* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| Demand | 2 | 1 | 4 | 6 | 5 | 8 | 7 | 12 |

**Table 5.9** The demand for the last 8 periods.

a Determine the standard deviation of the demand during these 8 periods.

b What would have been the forecast for period 7 and period 8 if the forecast had been based on using a weighted moving average with wt-i-1:wt-i-2:wt-i-3:wt-i-4 = 5:3:1:1?

c What would have been the forecast for period 7 and period 8 if the forecast had been based on exponential smoothing with alpha = 0.20 and the forecast for period 6 would have been 5?

d What would be the forecast for period 9 if a model was used based on linear regression? (*So: first determine the model, then use that model to create a forecast*).

e Which of these three forecasting models would you prefer? Explain.

**Exercise 5.3.6**

Table 5.10 shows demand data for a product for periods 4 to 10.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *Period* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
| Demand | 9 | 9 | 7 | 6 | 4 | 5 | 3 |

**Table 5.10** The demand for a product for the periods 4 to 10.

a What would be the forecast for the demand in the next period (period 11) if a model was used based on linear regression? (*So: first determine the model, then use that model to create a forecast*).

b Starting at the end of period 8, another forecasting model is considered for the situation shown in the table above, based on double exponential smoothing. As a starting point for such a model, the starting values for Fa(8) and Fb(8) should be chosen. Which of the options given in Table 5.11 would be the best considering the quality of future forecasts? Explain your answer.

(*Note: you don't have to calculate the new forecast*).

|  |  |  |
| --- | --- | --- |
|  | Fa(8) | Fb(8) |
| option 1 | 4 | 1 |
| option 2 | 6 | -1 |
| option 3 | 1 | 4 |
| option 4 | -1 | 6 |

**Table 5.11** Different options for the starting values of the forecasting model.

c Again, consider the situation shown in the table above. Assume now that a forecasting model would be used based on a weighted moving average and N=4. Two options for the distribution of the weights may be considered:

I: wt-1 : wt-2 : wt-3 : wt-4 = 5:4:3:2

II: wt-1 : wt-2 : wt-3 : wt-4 = 2:3:4:5

Which option would you prefer?

And what would the forecast be for the demand in the next period if your option would be used (period 11)?

*Order Sizes:*

**Exercise 5.3.7**

The company CUP sells cups, mugs, cups with saucers, etc. They purchase from various manufacturers and mainly supply to the retailer Blocker. The absolute best seller at Blocker is Cuppacof, the perfect coffee cup, which has been selling well for years. The cost price of the Cuppacof is €1.25, and the selling price to Blocker is €1.50. Besides the cost price, the supplier of the Cuppacof calculates €100 for each time CUP orders a new batch. Blocker's average demand for the Cuppacof is 50000 pieces per quarter. For its internal calculations of holding costs CUP uses a surcharge percentage of 18% of the cost per item per year.

a Given these data, how many times a year will CUP order from their supplier to minimize the total cost for the Cuppacof?

b At a certain point in time, CUP decides to take a closer look at just how accurate that surcharge percentage of 18% is. Then it turns out that it should be 23.12%. Would that influence the number of times the product is ordered a year? If yes, explain whether that number would increase or decrease. If not, explain why not.

The supplier realizes that CUP is, indeed, a major customer and proposes a discount scheme:

* From 15000 per order: €1.22 per piece
* From 30000 per order: €1.20 per piece

c To minimize the total costs per year, how many will CUP order from the supplier per order? You may assume the surcharge percentage of 23.12% of the cost per item per year for holding costs.

**Exercise 5.3.8**

In the cafeteria of University AS, students are complaining about the excessively high price (€2.50) of the Sausage Sandwich. The result of this high price is that 30% of the customers are no longer buying. The head purchaser of the cafeteria, Peter, is taking a look at his order volume for the Sausage Sandwich. Peter feels that the price could be reduced.

The academic year consists of four periods of ten weeks each. Each week consists of 5 working days (school days). The cafeteria is open for 6 hours every workday. Between 12.00 o’clock and 14.00 o’clock, the cafeteria sells on average 20 Sausage sandwiches. During the other opening hours, the cafeteria sells on average 4 Sausage sandwiches per hour.

Peter buys the Sausage Sandwiches from a wholesaler who specializes in food products. This supplier sells large volumes of Sausage products. There are 18 Sausage Sandwiches in one box. At this time, Peter buys 20 boxes of Sausage sandwiches per order. The supplier hereby applies the quantum discount (shown in Table 5.12).

|  |  |  |
| --- | --- | --- |
| Minimum no. boxes | Maximum no. boxes | Price/box |
| 0 | 59 | €15.00 |
| 60 | 99 | €14.95 |
| 100 | 150\* | €14.90 |

**Table 5.12** Quantum discount for the cafeteria(\* You may order a maximum of 150 boxes per order from this wholesaler since the supplier of this company cannot process all its customer orders currently coming in).

Administration costs per order amount to €5.00. Transport costs for delivery of one order come to €15.00. Annual inventory holding costs of one box (18 Sausage Sandwiches) at this moment are €5.20.

a What is the average demand per school year?

b Calculate the cost-optimal order quantity for Peter.

c How much can Peter save on costs if he orders the cost-optimal quantity determined at c. instead of his present order quantity?

d If the profit margin remains unchanged, what will a Sausage Sandwich cost in the new situation?

e What would be the new order frequency?

**Exercise 5.3.9**

A regional warehouse in audio equipment delivers among other things turntables to a group of associated retailers. The demand for a certain type of turntable for the next 12 periods is forecasted according to Table 5.13.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| demand | 70 | 50 | 20 | 90 | 60 | 100 | 40 | 50 | 120 | 30 | 60 | 90 |

**Table 5.13** Demand for the next 12 periods.

Inventory holding costs per turntable per period are about € 1. The fixed order costs for the warehouse are €300,= per order.

a Suppose the planner of the warehouse uses the Part-Period-Balancing method for making decisions about her orders. In which periods will she order and what will be the total costs?

b To which solution would the Wagner-Whitin method lead?

c Which solution would the planner obtain if she used the Silver-Meal approach to solve this rolling horizon problem?

**Answers**

**Theory**

**Question 5.1.1**

a Order release and ordering for supply

b p.50 (make-to-stock vs. make-to-order)

c Demand, lead time of supply process, order batch size

d p.51

e ROP, ESC, MRP, LRP

**Question 5.1.2**

a Demand includes lost sales (or: actual sales is demand that can be met)

b p.54/55

c Not related to the fulfillment of actual customer orders

d OTIF: on time in full (p.55); CLIP: conformed line item performance (p.56)

e A high ITR frees cash that a company can use (e.g. to pay suppliers or investments)

f Because of the number of variables involved, plus the assumptions that need to be made if all performance indicators would be translated into money value (€)

**Question 5.1.3**

a Bread, soap

b Ice cream, swimming suits

c The newest model smartphone (and the oldest model smartphone)

d Causal: shows a relation between explaining variable and demand (like temperature and demand for ice cream); time series: past demand explains the expected new demand

e If all weights are chosen equal, then the weighted moving average model turns into a normal moving average model

f If the weights are chosen as α∙(1-α)n-1 with n: number of periods in the past

g ME, MSE, and MAD

h Exp. smoothing is used twice, namely both for the base and for the step in the trend

**Question 5.1.4**

a Holding costs and ordering costs

b p.72

c p.72

d Total cost curve is flat around the cost-optimal Q

e POQ = EOQ / D (with D: average demand per period)

f Known varying demand

g At least interest costs are related to the purchasing price

h The EOQ calculated might not be a valid value in the area where the price used is valid, plus the difference in purchasing costs per period should be considered as well (not taken into account in the EOQ)

i Otherwise there will always be 'useless' remaining stock

j For reasons of storage or transportation

**Answers**

**Basic Exercises**

**Exercise 5.2.1**

1. Nr.orders: 23; P1 = 0.8696; P2 = 0.9826

**Exercise 5.2.2**

2. P1 = 70.70; P2 = 0.90

**Exercise 5.2.3**

a P1 = 0.6667

b P2 = 0.9486

c 4

**Exercise 5.2.4**

ITR = 8.33

**Exercise 5.2.5**

a The weight wt for the demand in a period t.

b High value: demand in that period has a high impact on the forecast;

Low value: demand in that period has only a low impact on the forecast.

c "Normal": all periods get an equal weight (so if n periods from demand in the past are used, the weight for each period would be 1/n); "weighted": periods get different weights (e.g.: recent periods get a higher weight than periods further in the past).

d When all weights are chosen 1/n.

e For instance when recent demand tends to give a better forecast for the expected demand than demand further in the past.

f If demand shows a trend, the moving average will lag while linear regression does not; the disadvantage would be that for linear regression usually more data from the past need to be used (and the forecasting model is more complex).

g Double exponential smoothing uses far less data (and puts less emphasis on data from far back in the past), but the forecasting model is more difficult to understand.

h Because if the parameters are chosen correctly in a forecasting model, the systematic error (=average) should be 0 because the positive errors should (on average) be equal to the negative errors.

**Exercise 5.2.6**

a ME = 1.2625

b MAD = 1.4375

c MSE = 2.95375

**Exercise 5.2.7**

a Chold(yr) = €30

b Chold(month) = €2.50

**Exercise 5.2.8**

EOQ = 125

**Exercise 5.2.9**

Average nr.orders = 5.33

**Exercise 5.2.10**

25

**Exercise 5.2.11**

a D(yr) = 3000

b EOQ = 100

c Order freq. = 30

d Order costs/year = €1500

e Holding costs/year = €1500

**Exercise 5.2.12**

a EOQ) = 1935 (rounded)

b See Table 5.14

|  |  |  |  |
| --- | --- | --- | --- |
| Q | 1000 | 1935 |  |
| ord | 2340 | 1209 |  |
| hold | 625 | 1209 | saving: |
| total | 2965 | 2418 | 547 |

**Table 5.14** The different costs for two order sizes.

**Exercise 5.2.13**

a EOQ = 851

b nr.orders/yr = 49.35

c purchasing: €60 900 0

ordering: €1233.84

holding: €1233.95

total: €611 467.80

**Exercise 5.2.14**

a*cu* =2

co =1

Q\*= 15

b*E*[number of stockouts]=0.75

c *E*[profit] =15

d Q\*:0.667

k = 0.43

14

**Answers**

**Complex Exercises**

**Exercise 5.3.1**

a P1 = 0.3636

b P2 = 0.6356

c 1-10: P1 = 0/2 = 0; 11-20: P1 = 0.75; 21-30; P1 = 0.33; 31-40: P1 = 0/2 = 0

d 1-10: P2=0.42; 11-20: P2=0.66; 21-30; P2=0.91;

31-40: P2=0.29

**Exercise 5.3.2**

Line: y=a+bx (with x: job hours; and y: nr. spare parts);

Formulas to be used:

Step-by-step calculation: see Table 5.14.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| xi | yi |  |  | xi- | yi- | (xi-)\*( yi- ) |
| 5 | 30 | 19.83333 | 47 | -14.8333 | -17 | 252.1667 |
| 7 | 35 |  |  | -12.8333 | -12 | 154 |
| 13 | 40 | sx | sy | -6.83333 | -7 | 47.83333 |
| 25 | 49 | 13.36288 | 14.92649 | 5.166667 | 2 | 10.33333 |
| 33 | 59 |  |  | 13.16667 | 12 | 158 |
| 36 | 69 |  |  | 16.16667 | 22 | 355.6667 |
|  |  |  |  |  | Total: | 978 |

**Table 5.14** Step-by-step calculation.

So r = 0.980643

Then b = 1.095 389

and a = 25.27

**Exercise 5.3.3**

a See Table 5.15.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-8 | t-7 | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | t |
| F(t) | 15.0 | 17.0 | 18.5 | 17.5 | 18.0 | 19.0 | 18.5 | 20.5 | 22.5 |

**Table 5.15** Forecast of the parts used based on the Moving Average with N=2.

b See Table 5.16.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | t |
| F(t) | 16.75 | 17.25 | 18.25 | 18.25 | 18.25 | 19.75 | 20.50 |

**Table 5.16** Forecast of the parts used based on the Moving Average with N=4.

c See Table 5.17.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | t |
| F(t) | 15.45 | 17.05 | 18.10 | 18.20 | 17.65 | 19.35 | 19.15 |

**Table 5.17** Forecast of the parts used based on the weighted Moving Average (1:3:6:10).

d. It would (and does) improve, cause there seems to be a growing trend in demand, in the forecast more weight is given to the most recent demand; see also Table 5.18.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | t | average |
| F(t) 5.3.3d. | 18.00 | 17.20 | 18.55 | 18.35 | 18.70 | 20.40 | 21.85 | 19.00 |
| E(t) 5.3.3d. | 2.00 | -2.80 | 0.55 | -0.65 | -3.30 | -2.60 |  | -1.13 |
| E(t) 5.3.3c. | -0.55 | -2.95 | 0.10 | -0.80 | -4.35 | -3.65 |  | -2.03 |

**Table 5.10 C**omparison of the forecast errors for the two different weight ratios.

e See Table 5.18.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-8 | t-7 | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | t |
| F(t) | 16.00 | 17.80 | 18.88 | 16.29 | 19.63 | 18.16 | 18.92 | 21.69 | 22.87 |

**Table 5.18** Forecast of the parts used based on Exponential Smoothing with α = 0.1.

f See Table 5.19.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-8 | t-7 | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | t |
| F(t) | 16.00 | 16.20 | 16.48 | 16.43 | 16.79 | 16.91 | 17.12 | 17.61 | 18.15 |

**Table 5.19** Forecast of the parts used based on Exponential Smoothing with α = 0.9.

g See Table 5.20.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-8 | t-7 | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | average |
| E2(t) 3e | 4.00 | 1.44 | 8.29 | 13.78 | 2.65 | 0.70 | 9.51 | 1.71 | 5.26 |
| E2(t) 3f | 4.00 | 7.84 | 0.23 | 12.73 | 1.47 | 4.37 | 23.82 | 29.08 | 10.44 |

**Table 5.20** The Mean Squared Errors for the forecasts based on Exponential Smoothing.

Lower alpha follows the trend more quickly.

h See Table 5.21.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | t-8 | t-7 | t-6 | t-5 | t-4 | t-3 | t-2 | t-1 | average |
| |E(t)| 3e | 2.00 | 1.20 | 2.88 | 3.71 | 1.63 | 0.84 | 3.08 | 1.31 | 2.08 |
| |E(t)| 3f | 2.00 | 2.80 | 0.48 | 3.57 | 1.21 | 2.09 | 4.88 | 5.39 | 2.80 |

**Table 5.21** The Mean Absolute Deviations for the forecasts based on Exponential Smoothing.

**Exercise 5.3.4**

a See Table 5.22.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Period | 15 | 16 | 17 | 18 | 19 | 20 |
| F(t) | 45 | 46.5 | 47 | 47.5 | 46.5 | 47 |

**Table 5.22** Forecasts using the Moving Average with N=2.

b See Table 5.23.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Period | 15 | 16 | 17 | 18 | 19 | 20 |
| F(t) | 42.83 | 43.67 | 44.83 | 45.67 | 46.17 | 47.00 |

**Table 5.23** Forecasts using the Moving Average with N=6.

c N=2(cause follows trend quicker); see also average error

d. Small alpha (trend!)

e F(t) = 31.58 + (0.68 x t)

f Lower, since the method attempts to create a good fit while single exp. smoothing always will lag.

g Fa(18) 48

Fb(18) = 0.75

F(18) = 48.75

Fa(19) = 48.375

Fb(19) = 0.675

F(19) = 49.05

Fa(20) = 49.045

Fb(20) = 0.674

F(20) = 49.72

**Exercise 5.3.5**

a Std.dev. = 3.50 (assuming 'sample')

b F(7)=5.1 and F(8)=6.0

c F(7)=7.40 and F(8)=7.08

d a=-0.32143; b=1.321429; F(9) = 11.57

e Linear regression causes no lag

**Exercise 5.3.6**

a F(11)=2.0 (a=13.39286; b=-1.03571)

b Option 2: negative "step" of -1 (see calculated b on 6a), starting at level 6

c Option I: more weight on most recent demand due to trend

F(11)= 4.21

**Exercise 5.3.7**

a Qopt=13333; nr.orders/yr = 15

b Qopt goes down, so nr.ord/yr goes up

c Qopt=30000

**Exercise 5.3.8**

a D = 7 200 SSW

b Qopt = 60 boxes

c €182.67

d Margin=€1.60; new price: €2.47

e 6.67 times/year

**Exercise 5.3.9**

a Period 1 (Q=230), period 5 (Q=250) and period 9 (Q=300); total costs: 2010

b Period 1 (Q=140), 4 (Q=150), 6 (Q=190) and 9 (Q=300); total costs €1910

c Period 1 (Q=140), 4 (Q=150), 6 (Q=190), 9 (Q=210), and 10 (Q=90); total costs €1940

**6 Reorder Point Control**

**Errata book (first edition)**

- p93, intro, 4th sentence: If demand *during lead time* is deterministic, keeping stock ...

- p93, 6.1, 1st sentence: “…., and demand at a decoupling point is *considered to be* independent “

- fig.6.15 and 6.16 have been swapped

- p109: Camps' formula (*also known as the Economic Order Quantity (EOQ) formula*; see 5.30)

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

*- On-stock situation*

*- On-order situation*

- *Lead time*

*- Technical stock*

*- Available stock*

*- Inventory position*

*- Backordering*

*- Lost sales*

*- Re-Order Point (ROP) System*

*- Reorder level or reorder point*

*- Review period*

*- (s, Q) system*

*- (s, S) system*

*- (R, s, Q) system*

*- (R, s, S) system*

*- (Re-)order cycle*

*- Multi-bin system*

*- Inventory (holding) costs*

*- Setup costs/ordering costs*

*- Stock-out costs/shortage costs*

*- Economical Order Quantity (EOQ)*

*- Safety stock*

*- P1, P2 and P3 service level*

*- Undershoot*

**Theory**

**Question 6.1.1**

What are the four basic methods for ROP? Describe the differences.

**Question 6.1.2**

Technical stock can never get negative, but the available stock could. Explain.

**Question 6.1.3**

Explain why the inventory position never will be lower than the available stock.

**Question 6.1.4**

A Lost Sales situation is different and often worse than a Backordering situation. Explain.

**Question 6.1.5**

What is the reason that the re-order level used in an ROP system with continuous review always is based on the demand during lead time?

**Question 6.1.6**

Both in the case of an ROP system with a review period and in case of lumpy demand, undershoot may occur. Explain.

**Question 6.1.7**

Give two examples of costs belonging to:

- inventory costs;

- ordering costs.

**Question 6.1.8**

What is the difference between the P1-service level and the P2-service level?

**Question 6.1.9**

Assuming a demand distribution that is symmetrical (like a Normal distribution), what would be the P1 service level if the re-order level in a (s, Q)-system is based on the average demand during the lead time?

**Question 6.1.10**

Would the P1 service level in an (R, s, Q)-system be the same as in an (s, Q) system if in both systems the same re-order level would be used? Explain.

**Question 6.1.11**

Why would it make no sense to keep stock "just in case" in a situation where demand during lead time is deterministic?

**Question 6.1.12**

Explain what is meant by a s=S system.

**Question 6.1.13**

Explain why a multi-bin system can be regarded as a (s, Q)-system.

**Basic Exercises**

**Exercise 6.2.1**

If demand for a particular item is on average 10 per week and a safety stock is used of 5, while the lead time is 2 weeks, what would be the re-order level for that item?

**Exercise 6.2.2**

If demand for an item is normally distributed with a standard deviation of 3 per day, while the lead time is 5 days, what would be the standard deviation of the demand during the lead time?

**Exercise 6.2.3**

If the standard deviation of demand during lead time is 6.90, what safety stock would be required if the required probability of not stocking out during a re-order cycle is 90% and the demand is normally distributed?

**Exercise 6.2.4**

Consider the distribution of demand during the lead time of supply given in Table 6.1.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| demand | 5 | 6 | 7 | 8 | 9 |
| probability | 10% | 30% | 40% | 15% | 5% |

**Table 6.1** The distribution of demand during the lead time of supply.

a Determine the average demand during lead time.

b What would be the P1-service level if an (s, Q)-system is used for re-ordering with R=7?

c What would be the P2-service level if an (s, Q)-system is used for re-ordering with R=7 and Q=30?

**Exercise 6.2.5**

A company delivers vacuum cleaners from a central stock point somewhere in the country. The average demand is 60 vacuum cleaners per week (there are 50 weeks in 1 year). The cost per order at the supplier is € 50.- and the delivery time is 2 weeks. The standard deviation of the demand during the lead time is 10 vacuum cleaners; demand is normally distributed. The interest rate for holding stock is 25%. The purchase price of a vacuum cleaner is € 120.-. The service level that this company wants to offer is 92%.

a How much is the yearly demand (D)?

b What is the safety stock level?

c What is the reorder point if a (s, Q)-system is used?

d What is the cost-optimal order quantity (EOQ)?

e What is the order frequency per year?

f What is the ordering cost per year?

g What are the inventory holding costs per year?

**Exercise 6.2.6**

a Assume that the demand for a part in a week resembles a random draw from a Normal distribution with an average of 100 and a standard deviation of 10. The lead time for this part is 3 weeks. What should be the re-order level in a (s, Q)-system for this situation if a service level of 95% should be achieved during a re-order cycle?

b Assume that the demand during lead time resembles a random draw from a Normal distribution with an average of 300 and a standard deviation of 20. The lead time for this part is 3 weeks. What should be the re-order level in a (s, Q)-system for this situation if a service level of 90% should be achieved during a re-order cycle?

**Exercise 6.2.7**

Consider the distribution of demand during the lead time of supply given in Table 6.2.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| demand | 5 | 6 | 7 | 8 | 9 |
| probability | 15% | 25% | 35% | 20% | 5% |

**Table 6.2** The distribution of demand during the lead time of supply.

For reordering a (s, S)-system is used with S=15.

a What needs to be chosen if the P1-service level needed would be 90%?

b Using the result from question a, how much needs to be ordered if, at a certain moment in time, the available stock is 6?

c Using the result from question a, how much needs to be ordered if, at a certain moment in time, the available stock is 11?

**Complex Exercises**

**Exercise 6.3.1**

An international trader in electronic planners has a yearly turnover of about 50 000 pieces. The purchasing costs are € 20,-- a piece; the sales price is € 30,--.

A year consists of 50 weeks.

The cost of keeping one unit in stock for a year is 20% of the purchasing price; the ordering costs are €60.-- per order.

The number of stockouts he accepts in a year is 1 (on average), using a cost-optimal order size.

Demand is more or less Normal distributed with a standard deviation of 100 per 2 weeks. The supplier has a delivery time of 2 weeks.

The trader uses a (s, Q)-system.

a Calculate the cost-optimal order size

b Calculate the re-order level

c Calculate the total affected costs per year (= total inventory costs plus total ordering costs)

d If at a certain moment the stock level is 2500 and then a large customer order is received of 200 pieces, how many electronic planners would then be re-ordered by the trader?

**Exercise 6.3.2**

Given:

- Ordering cost: €80,=

- Inventory holding cost: 15% a year based on purchasing cost

- Purchasing cost: €20,= a piece

- Average demand: 300 a day

- 200 days/year

- Lead time: 3 days

- Re-order level: 1000 pieces

- Probability distribution of demand during 3 days (= demand during lead time) as in Table 6.3.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| demand | 500 | 600 | 700 | 800 | 1000 | 1100 | 1200 | 1300 |
| probability | 5% | 10% | 15% | 20% | 20% | 15% | 10% | 5% |

**Table 6.3** Probability of demand.

a Determine the P1-service level and calculate the safety stock.

b Determine the expected number of re-order cycles with delivery problems within a year if a cost-optimal order size is used.

c Determine the P2-service level if a cost-optimal order size is used.

**Exercise 6.3.3**

For a product in a warehouse, the demand per day is on average 10 with a standard deviation of 5 (the distribution resembles a normal distribution). The lead time of supply for this product is 11 days. Every 5 days the stock level is checked against the re-order level for this product. The service level required is 90%, where service level is defined as the probability that the available stock will be sufficient to fulfill all demand during a re-order cycle. An (R, s, S)-system is used with s=S.

a If at the moment of reviewing the available stock is 120, how much should be re-ordered, assuming that the parameters used are chosen such that the service level will be reached?

b if the company would have used an (s, S)-system instead of an (R, s, S)-system (also with s=S), how much should be re-ordered in that situation if the available stock is 120 (same service level)?

**Exercise 6.3.4**

Consider the review periods with demand and deliveries as given in Table 6.4.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Review | 1 | 2 | 3 | 4 | 5 | 6 |
| Demanded | 50 | 60 | 55 | 46 | 48 | 52 |
| Delivered | 50 | 50 | 55 | 40 | 48 | 52 |

**Table 6.4** Demands and deliveries for 6 review periods.

a What would be the P1-service level for these 6 review periods?

b What would be the P2-service level for these 6 review periods?

c If a year would consist of 12 review periods, what would be the expected number of times a delivery problem might occur assuming the calculated service levels?

**Exercise 6.3.5**

A company producing fireplaces for private houses purchases the windows for these fireplaces from an external supplier. One particular type of window is the window RX47-5. The demand for his window follows a normal distribution with an average of 66 per working week (there are 50 working weeks in a year); the standard deviation of the demand during the delivery time is 25. The cost-optimal order size is 200. The company uses a (s, Q)-system with a re-order level sufficient for achieving a service level of 94.5% of the re-order cycles.

a How many re-order cycles would there be in a year (on average)?

b What is the safety stock the company is using for this window?

c How many times on average during a year will the company have issues with the delivery of this window because of running out of stock?

**6.3.6** (pretty difficult)

The demand for an item in a single week changes according to the discrete probability distribution given in Table 6.5.

|  |  |  |  |
| --- | --- | --- | --- |
| D=x | 0 | 1 | 2 |
| P(D=x) | 1/2 | 1/4 | 1/4 |

**Table 6.5** The discrete probability distribution for the demand of exercise 6.3.6.

Inventory is replenished according to a periodic review (R,s,nQ) policy with a 2-week review period, a 1-week replenishment lead time, a case pack size Q = 2, and reorder level s = 2.

a Calculate the mean and the variance of the single-week demand. Calculate the four missing values in Tables 6.6 and 6.7 for the demand distribution for 2 and 3 weeks using the convolution of independent random variables.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| D2=x | 0 | 1 | 2 | 3 | 4 |
| P(D2=x) | 4/16 | 4/16 |  |  | 1/16 |

**Table 6.6** The demand distribution for 2 weeks.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| D3=x | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
| P(D3=x) | 8/64 |  | 18/64 |  | 9/64 | 3/64 | 1/64 |

**Table 6.7** The demand distribution for 3 weeks.

b Determine the expected number of order lines and the expected order size.

c Determine the fill rate.

**Answers**

**Theory**

**Question 6.1.1**

See Fig. 6.4, p.96.

**Question 6.1.2**

Technical is physical; when available stock is negative there are backorders.

**Question 6.1.3**

Inventory position = available stock + pipeline stock.

**Question 6.1.4**

Lost sales means when demand cannot be fulfilled it will be lost (the customer goes somewhere else), while with back ordering the customer will wait till the product can be supplied again.

**Question 6.1.5**

That level should be enough to cover the demand till the next supply.

**Question 6.1.6**

Undershoot is the difference between the reorder level en stock level at the moment of reordering; that amount is higher than zero when demand is lumpy (see fig.6.15) or when the moment of checking is not done continuously (see fig.6.16).

**Question 6.1.7**

Inventory costs: holding costs as described on p72.

Ordering costs: described on p72.

**Question 6.1.8**

See p54.

**Question 6.1.9**

50%.

**Question 6.1.10**

No, it would be lower: in an (R, s, Q)-system, s should be based on demand during (lead time + review time), while in a (s, Q)-system s is based on demand only during lead time.

**Question 6.1.11**

Supply can always be done "on order" without having to make any inventory costs (note: this does not mean that keeping stock might not be a good idea when looking at the costs).

**Question 6.1.12**

ROP system with a re-order level equal to the amount maximum in stock (so as soon as one or more items are demanded, a re-supply is ordered).

**Question 6.1.13**

Q=content one bin; s = (nr.bins-1)xQ.

**Answers**

**Basic Exercises**

**Exercise 6.2.1**

s = 25.

**Exercise 6.2.2**

σ(D(L)) = 6.71 (so: 7).

**Exercise 6.2.3**

z(90%) ≈ 1.28; ss = 8.83 (so: 9).

**Exercise 6.2.4**

a 6.75.

b 80%.

c E(BO) = 0.25; P2 = 99.17%.

**Exercise 6.2.5**

a 3000.

b z(92%) ≈ 1.40; ss = 14.

c s = 134.

d Qopt = 100.

e 30.

f €1500.

g €1500.

**Exercise 6.2.6**

a s = 329.

b s = 326.

**Exercise 6.2.7**

a s=8.

b 9.

c 0.

**Answers**

**Complex Exercises**

**Exercise 6.3.1**

a Qopt = 1225.

b s = 2197.

c total: € 5688,=.

d 0.

**Exercise 6.3.2**

a 70%.

b 10.

c P2 = 97.2%.

**Exercise 6.3.3**a 66

b 12

**Exercise 6.3.4**

a 0.67 (4 out of 6 ok).

b 0.9486.

c 4x/yr (using P1).

**Exercise 6.3.5**

a 16.5.

b 40 (=1.60x25).

c 0.9075 issues/yr.

**Exercise 6.3.6**

a Table 6.6: 5/16 and 2/16

Table 6.7: 12/64 and 13/64

The two moments for the single period are and variance

b

c

**7 MRP Control Systems**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *BOM*

*- Parent*

*- Child*

*- Low-Level Code (LLC)*

*- Dependent demand*

*- Independent demand*

- *MRP I*

*- MRP II*

*- MRP II framework*

*- RCCP*

*- MPS*

*- Aggregate Production Plan*

*- Shop Floor Control*

- *Gross requirement*

*- Scheduled receipts*

*- Net requirement*

- *Planned inventory*

*- Planned receipt*

*- Planned release*

*- Netting*

*- Time off-setting*

*- Rescheduling assumption*

*- Safety stock*

*- (Planned) lead time*

*- Safety stock*

*- Exception message*

*- On-hand inventory*

*- Lot-sizing*

*- Order multiple*

*- Minimum order quantity (MOQ)*

*- Lot-for-Lot (L4L)*

*- (Time) bucket*

*- DRP*

*- Bill of Distribution*

*- Tiers*

**Theory**

**Question 7.1.1**

What is the difference in planning and control methods between a situation with dependent demand and a situation with independent demand? Give for each of these two situations an example of a materials planning and control method.

**Question 7.1.2**

What information is required to be able to make an MRP-I calculation?

**Question 7.1.3**

Which of the following statements on MRP-I is/are true?

I The scheduled inventory can never get negative.

II The planned inventory can never get negative.

**Question 7.1.4**

Give two examples showing that MRP-I cannot deal with uncertainty.

**Question 7.1.5**

Explain the following statement: In MRP-I safety stock is considered to be “dead stock”.

**Question 7.1.6**

What are the additional planning modules to MRP-I that are known to be the elements of MRP-II? What is the logic behind each of these extra planning modules?

**Question 7.1.7**

The MRP-I calculations require a certain accuracy of data. Indicate what the consequences

might be when we use MRP-I calculations in each of the following situations:

- Real inventory is higher than the inventory according to the administration.

- Real inventory is lower than the inventory according to the administration

- Actual lead time is longer than the lead time used in MRP.

- Actual lead time is shorter than the lead time used in MRP.

- BOM’s are not up-to-date.

**Question 7.1.8**

The purpose of the MPS can be described best as:

a A plan from which Sales can derive sales forecasts.

b A production plan in which Sales specifies what needs to be produced.

c A production plan that specifies how much needs to be produced of what

product and when.

d A mechanism for the evaluation of production results.

**Question 7.1.9**

Which statement(s) is (are) true?

a In a make-to-order situation the MPS mainly depends on forecasts.

b In a make-to-stock situation the MPS mainly depends on forecasts.

c A RCCP is based on all MPS items, but not on all capacities.

d A RCCP is based on all capacities, but not on all MPS-items.

**Question 7.1.10**

The MPS-planning horizon should cover at least the maximum lead time of the MRP-BOM. Explain this statement by explaining first what is meant by the maximum lead time of the MRP-BOM, and then why the horizon indeed should cover that maximum lead time.

**Question 7.1.11**

Explain why in the case of an MRP system the BOM has a crucial role in the logic used, while in an ROP system, the BOM hardly is used at all.

**Question 7.1.12**

What is the purpose of the Low-Level Code and how is that determined?

**Basic Exercises**

**Exercise 7.2.1**

Determine the net requirement for an item in period *t* if:

- the gross requirement for that item in *t* is 150;

- stock on hand at the end of *t-1* is 40;

- at the start of *t* an order of 30 is scheduled to be received (also known as "on order").

**Exercise 7.2.2**

Complete Table 7.1 if the lead time for the item considered is 2 periods.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *period* | *t* | *t+1* | *t+2* | *t+3* | *t+4* | *t+5* | *t+6* |
| planned receipt | 0 | 0 | 15 | 0 | 12 | 20 | 0 |
| planned release |  |  |  |  |  |  |  |

**Table 7.1** Table to be completed.

**Exercise 7.2.3**

Determine the net requirement for an item in period *t* if:

- the gross requirement for that item in *t* is 250;

- physical stock at the end of *t-1* is 120;

- the required safety stock is 30;

- during *t* no order is scheduled to be received.

**Exercise 7.2.4**

Determine the planned receipt for an item in period *t* if:

- the gross requirement for that item in *t* is 80;

- stock on hand at the end of *t-1* is 20;

- at the beginning of *t* an order of 40 is scheduled to be received (also known as "on order");

- a lot size of 8 (or multiple) is used.

**Exercise 7.2.5**

Consider the BOM in Figure 7.1.

|  |
| --- |
| A screenshot of a computer  Description automatically generated |

**Figure 7.1** The BOM for the product in exercise 7.2.5.

If a production order for 50 pieces of A is supposed to be released at time *t*, how many parts B and how many parts C would be needed to be available at that moment?

**Exercise 7.2.6**

Determine the low-level codes for the items A, B, C, and D in the BOM shown in Figure 7.2.

|  |
| --- |
| A screenshot of a computer  Description automatically generated |

**Figure 7.2** The BOM for the product in exercise 7.2.6.

**Exercise 7.2.7**

Consider the BOM shown in Figure 7.3.

|  |
| --- |
| A computer screen shot of a diagram  Description automatically generated |

**Figure 7.3** The BOM for the product in exercise 7.2.7.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Item:* | Chair | *LLC:* | 0 | *L:* | 1 |  |  |  |  |
| *Stock:* | 100 | *SS:* | 50 | *Q:* | n x 100 |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| *period* | *now* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| *GrossReq* |  | 50 | 130 | 90 | 250 | 300 | 130 | 110 | 100 |
| *SchedRec* |  | 100 |  |  |  |  |  |  |  |
| *SchedInv* |  |  |  |  |  |  |  |  |  |
| *NetReq* |  |  |  |  |  |  |  |  |  |
| *PlanRec* |  |  |  |  |  |  |  |  |  |
| *PlanInv* |  |  |  |  |  |  |  |  |  |
| *PlanRel* |  |  |  |  |  |  |  |  |  |

**Table 7.2** The MRP-I diagram for the chair in Figure 7.3.

1. Complete the MRP-I diagram for the 'Chair' (Table 7.2).

b. Complete the MRP-I diagram for the 'Leg' (Table 7.3) for the same periods, using the results from a).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Item:* | Leg | *LLC:* | 1 | *L:* | 2 |  |  |  |  |
| *Stock:* | 500 | *SS:* | 60 | *Q:* | n x 150 |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| *period* | *now* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| *GrossReq* |  |  |  |  |  |  |  |  |  |
| *SchedRec* |  |  | 400 |  |  |  |  |  |  |
| *SchedInv* |  |  |  |  |  |  |  |  |  |
| *NetReq* |  |  |  |  |  |  |  |  |  |
| *PlanRec* |  |  |  |  |  |  |  |  |  |
| *PlanInv* |  |  |  |  |  |  |  |  |  |
| *PlanRel* |  |  |  |  |  |  |  |  |  |

**Table 7.3** The MRP-I diagram for the leg in Figure 7.3.

c. Recalculate the MRP-I diagram for the 'Leg' if the lot-sizing policy would be changed to Lot-for-Lot instead of Q=150 (or multiple).

**Exercise 7.2.8**

Table 7.4 gives a part of an MRP-I schedule.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *period* | *t* | *t+1* | *t+2* | *t+3* | *t+4* | *t+5* | *t+6* | *t+7* |
| *gross requirement* | 10 | 20 | 15 | 20 | 15 | 10 | 20 | 15 |
| *scheduled receipt* | 25 |  |  |  |  |  |  |  |

**Table 7.4** Part of a certain MRP-I schedule.

The starting inventory position is 10 and the lead time for this item is 2 periods. The order quantity should be 25 (or a multiple of that). There is no safety stock.

Which of the following statements is/are true (if any)?

I In period t+6 the planned receipt is 50

II In period t+3 the planned release is 25

**Complex Exercises**

**Exercise 7.3.1**

The AlphaBetComp company produces several products, one of them being product A. Product A is assembled in a specialized production cell using one part B and three parts C.

The company has 8 pieces of A in stock and 6 of B (no safety stocks are used). Table 7.5 gives the forecasted requirements for A for the next 7 periods. One order for 5 A's is already on its way in the production cell; the expected time these 5 A's should be ready is in (the beginning of) period t+1. Also, the external supplier has been given an order for B: this is an order for 12 parts that are expected to arrive in (the beginning of) period t. The lead time both for A and B is 2 periods.

The production batch size for A is 5; the order batch size for B is 12.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| period | t | t+1 | t+2 | t+3 | t+4 | t+5 | t+6 |
| gross requirement | 6 | 7 | 6 | 3 | 4 | 5 | 4 |

**Table 7.5** Forecast of the requirements for product A for the next 7 periods.

a. Show the BOM for product A.

b. Determine using the MRP-I-logic the amount of A to be released for the next 7 periods (= period t till t+6). Show the entire MRP table.

c. Determine using the MRP-I-logic the amount of B to be released during the next 7 periods. Again, show the MRP-table:

**Exercise 7.3.2**

A company produces desks for new or restyled office buildings. A desk consists of:

* 4 legs
* 1 tabletop
* 2 drawers
* 4 rails
* 60 screws

Assembly of the desk takes a week. The legs can have different colors and are made in a series of 200 pieces in three weeks (sawed, deburred, and spray painted). To make the legs, stainless steel tubes are purchased. Four legs can be sawed from one tube.

a. Provide the complete BOM, including the LLCs.

b. Determine the MRP schedules for the desk, legs, and tubes, based on the data given in Table 7.6, assuming that for none of the MRP items scheduled receipts are expected.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *Item:* | desk | *LLC:* | 0 | *L:* | *1* |  |  |  |  |
| *Stock:* | 0 | *SS:* | 0 | *Q:* | L4L |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| *Period* | *now* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| *GRD* |  | 0 | 0 | 0 | 0 | 0 | 540 | 450 | 480 |
|  |  |  |  |  |  |  |  |  |  |
| *Item:* | leg | *LLC:* | 1 | *L:* | 3 |  |  |  |  |
| *Stock:* | 70 | *SS:* | 70 | *Q:* | n x 200 | |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| *Item:* | tube | *LLC:* | 2 | *L:* | 1 |  |  |  |  |
| *Stock:* | 35 | *SS:* | 0 | *Q:* | n x 100 | |  |  |  |

**Table 7.6** Relevant data for the production of desks for the next 8 periods. (GRD = Gross Requirements Desk)

**Exercise 7.3.3**

Product A has the Bill of Material structure as given in Figure 7.4.

|  |
| --- |
| A screenshot of a computer  Description automatically generated |

**Figure 7.4** The BOM of a certain product.

Use the MRP schedules given in Figure 7.5 to determine how many products B and how many C products are required for 1 product A and how many products C are required for 1 product B. Determine also the LLC for all items.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| *Item:* | A | *LLC:* |  | *L:* | *2* |  |
| *Stock:* | 0 | *SS:* | 0 | *Q:* | nx15 |  |
| *Period* | *now* | *1* | *2* | *3* | *4* | *5* |
| *Gross requirements* |  | 0 | 0 | 0 | 20 | 35 |
| *Scheduled Receipts* |  | 0 | 0 | 0 | 0 | 0 |
| *Planned inventory* | 0 | 0 | 0 | 0 | 10 | 5 |
| *Planned order receipts* |  | 0 | 0 | 0 | 30 | 30 |
| *Planned order release* |  | 0 | 30 | 30 | 0 | 0 |
|  |  |  |  |  |  |  |
| *Item:* | B | *LLC:* |  | *L:* | 1 |  |
| *Stock:* | 20 | *SS:* | 0 | *Q:* | nx5 |  |
| *Period* | *now* | *1* | *2* | *3* | *4* | *5* |
| *Gross requirements* |  | 0 | 30 | 30 | 0 | 0 |
| *Scheduled Receipts* |  | 0 | 0 | 0 | 0 | 0 |
| *Planned inventory* | 20 | 20 | 0 | 0 | 0 | 0 |
| *Planned order receipts* |  | 0 | 10 | 30 | 0 | 0 |
| *Planned order release* |  | 10 | 30 | 0 | 0 | 0 |
|  |  |  |  |  |  |  |
| *Item:* | C | *LLC:* |  | *L:* | 1 |  |
| *Stock:* | 50 | *SS:* | 0 | *Q:* | nx100 |  |
| *Period* | *now* | *1* | *2* | *3* | *4* | *5* |
| *Gross requirements* |  | 20 | 90 | 30 | 0 | 0 |
| *Scheduled Receipts* |  | 0 | 0 | 0 | 0 | 0 |
| *Planned inventory* | 50 | 30 | 40 | 10 | 10 | 10 |
| *Planned order receipts* |  |  | 100 | 0 | 0 | 0 |
| *Planned order release* |  | 100 | 0 | 0 | 0 | 0 |

**Figure 7.5** The MRP schedules that need to be filled in exercise 7.3.3.

**Exercise 7.3.4**

A company called Wanzeeroh BV produces the Digital Communication recorder (DCR). This DCR is assembled from subassemblies and parts, being:

- a lid;

- an assembled wheel mechanism;

- an assembled printed circuit board (PCB);

- a wire loom.

The wheel mechanism has a lead time of 5 periods and is assembled in quantities of 40 parts (or in multiples). This part is also sold as a separate service part. The demand for the wheel mechanism as a service part is on average 5 pieces a period. Because the demand for service parts is not always known in advance, a safety stock of 10 items is used. The dependent demand for wheel mechanisms is given in Table 7.7.

At the end of period 0, the physical inventory of the wheel mechanism is 40 pieces. In period 2 a scheduled receipt of 40 pieces of wheel mechanisms is expected.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period: | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| DP Demand: | 0 | 25 | 20 | 0 | 0 | 40 | 0 | 20 | 0 | 10 |

**Table 7.7** Dependent demand for the wheel mechanism.

a. Determine a full-10 full-10-period MRP‑schedule for the wheel mechanism using the data given above.

b. In period 1 the planner follows exactly what the MRP system has suggested. The gross requirements for the wheel mechanism remain the same as before. The actual service demand in period 1 has been 3 instead of the predicted 5. Determine the new MRP schedule for the wheel mechanism that will appear at the beginning of period 2 for periods 2 to 10.

**Exercise 7.3.5**

Product X is assembled in batches of 4 (or multiples) from three items Y and one part Z per product. It takes two periods to assemble a batch of X. The supply of Z takes one period (batch size 4 or multiples); Y is supplied with a delivery time of three periods (batch size 8 or multiples).

The demand for X per period follows a normal distribution with an average of 10.50 and a standard deviation of 2.42.

You may assume:

- The safety stock for X is based on the requirement that in 96% of the re-order cycles demand should be fulfilled completely.

- The physical inventory of X (end period 0) is 7.

- The scheduled receipts for X in periods 1 and 2 are resp. 8 and 12.

a. Determine the MRP diagram for X at the beginning of period 1, given the gross

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *period* | *0* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
| gross requirement |  | 8 | 11 | 9 | 14 | 11 | 13 | 11 | 9 | 6 | 7 |

**Table 7.8** Gross requirements of product X.

requirements as given in Table 7.8.

b.For part Y both in period 1 and in period 2 a receipt is scheduled for 40 parts; for period 3 a scheduled receipt of 32 is expected. Determine based on the MRP schedule for X the planned order releases for Y. You may assume that the physical inventory of Y at the end of period 0 is exactly the safety stock for this item.

c. Part Z is also provided as a service part. To cover that independent demand 2 extra items are added to the dependent demand to get the gross requirement for Z. For part Z a scheduled receipt is expected in period 1 of 12. Same as for Y, the physical stock for Z at the end of period 0 is equal to the safety stock. Determine the planned order releases for Z for periods 1 to 10.

d. In another calculation (not shown in this exercise) the EOQ formula showed that the cost-optimal batch size for Y is 7 (and not 8). Give two reasons why 8 still might be a better choice.

**Exercise 7.3.6**

LMSA Ltd. is a company that produces ATMs and sells these machines worldwide. On top of that, LMSA also produces spare parts for ATMs and distributes these parts through its distribution network. One of these parts is the card reader type CR-14X3. Since this part of the ATM frequently has to be replaced, the part is stored both in the central DC of a region and in the local warehouse in a particular country or area.

In the region of Australia, one central DC is positioned in Sydney. The local warehouse for Australia Southeast (SE) is positioned just to the opposite of the street of this DC. Two other (local) warehouses are located in Australia, i.e. in the Northeast (NE; near Cairns) and the West (W; near Perth). The lead time from DC to SE is just one day. It takes two days to distribute products from the DC to the warehouse

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| SE | 1 | 2 | 4 | 1 | 1 | 0 | 4 | 7 |
| NE | 2 | 4 | 7 | 4 | 2 | 5 | 7 | 6 |
| W | 1 | 2 | 0 | 1 | 0 | 0 | 1 | 1 |

**Table 7.9** Demand for CR-14X3.

Northeast (NE). The lead time from DC to warehouse West (W) is three days. The lead time from the production site of CR-14X3 to the central DC Australia is five days. Demand per region for the part CR-14X3 in the near future is given in Table 7.9. The batch size from central DC to a local warehouse is 6 (or a multiple).

Planning and control of stocks and supply from central DC to the local warehouse is done using an MRP system. The DC has just sent one batch of 6 to NE to arrive at the beginning of day 2. At this moment, the physical stock of CR-14X3 in NE is 8. Safety stock for this part in NE is 2. In SE the physical stock for CR-14X3 is 6; the safety stock is 1 and no orders are expected in SE as scheduled receipts.

a Fill in an MRP-table for the CR-14X3 at the local warehouse NE and another MRP-table for the local warehouse SE.

b Determine the gross requirements for the DC for days 1 to 8, assuming that W has stock enough to cover all of its demands for these days.

c As explained, the lead time from the production site to the DC is 5 days. Lately, some doubts have arisen on the appropriateness of that lead time. After studying historical data, the distribution of the actual lead times has been determined. This distribution is given in Table 7.9.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| lead time (days) | 3 | 4 | 5 | 6 | 7 | 8 |
| % of deliveries | 5 | 10 | 55 | 15 | 10 | 5 |

**Table 7.9** Distribution of the actual lead times.

If a delivery reliability of 90% would be required, is the lead time of 5 days then sufficient? If not, what should it be? If yes, explain why.

**Exercise 7.3.7**

A product AB is assembled from 1 part A and 2 parts B. It takes one period to assemble a batch of AB from its parts. Supplying a batch of part A takes two periods; providing a new batch of B takes three periods.

Table 7.10 shows the distribution of demand for AB from the past. You may assume that the table shows the entire population of the distribution (and not just a sample).

In Table 7.11 the forecast for the demand for the coming 10 periods is given.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| demand | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| % | 2 | 3 | 5 | 12 | 9 | 11 | 15 | 13 | 10 | 8 | 7 | 3 | 2 |

**Table 7.10** Demand distribution AB per period.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Forecast | 20 | 14 | 15 | 15 | 11 | 9 | 18 | 10 | 14 | 17 |

**Table 7.11** Forecast demand AB for the periods 1-10.

You may assume:

- The safety stock for AB is 1. For A the safety stock is 5; for B 15.

- For AB an order is expected to be completed in period 1 (“scheduled receipt”) of 15 items (this order has been released in the past).

- For part A one order of 10 parts is scheduled to arrive in period 2.

- For part B both in period 2 and period 3 an order is scheduled to be received for 28 parts.

- The physical stock at the end of period 0 ("now") is equal to the average demand per period for the item concerned (AB, A, or B) plus the safety stock.

Answer the following questions in case QAB = QA = QB = 1 (or multiples).

a Determine the planned order releases for the next 9 periods for AB in case an MRP-I-system is used.

b Determine the planned order releases for the next 7 periods for A if an MRP-I-system is used.

c Determine the planned order releases for the next 6 periods for B if an MRP-I-system is used.

d Repeat the questions a, b, and c in case QAB=5, QA=10, and QB=14 (or multiples).

e Explain the differences you see in the "planned inventories" in question d compared to the situations in questions a, b, and c.

**Exercise 7.3.8**

A device consists of two modules A and B. Each device contains 2 A and 1 B. Assembly of A and B into a final product takes a week. Two machines I and II are used for this assembly. The capacity requirement on machine I is 1 hour per device and on machine II 1.5 hours per device. Production of Module A also lasts a week. Machines I and II are also used for this. The capacity requirement for making module A is 0.5 hours on machine I and 0.75 hours on machine II. Module B is a purchased item.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Week | 1 | 2 | 3 | 4 | 5 | 6 |
| Demand | 25 | 25 | 20 | 30 | 25 | 30 |

**Table 7.12** The demand for the device in exercise 7.3.8.

The demand for the device for the coming weeks is given in Table 7.12. There are still 50 devices in stock and 25 modules A.

Determine the capacity requirement for machines I and II.

**Answers**

**Theory**

**Question 7.1.1**

With: requirement for an item is dependent on the need for another item (MRP, using BOM-relation)

Without: requirement for an item is independent of demand for other items, so no relation is needed in planning and control (like in an ROP system)

**Question 7.1.2**

Gross requirements, lead time, batch size, inventory position, safety stock, scheduled receipts

**Question 7.1.3**

I wrong, II true

**Question 7.1.4**

ss is used as 'dead stock' (like it's not there), lead times are considered 'fixed'

**Question 7.1.5**

The aim is to always have at least the ss available (so: MRP will never use that stock)

**Question 7.1.6**

See Fig. 7.3, p120

**Question 7.1.7**

1st: too much stock which will not be used

2nd: out-of-stock without MRP noticing it

3rd: out-of-stock cause of delays; inventory position will be corrected as soon as the order is done

4th: too much stock will occur, which will be corrected by MRP after it's there

5th: wrong parts may be ordered (or wanted parts are not ordered)

**Question 7.1.8**

c

**Question 7.1.9**

b and c are true

**Question 7.1.10**

Max.lt.: the maximum time it takes from the start of production of the first part of a product till the finishing of the complete product

Horizon: planning the start of production of the first part is dependent on the needs for the final product

**Question 7.1.11**

Due to the dependent demand

**Question 7.1.12**

Gives the sequence in which MRP calculations should be made; LCL is the lowest level in BOM an item is positioned.

**Answers**

**Basic Exercises**

**Exercise 7.2.1**

NetReq = 80

**Exercise 7.2.2**

See Table 7.13.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *period* | *t* | *t+1* | *t+2* | *t+3* | *t+4* | *t+5* | *t+6* |
| planned receipt | 0 | 0 | 15 | 0 | 12 | 20 | 0 |
| planned release | 15 |  | 12 | 20 |  |  |  |

**Table 7.13** Completed table.

**Exercise 7.2.3**

NetReq = 160

**Exercise 7.2.4**

NetRec = 20; PlanRec = 24

**Exercise 7.2.5**

B: 100; C: 50

**Exercise 7.2.6**

LLC(A)=0; LLC(B)=1; LLC(C)=2; LLC(D)=2

**Exercise 7.2.7**

a See Table 7.14

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stock | 100 | SS | 50 | Q | 100 | L | 1 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 50 | 130 | 90 | 250 | 300 | 130 | 110 | 100 |
| Sch.rec. |  | 100 |  |  |  |  |  |  |  |
| Sch. inv. | 50 | 100 | -30 | -120 | -370 | -670 | -800 | -910 | -1010 |
| Net.req. |  | 0 | 30 | 90 | 250 | 300 | 130 | 110 | 100 |
| Plan. rec. |  | 0 | 100 | 100 | 200 | 300 | 100 | 200 | 100 |
| Plan. inv. | 50 | 100 | 70 | 80 | 30 | 30 | 0 | 90 | 90 |
| Plan. Rel. | 0 | 100 | 100 | 200 | 300 | 100 | 200 | 100 | 0 |

**Table 7.14** Completed MRP-I diagram for “Chair”.

b See Table 7.15.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stock | 500 | SS | 60 | Q | 150 | L | 2 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 400 | 400 | 800 | 1200 | 400 | 800 | 400 | 0 |
| Sch.rec. |  |  | 450 |  |  |  |  |  |  |
| Sch. inv. | 440 | 40 | 90 | -710 | -1910 | -2310 | -3110 | -3510 | -3510 |
| Net.req. |  | 0 | 0 | 710 | 1200 | 400 | 800 | 400 | 0 |
| Plan. rec. |  | 0 | 0 | 750 | 1200 | 450 | 750 | 450 | 0 |
| Plan. inv. | 440 | 40 | 90 | 40 | 40 | 90 | 40 | 90 | 90 |
| Plan. Rel. | 0 | 750 | 1200 | 450 | 750 | 450 | 0 | 0 | 0 |

**Table 7.15** Completed MRP-I diagram for “Leg”.

c See Table 7.16.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stock | 500 | SS | 60 | Q | 1 | L | 2 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 400 | 400 | 800 | 1200 | 400 | 800 | 400 | 0 |
| Sch.rec. |  |  | 450 |  |  |  |  |  |  |
| Sch. inv. | 440 | 40 | 90 | -710 | -1910 | -2310 | -3110 | -3510 | -3510 |
| Net.req. |  | 0 | 0 | 710 | 1200 | 400 | 800 | 400 | 0 |
| Plan. rec. |  | 0 | 0 | 710 | 1200 | 400 | 800 | 400 | 0 |
| Plan. inv. | 440 | 40 | 90 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plan. Rel. | 0 | 710 | 1200 | 400 | 800 | 400 | 0 | 0 | 0 |

**Table 7.16 Recalculated** MRP-I diagram for “Leg” (other lot sizing policy).

**Exercise 7.2.8**

Only II is true (plan.rec.(t+6)=0)

**Answers**

**Complex Exercises**

**Exercise 7.3.1**

a

A screenshot of a computer

AI-generated content may be incorrect.

b

See Table 7.17.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| A stock | 8 | SS | 0 | Q | 5 | L | 2 | MaxPer | 7 |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |  |
| Gr.req. |  | 6 | 7 | 6 | 3 | 4 | 5 | 4 |  |
| Sch.rec. |  |  | 5 |  |  |  |  |  |  |
| Sch. inv. | 8 | 2 | 0 | -6 | -9 | -13 | -18 | -22 |  |
| Net.req. |  | 0 | 0 | 6 | 3 | 4 | 5 | 4 |  |
| Plan. rec. |  | 0 | 0 | 10 | 0 | 5 | 5 | 5 | 0 |
| Plan. inv. | 8 | 2 | 0 | 4 | 1 | 2 | 2 | 3 |  |
| Plan. Rel. | 0 | 10 | 0 | 5 | 5 | 5 | 0 | 0 |  |

**Table 7.17** The amount of A to be released for the next 7 periods.

c

See Table 7.18.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| B stock | 6 | SS | 0 | Q | 12 | L | 2 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |  |
| Gr.req. |  | 10 | 0 | 5 | 5 | 5 | 0 |  |  |
| Sch.rec. |  | 12 |  |  |  |  |  |  |  |
| Sch. inv. | 6 | 8 | 8 | 3 | -2 | -7 | -7 | -7 |  |
| Net.req. |  | 0 | 0 | 0 | 2 | 5 | 0 | 0 |  |
| Plan. rec. |  | 0 | 0 | 0 | 12 | 0 | 0 | 0 | 0 |
| Plan. inv. | 6 | 8 | 8 | 3 | 10 | 5 | 5 | 5 |  |
| Plan. Rel. | 0 | 0 | 12 | 0 | 0 | 0 | 0 | 0 |  |

**Table 7.18** The amount of B to be released for the next 7 periods.

**Exercise 7.3.2**

a LLC(desk)=0; LLC(leg, top, drawer, rail, screw)=1; LLC(tube)=2

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Desk stock | 0 | SS | 0 | Q | 1 | L | 1 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 0 | 0 | 0 | 0 | 0 | 540 | 450 | 480 |
| Sch.rec. |  |  |  |  |  |  |  |  |  |
| Sch. inv. | 0 | 0 | 0 | 0 | 0 | 0 | -540 | -990 | -1470 |
| Net.req. |  | 0 | 0 | 0 | 0 | 0 | 540 | 450 | 480 |
| Plan. rec. |  | 0 | 0 | 0 | 0 | 0 | 540 | 450 | 480 |
| Plan. inv. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plan. Rel. | 0 | 0 | 0 | 0 | 0 | 540 | 450 | 480 | 0 |
|  |  |  |  |  |  |  |  |  |  |
| Leg stock | 70 | SS | 70 | Q | 200 | L | 3 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 0 | 0 | 0 | 0 | 2160 | 1800 | 1920 | 0 |
| Sch.rec. |  |  |  |  |  |  |  |  |  |
| Sch. inv. | 0 | 0 | 0 | 0 | 0 | -2160 | -3960 | -5880 | -5880 |
| Net.req. |  | 0 | 0 | 0 | 0 | 2160 | 1800 | 1920 | 0 |
| Plan. rec. |  | 0 | 0 | 0 | 0 | 2200 | 1800 | 2000 | 0 |
| Plan. inv. | 0 | 0 | 0 | 0 | 0 | 40 | 40 | 120 | 120 |
| Plan. Rel. | 0 | 0 | 2200 | 1800 | 2000 | 0 | 0 | 0 | 0 |
|  |  |  |  |  |  |  |  |  |  |
| Tube stock | 35 | SS | 0 | Q | 100 | L | 1 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 0 | 550 | 450 | 500 | 0 | 0 | 0 | 0 |
| Sch.rec. |  |  |  |  |  |  |  |  |  |
| Sch. inv. | 35 | 35 | -515 | -965 | -1465 | -1465 | -1465 | -1465 | -1465 |
| Net.req. |  | 0 | 515 | 450 | 500 | 0 | 0 | 0 | 0 |
| Plan. rec. |  | 0 | 600 | 400 | 500 | 0 | 0 | 0 | 0 |
| Plan. inv. | 35 | 35 | 85 | 35 | 35 | 35 | 35 | 35 | 35 |
| Plan. Rel. | 0 | 600 | 400 | 500 | 0 | 0 | 0 | 0 | 0 |

**Table 7.19** The MRP schedules for the desk, legs, and tubes.

b See Table 7.19.

**Exercise 7.3.3**

#B/A=1; #C/A=1; #C/B=2 ; LLC(A)=0; LLC(B)=1; LLC(C)=2

**Exercise 7.3.4**

a See Table 7.20.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stock | 40 | SS | 10 | Q | 40 | L | 5 |  |  |  |  |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Gr.req. |  | 5 | 30 | 25 | 5 | 5 | 45 | 5 | 25 | 5 | 15 |
| Sch.rec. |  |  | 40 |  |  |  |  |  |  |  |  |
| Sch. inv. | 30 | 25 | 35 | 10 | 5 | 0 | -45 | -50 | -75 | -80 | -95 |
| Net.req. |  | 0 | 0 | 0 | 0 | 0 | 45 | 5 | 25 | 5 | 15 |
| Plan. rec. |  | 0 | 0 | 0 | 0 | 0 | 80 | 0 | 0 | 0 | 40 |
| Plan. inv. | 30 | 25 | 35 | 10 | 5 | 0 | 35 | 30 | 5 | 0 | 25 |
| Plan. Rel. | 0 | 80 | 0 | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 |

**Table 7.20** MRP schedule for the wheel mechanism.

b See table 7.21.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stock | 37 | SS | 10 | Q | 40 | L | 5 |  |  |  |
| period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Gr.req. |  | 30 | 25 | 5 | 5 | 45 | 5 | 25 | 5 | 15 |
| Sch.rec. |  | 40 |  |  |  | 80 |  |  |  |  |
| Sch. inv. | 27 | 37 | 12 | 7 | 2 | 37 | 32 | 7 | 2 | -13 |
| Net.req. |  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 13 |
| Plan. rec. |  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40 |
| Plan. inv. | 27 | 37 | 12 | 7 | 2 | 37 | 32 | 7 | 2 | 27 |
| Plan. rel | 0 | 0 | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 |

**Table 7.21** Revised MRP schedule for the wheel mechanism.

**Exercise 7.3.5**

a z(96%)=1.75; ss(X) ≈ 6

See Table 7.22.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stock | 7 | SS | 6 | Q | 4 | L | 2 |  |  |  |  | |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Gr.req. |  | 8 | 11 | 9 | 14 | 11 | 13 | 11 | 9 | 6 | 7 |
| Sch.rec. |  | 8 | 12 |  |  |  |  |  |  |  |  |
| Sch. inv. | 1 | 1 | 2 | -7 | -21 | -32 | -45 | -56 | -65 | -71 | -78 |
| Net.req. |  | 0 | 0 | 7 | 14 | 11 | 13 | 11 | 9 | 6 | 7 |
| Plan. rec. |  | 0 | 0 | 8 | 16 | 8 | 16 | 8 | 12 | 4 | 8 |
| Plan. inv. | 1 | 1 | 2 | 1 | 3 | 0 | 3 | 0 | 3 | 1 | 2 |
| Plan. rel. | 0 | 8 | 16 | 8 | 16 | 8 | 12 | 4 | 8 | 0 | 0 |

**Table 7.22** The MRP diagram for X.

b Planned releases for Y: 32 24 40 8 24 0 0 0 0

c Planned releases for Z: 16 12 16 12 12 8 8 4 0 0

|  |
| --- |
| d - 8 is multiple of the batch size (Q) of X |
| - a multiple of 4 is ok for the batch size (Q) of Z |
|  |

**Exercise 7.3.6**

a See Table 7.23.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stock | 8 | SS | 2 | Q | 6 | L | 2 |  |  |
| period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 2 | 4 | 7 | 4 | 2 | 5 | 7 | 6 |
| Sch.rec. |  |  | 6 |  |  |  |  |  |  |
| Sch. inv. | 6 | 4 | 6 | -1 | -5 | -7 | -12 | -19 | -25 |
| Net.req. |  | 0 | 0 | 1 | 4 | 2 | 5 | 7 | 6 |
| Plan. rec. |  | 0 | 0 | 6 | 0 | 6 | 0 | 12 | 6 |
| Plan. inv. | 6 | 4 | 6 | 5 | 1 | 5 | 0 | 5 | 5 |
| Plan. rel. | 0 | 6 | 0 | 6 | 0 | 12 | 6 | 0 | 0 |

**Table 7.23** The MRP diagram for the CR-14X3.

b gr.req 6 6 6 0 12 12 6 0

c Leadtime (LT) should be 7 days (then reliability = 95%)

**Exercise 7.3.7**

a 0 5 15 15 11 9 18 10 14 17 0

b 0 11 11 9 18 10 14 17 0 0 0

c 0 8 18 36 20 28 34 0 0 0 0

d AB: 0 5 15 15 15 5 20 10 15 15 0

A: 0 20 10 10 20 10 10 20 0 0 0

B: 0 28 0 42 28 28 28 0 0 0 0

e If Q>1: left-over stock due to "non-matching batch sizes"!

**Exercise 7.3.8**

M1 7.5 50 55 55 30 0

M2 11.25 75 82.5 82.5 45 0

**8 Systems using Echelon Stock (ESC, LRP)**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *Echelon stock*

*- Echelon lead time*

*- Echelon inventory position*

*- Echelon stock control (ESC)*

*- Line requirements planning (LRP)*

*- ROP system*

*- MRP system*

*- BOM*

- *Upstream*

*- Downstream*

*- Supply chain stages*

*- Remnant stock*

*- Linear supply chain*

*- Convergent supply chain*

*- Divergent supply chain*

**Theory**

**Question 8.1.1**

Echelon stock control systems tend to reduce the amount of stock in a supply chain. Explain why that would be the case.

**Question 8.1.2**

In a divergent supply chain, an echelon stock control system might require relocation of stock. Explain.

**Question 8.1.3**

What is the reason that an echelon stock control system has to assume lot size flexibility?

**Question 8.1.4**

a An LRP system prevents the distortion of information on the actual demand as is the case in an MRP system. Explain.

b Would that be different when comparing an ESC system with an ROP system used in a supply chain?

**Question 8.1.5**

What information is required to be able to make an LRP calculation?

**Question 8.1.6**

For Unit Control the difference between an echelon stock control system or a regular stock control system doesn't matter much. Explain.

**Question 8.1.7**

The formulas used to determine reorder levels in ESC are the same as in ROP systems, only the value of the parameters used is different. Explain why that is the case.

**Question 8.1.8**

As with MRP, in the case of an LRP system, the BOM has a crucial role in the logic used. But also in the case of an ESC system that BOM is used, while that is not true in a ROP system. Explain.

**Basic Exercises**

**Exercise 8.2.1**

Determine the echelon stock of each stage in the case of a supply chain consisting of 3 stages, with the characteristics as given in Figure 8.1.

|  |  |  |
| --- | --- | --- |
| schedrec 3  stage 1  stage 2  stage 3  schedrec 2  schedrec 1 | | |
| Stage | Inventory in stage | Scheduled receipts |
| 1 | 20 | 15 |
| 2 | 30 | 10 |
| 3 | 25 | 35 |

**Figure 8.1** Characteristics of the supply chain relevant to Exercise 8.2.1.

**Exercise 8.2.2**

Assume that the lead times for the three stages from question 1 are as follows:

- stage 1: 3 days

- stage 2: 4 days

- stage 3: 5 days

What would be the echelon lead time of stage 2?

**Exercise 8.2.3**

Assume that the stock in stage 2 from the supply chain shown in question 1, is controlled using an (s, Q) - ESC-system. At stage 1, the expected demand per day is 5, with a standard deviation of 3.

a What would be the safety stock needed at stage 2 to achieve a P1-service level of 90%?

b What would be the reorder level needed at stage 2 to achieve that P1-service level?

**Exercise 8.2.4**

Consider the situation shown in Figure 8.4 from the book, where an LRP control system is applied. If the batch size policy of the product FP from the example shown would have been "nQ with Q=30", what impact would that have had on the gross requirements for PY?

**Complex Exercises**

**Exercise 8.3.1**

The company SMS buys expensive metal sheet P and transforms this with several manufacturing steps into sheet B. The weekly demand for B has a normal probability density function with a mean of 6 and a variance of 5. The lot sizes are determined by the EOQ formula and are: QP=52 and QB=30. The lead time of P is 3 weeks and the lead time of B is 2 weeks. Customers buying B accept a lead time of 6 weeks. There are no safety stocks. For the determination of the purchase orders for B, SMS uses an MRP system.

At the beginning of week t, there is an inventory of 19 items B and 27 items P. The expected demand for B for the next 8 periods (to begin with period t) is: 6, 8, 5, 7, 11, 4, 6, 6.

a Give the MRP schemes for B and P.

b Give planned purchase orders for P using the LRP logic.

c What causes the difference between the purchase orders based on the MRP logic and the purchase orders based on the LRP logic?

d Suppose the inventory of B at the beginning of period t is equal to 0 and there is a scheduled receipts for B: one lot to be received in period t. Give the purchase orders for P using the MRP logic and give the purchase orders for P using the LRP logic.

**Exercise 8.3.2**

Consider the situation described in exercise 8.3.1. What would happen if SMS used ROP systems or ESC systems instead of an MRP- resp. LRP-system?

a Assume that for B an (s, Q)-system would be used, with a required P1-service level of 90%. Determine the required reorder level s.

b Would it be possible to determine the reorder level for P in a similar way as done for B? Explain.

c If an ESC system had been used, what would have been the re-order level and safety stock required for P assuming a P1-service level of 90%?

**Answers**

**Theory**

**Question 8.1.1**

If enough stock is available in the downstream part of the chain, then no stock is added. In non-echelon stock systems, each stage of the chain is optimized locally.

**Question 8.1.2**

Enough echelon stock does not guarantee enough stock in each branch of the chain in case of a divergent chain, only the combination of the branches. Therefore: items may need to be exchanged between the branches.

**Question 8.1.3**

Lot sizing enlarges the demand for an item, and thus is ignored in an echelon stock system. In a real-life situation, this may result in material availability that is enough to cover the final demand, but not necessarily the enlarged lot sizes. In such a case the actual batch size chosen should be adapted to the materials available.

**Question 8.1.4**

a Both the delay of information (due to lead time offsetting) and the actual demand differing from the gross requirement due to batch sizing are prevented.

b No, that would be similar.

**Question 8.1.5**

Gross requirement of the final product, echelon stock, echelon lead times, echelon inventory position, batch sizes, and safety stocks.

**Question 8.1.6**

Once an order is released for a (production unit), the same rules apply (with the same focus: trying to complete the order within the given period, while optimizing the use of resources).

**Question 8.1.7**

The same logic is used, only now echelon parameters are used (not stage-related parameters).

**Question 8.1.8**

In an ESC system, the BOM is used to determine for each item in a BOM what the demand would be (so the demand for the final product is multiplied by the number of items per product as specified in the BOM). Also, for the echelon lead time, the BOM is used to determine what lead times from which stages need to be included.

**Answers**

**Basic Exercises**

**Exercise 8.2.1**

ES(1) = 35; ES(2) = 75; ES(3) = 135

**Exercise 8.2.2**

EL(2) = 7 days

**Exercise 8.2.3**

a ss = 10.15, so 11

b s(2) = 46

**Exercise 8.2.4**

None

**Answers**

**Complex Exercises**

**Exercise 8.3.1**

a See Table 8.1.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| B |  |  |  |  |  |  |  |  |  |
| Stock | 19 | SS | 0 | Q | 30 | L | 2 |  |  |
| Period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 6 | 8 | 5 | 7 | 11 | 4 | 6 | 6 |
| Sch. rec. |  |  |  |  |  |  |  |  |  |
| Sch. inv. | 19 | 13 | 5 | 0 | -7 | -18 | -22 | -28 | -34 |
| Net. req. |  | 0 | 0 | 0 | 7 | 11 | 4 | 6 | 6 |
| Plan. rec. |  | 0 | 0 | 0 | 30 | 0 | 0 | 0 | 30 |
| Plan. inv. | 19 | 13 | 5 | 0 | 23 | 12 | 8 | 2 | 26 |
| Plan. rel. | 0 | 0 | 30 | 0 | 0 | 0 | 30 | 0 | 0 |
| P |  |  |  |  |  |  |  |  |  |
| Stock | 27 | SS | 0 | Q | 52 | L | 3 |  |  |
| Period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Gr.req. |  | 0 | 30 | 0 | 0 | 0 | 30 | 0 | 0 |
| Sch. rec. |  |  |  |  |  |  |  |  |  |
| Sch. inv. | 27 | 27 | -3 | -3 | -3 | -3 | -33 | -33 | -33 |
| Net. req. |  | 0 | 3 | 0 | 0 | 0 | 30 | 0 | 0 |
| Plan. rec. |  | 0 | 52 | 0 | 0 | 0 | 0 | 0 | 0 |
| Plan. inv. | 27 | 27 | 49 | 49 | 49 | 49 | 19 | 19 | 19 |
| Plan. rel. | 52 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 8.1** The MRP schemes for B and P.

b Planned releases P: 0 0 52 0 0 0 0 0 0

c GrossReq is based on final demand, not on planned receipts of the higher item; no influence of QB

d Planned releases P using MRP: 52 0 0 0 0 0 0 0 0

Planned releases P using LRP: 0 0 0 0 0 0 0 0 0

**Exercise 8.3.2**

a s(B) ≈ 16

b No, cause the demand for P does not follow a Normal distribution anymore (it is 30 or (very often) 0).

c LRP: s(P) = 37; ss(P) = 7

**9 Choosing an Appropriate DPC System**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

*- Decoupling Point Control (DPC)*

- *“Just-in-case”*

*- “Just-in-time”*

*- Parameters*

*- Service level*

*- Back-ordering*

*- Loss sales*

*- Program-controlled DPC*

*- Stock-controlled DPC*

*- Re-order point system (ROP)*

*- Echelon-stock control (ESC)*

*- Material Requirements Planning (MRP)*

*- Line Requirements Planning (LRP)*

*- Low-level code*

- *Upstream*

*- Downstream*

*- Bull-whip effect*

*- Variance amplification*

*- Lot size flexibility*

*- Safety stock*

*- Convergent supply chain*

*- Divergent supply chain*

*- Make-to-stock*

*- Make-to-order*

*- ABC categorization*

*- XYZ categorization*

*- Variation coefficient*

**Theory**

**Question 9.1.1**

Give an example of a performance measure related to the external customer perspective and an example of performance related to the internal delivery perspective.

**Question 9.1.2**

Explain the following statements:

a An ROP method only uses local historical information.

b The foundation of ESC is the use of the same demand information.

c MRP can’t use safety stock to handle uncertainty.

d LRP assumes that batch sizes are flexible.

**Question 9.1.3**

The bullwhip effect tends to increase with less accurate forecasts and longer reaction times. Explain why that would be the case.

**Question 9.1.4**

In supply chains, it is wise to concentrate stock safety stock on one level.

a Why would that point often be the most downstream level?

b Why is it not always the best solution to concentrate safety stock at the most downstream level?

**Question 9.1.5**

a Name three advantages of an ROP system.

b Name three advantages of an MRP system.

**Question 9.1.6**

Name the three categories of characteristics of a supply chain situation that should be considered when determining the DPC method to be used.

**Question 9.1.7**

When an ABC-XYZ categorization is used for determining the DPC method and parameters to be applied, both dimensions could be interpreted in at least two ways.

a Give two interpretations that could be used for creating the ABC-categorization.

b Give two interpretations that could be used for creating the XYZ-categorization.

**Question 9.1.8**

Why should a categorization of items to determine the DPC method to be used, be reconsidered on a regular base?

**Basic Exercises**

**Exercise 9.2.1**

Consider the data on turnover for a set of items given in Table 9.1.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Item-nr. | 5348 | 6412 | 9377 | 2843 | 5593 | 4029 | 3824 |
| Turnover (k€) | 9 | 29 | 2 | 60 | 0 | 95 | 5 |

**Table 9.1** Turnover data for a set of items.

Create an ABC classification for these items, using the following criteria:

* A: covers around 75-80% of sales turnover
* B: covers extra till around 90% of sales turnover
* C: rest

**Exercise 9.2.2**

The demand per month for a product shows variation as shown in Table 9.2.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug |
| Demand | 235 | 315 | 280 | 304 | 225 | 356 | 295 | 322 |

**Table 9.2** Demand per month for a certain product.

a Determine the average demand per month.

b Determine the standard deviation if the demand per month for this product.

c Determine the variation coefficient of the demand per month for this product.

**Complex Exercises**

**Exercise 9.3.1**

Consider the data on items in stock for a company as given in Table 9.3.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | A | B | C | D | E | F | G | H | I |
| price € | 6 | 4 | 12 | 20 | 21 | 10 | 2 | 1 | 10 |
| average demand/month | 70 | 20 | 200 | 110 | 600 | 10 | 450 | 250 | 50 |
| std.dev. demand/month | 17.50 | 10.00 | 20.00 | 99.00 | 480.00 | 12.00 | 22.50 | 100.00 | 50.00 |
| Item | J | K | L | M | N | O | P | Q | R |
| price € | 2 | 5 | 30 | 8 | 1 | 15 | 9 | 4 | 11 |
| average demand/month | 100 | 80 | 85 | 30 | 800 | 105 | 60 | 5 | 75 |
| std.dev. demand/month | 60.00 | 52.00 | 46.75 | 21.00 | 120.00 | 21.00 | 66.00 | 5.25 | 93.75 |

**Table 9.3** Data on items in stock.

a Create an ABC categorization based on demand volume, using the following criteria:

A: D>=400; B: 400>D>=100; C: D<100.

b Create an ABC categorization based on yearly turnover, using the following criteria:

A: D>=2500; B: 2500>D>=1000; C: D<1000.

c Create an XYZ-categorization based on the variation coefficient of the demand per month (vc), using the following criteria:

X: vc<=0.20; Y: 0.20<vc<=0.60; Z: vc>0.60

d Determine for each item the ABC-XYZ-category if demand volume is used for the ABC (as indicated in question a).

e Determine for each item the ABC-XYZ-category if turnover is used for the ABC (as indicated in question b).

**Exercise 9.3.2**

A company wants to determine what items need to be included in their MRP system, and for what items the inventory can be controlled using an ROP system. For that, an ABC-XYZ categorization needs to be created based on demand volume and predictability of demand. The data in Table 9.4 are drawn from their historical records (with forecast error = |forecasted

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | A | B | C | D | E | F | G | H |
| average demand/month | 150 | 1200 | 220 | 5000 | 960 | 75 | 200 | 800 |
| average forecast error/month | 20 | 50 | 10 | 75 | 15 | 15 | 50 | 25 |

**Table 9.4** Demand data for several items determined from historical records.

demand - actual demand|).

a Create an ABC categorization based on demand volume/month, using the following criteria:

A: D>=1000; B: 1000>D>=300; C: D<300.

b Create an XYZ categorization based on the demand predictability, where:

predictability 'P' = average forecast error / average demand

and the following criteria for categorization are used:

X: P≤0.03; Y: 0.03<P≤0.10; Z: P>0.10.

c Create an ABC-XYZ-categorization using the categorizations determined in a and b.

**Exercise 9.3.3**

Producer EEA produces modules that are supplied to customers such as ASML, ThermoFisher Scientific, and Philips Healthcare. The company wants to make an ABC-XYZ analysis for all parts it purchases from one particular supplier (see Table 9.5). The ABC categorization is based on the average turnover per month with the criterion:

A: turnover/month≥€5000;

B: €1000<turnover/month≤€5000;

C: turnover/month≤€1000,

while the XYZ classification is determined based on the variability of demand, based on the coefficient of variation (vc) of demand per month, using as criteria:

X: vc<=0.20;

Y: 0.20<vc<=0.60;

Z: vc>0.60.

a Indicate which purchase parts fall into the AX category and which in CZ.

b The company is considering controlling the supply of purchasing parts by category:

- via MRP or a Re-Order Point Method;

- with a high service level or a low service level.

Indicate which choices should be made for AX parts and which for the CZ parts. Explain your answer.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | A | B | C | D | E | F | G | H | I |
| price € | 44 | 4 | 12 | 20 | 21 | 10 | 2 | 1 | 10 |
| average demand/month | 120 | 20 | 200 | 110 | 600 | 10 | 450 | 250 | 50 |
| std.dev. demand/month | 52 | 10 | 20 | 99 | 48 | 12 | 22.5 | 100 | 50 |

**Table 9.5** Supplier purchase parts data.

**Answers**

**Theory**

**Question 9.1.1**

External: % customer orders delivered on time in full

Internal: % production orders for unit X delivered on or before the order due date

**Question 9.1.2**

a Only info from demand and supply for the item concerned

b All gross requirements are based on the gross requirements for the top item (MPS-item)

c Safety stock is supposed to be there all the time (so is not planned to be used)

d If not all parts needed are available (because downstream enough parts are already available), the batch size should be reduced accordingly

**Question 9.1.3**

A less accurate forecast requires more safety to be added; longer reaction times require longer time horizons to be covered and slow down the reaction to change.

**Question 9.1.4**

a Closest to the actual demand, requiring the shortest reaction time

b No use of commonality between branches of a chain, nor of commonality in the BOM (items to stock often are customer specific, thus more variety in items to store, resulting in higher stocks)

**Question 9.1.5**

a Simple rule to be followed by planning, no need to keep BOMs, no need for complex demand forecast

b Possibly just-in-time, use of information on future demand, use of dependent demand

**Question 9.1.6**

Supply characteristics, demand characteristics, cost characteristics

**Question 9.1.7**

a Demand volume (in nr. of items) versus demand value (in €)

b Demand variation vs. demand predictability

**Question 9.1.8**

Because the characteristics used in the categorization may change over time.

**Answers**

**Basic Exercises**

**Exercise 9.2.1**

A: 4029, 2843;

B: 6412;

C: 5348, 3824, 9377, 5593

**Exercise 9.2.2**

a Daver = 291.5

b Dstddev = 44.0

c vc(D) = 0.15

**Answers**

**Complex Exercises**

**Exercise 9.3.1**

a A={N,E,G}; B={H,C,D,O,J}; C={L,K,R,A,P,I,M,B,F,G}

b A={E,L}; B={C,D,O}; C={G,R,N,P,I,A,K,H,M,J,F,B,Q}

c X={G, C, N, O}; Y={A, H, B, L, J}; Z={K, M, E, D, I, Q, P, F, R}

d See Table 9.6,

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R |
| C | C | B | B | A | C | A | B | C | B | C | C | C | A | B | C | C | C |
| Y | Y | X | Z | Z | Z | X | Y | Z | Y | Z | Y | Z | X | X | Z | Z | Z |

**Table 9.6** The ABC-XYZ category if demand volume is used for the ABC categorization.

e See Table 9.7.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R |
| C | C | B | B | A | C | C | C | C | C | C | A | C | C | B | C | C | C |
| Y | Y | X | Z | Z | Z | X | Y | Z | Y | Z | Y | Z | X | X | Z | Z | Z |

**Table 9.7** The ABC-XYZ category if turnover is used for the ABC categorization.

**Exercise 9.3.2**

a A-items: B, D; B-items: E, H; C-items: A, C, F, G

b X-items: D, E; Y-items: B, C, H; Z-items: A, F, G

c See Table 9.8.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | A | B | C | D | E | F | G | H |
| Category | C | A | C | A | B | C | C | B |
| Z | Y | Y | X | X | Z | Z | Y |

**Table 9.8** The ABC-XYZ categorization using the answers from a and b.

**Exercise 9.3.3**

a AX: item E; CZ: items F and I. See Table 9.9.

b AX: MRP, high service level.

CZ: ROP, low service level.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | A | B | C | D | E | F | G | H | I |
|  | A | C | B | B | A | C | C | C | C |
|  | Y | Y | X | Z | X | Z | X | Y | Z |

**Table 9.9** The purchase items that fall in category AX or CZ.

**10 General Discussion of PU Control Systems**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *Material complexity*

*- Capacity complexity*

*- Routing*

*- Job shop*

*- Project-based production*

*- Line assembly*

*- Production unit control*

*- Order acceptance (customer)*

*- Order release (production, purchasing)*

*- Capacity allocation (unit, station)*

*- Sequencing*

*- Shop floor control*

*- Order release plan*

*- Work-in-progress (Work-in-Process)*

**Theory**

**Question 10.1.1**

What are the three medium-/short-term control functions?

**Question 10.1.2**

What are the benefits of a Workload Control function??

**Question 10.1.3**

Check the table for the standard normal distribution. At what z-value is the probability of not exceeding 'z' 85%?

**Question 10.1.4**

Consider the Law of Little. If the time unit used for expressing the lead time is 'hours', and the Work-in-Progress is expressed in the number of products, what would be the unit to be used for the release of work to that production unit to use Little's formula?

**Basic Exercises**

**Exercise 10.2.1**

Assume the following lead times for 5 orders (all in days): 2, 5, 4, 7, 3

a What is the average lead time of these five orders?

b What is the standard deviation of their lead times (assuming that these five are the entire population)?

**Exercise 10.2.2**

1. Name two logistic issues typically for a job shop.
2. Name two logistic issues typically for line production.
3. Name two logistic issues typically for a one-step process.
4. Name two logistic issues typically for a project-based situation.
5. Describe the link between Decoupling Point Control and Production Unit Control (or: how does Decoupling Point Control affect Production Unit Control, and how does Production Unit Control affect Decoupling Point Control?).
6. Name two specific logistic decisions taken within production units.
7. In the "order tap model," two taps are mentioned related to capacity allocation. What is the difference between the two?

**Exercise 10.2.3**

Suppose the throughput time of a production unit can be characterized as almost normally distributed with an average of 32 hours and a standard deviation of 5 hours. What lead time should chain control then count on to get a reliability of 93%?

**Exercise 10.2.4**

What percentage of orders will be completed too late if the lead time by a production unit is 64 hours (8 days of 8 hours), while the throughput time can be characterized as normally distributed with an average of 56 hours and a variance of 64 hours2?

**Exercise 10.2.5**

Table 10.1 gives a throughput time distribution as determined in a production unit for orders of type X.

a Determine the average throughput time.

b Determine the standard deviation of the throughput time.

c What needs to be used as lead time if one wants to assume that 95% of the orders will be on time?

|  |  |
| --- | --- |
| *Throughput time (hrs.)* | *% of orders* |
| 16 | 10% |
| 18 | 10% |
| 20 | 15% |
| 22 | 18% |
| 24 | 12% |
| 26 | 8% |
| 28 | 10% |
| 30 | 7% |
| 32 | 8% |
| 34 | 2% |

**Table 10.1.** Throughput time distribution.

**Exercise 10.2.6**

In a production unit, an average of 40 production orders are released per day. The average throughput time of an order is 4 days. How many orders will be present in this production unit as work-in-progress on average?

**Exercise 10.2.7**

Frequent countings and observations have shown that in a production unit, an average of 240 products are present on the floor as work-in-progress. Suppose that the average batch size of an order consists of 10 pieces and that the frequency of order release is 4 per day, what is the average throughput time by this production unit?

**Exercise 10.2.8**

What is the difference between mix flexibility and volume flexibility? Illustrate this difference by giving two examples of each form in which the flexibility in question can be achieved.

**Exercise 10.2.9**

Assess the correctness of the following statements:

I The volume flexibility of process-wise fabrication is usually very low.

II The mix flexibility of small-series production is usually high.

Choose one of the following answers:

a I and II are right.

b Only I is right.

c Only II is correct.

**Exercise 10.2.10**

Which decision function determines the order in which the existing (and upcoming) orders at a workstation are handled?

* + 1. Sequencing
    2. Work order release
    3. Work order detail planning
    4. Capacity allocation/Capacity variation

**Exercise 10.2.11**

Which decision-making function is responsible for controlling the amount of work in progress concerning the control of the throughput time?

a Work order sequencing

b Work order detail planning

c Work order release

d Work order acceptance

**Exercise 10.2.12**

What are the goals of Production Unit Control from a logistics point of view?

**Complex Exercises**

**Exercise 10.3.1**

In an assembly production unit of a factory, test lines for Printed Circuit Boards are built. These lines consist of a varying number of test modules, transport modules, and repair modules. The exact configuration of a test line depends on the customer's specifications. Most test modules are purchased from a sister company of the same group. The transport modules and repair modules are assembled in the assembly production unit, using purchased parts. Depending on the size and complexity of the requested test line, five to ten assembly operations must be carried out at different workplaces. These operations range from assembling wiring harnesses and assembling frames to extensive line testing.

Bertrand et al. give a simple typology of Production Unit situations.

* + 1. How should the outlined situation be characterized following that typology?
    2. What can you say about the main points of attention for the control of this production unit?

**Exercise 10..3.2**

Boezz BV is a producer of beverages. Boezz currently uses 150 recipes, divided into various types of drinks such as soft drinks, juices, and *sports drinks.* These 150 different drinks are sold in various packaging, giving the company a total of approximately 400 different end products. The packaging can differ in material (can or cardboard) and in volume (0.2 to 2 liters).

The production process of Boezz is divided into two Production Units. In the first production unit, the raw materials such as concentrate, water, various flavors, and sweeteners are mixed into a syrup. This production unit is also called the Syrup Room*.* The syrup thus prepared is stored in tanks until one of the eight filling lines of the second production unit; the filling unit starts processing the syrup in question: depending on the recipe and the required packaging, there is a choice between one or more filling lines. Each filling line consists of a mixing station, a filling station, and a packing station. The syrup is first mixed with water and carbon dioxide to obtain the right mix of the drink. Then the drinks are filled. Finally, the filled product is packed in the packaging part of the filling line.

The throughput time of the total process is short. In a few minutes, the syrup is signed off and packaged. The stock within the production process is therefore small and consists only of the products that run over the filling line. However, the changeover times are considerable (a few hours) and also order-dependent. In particular, cleaning the equipment when changing the recipe (two to three hours) and changing the filling packaging (four to eight hours change over time, especially when changing diameter and/or content) takes a lot of time.

Boezz sells to wholesalers. Because these wholesalers buy in series, the demand for individual products shows a strongly fluctuating picture. Moreover, demand shows a clear seasonal pattern on some production lines. This applies mainly to the products that are filled on the can lines. Because of these demand and production characteristics, Boezz produces to stock.

a Bertrand et al. give a simple typology of Production Unit situations. How could the situation described in the filling unit be characterized following this typology and what does this characterization mean for the main attention points of the control of this production unit?

b Identify the four production unit decision-making functions and the three operation unit control target variables that can be distinguished in general. Indicate which of these decision-making functions and target variables are relevant to the filling production unit of Boezz BV (and why).

c What are the logistical parameters of the filling line and how are they related to the target

quantities?

**Exercise 10.3.3**

A certain company is a manufacturer of stoves in all shapes and sizes. The company buys most of the parts of the stoves and focuses mainly on assembling the stoves and painting the end product.

The Stove Assembly production unit consists of twelve processing stations, with the heaters passing through these stations in the same order (starting at station A, then to B, and so on up to and including station L). One or more parts are added per station, depending on the type of heater.

The Paint production unit consists of a semi-automated paint line. The mounted heaters are attached to a running chain by an operator and are then automatically painted in the set color. The paint line works in batches, where every week the three different colors (white - metallic gray - black) are finished successively. A batch therefore consists of various types of stoves that must all have the same color.

a. For such a type of production unit, what are two of the crucial logistic decisions to be taken?

b. Name two valid reasons why a decoupling point between the Stove Assembly production unit and the Paint production unit would be a good idea.

**Exercise 10.3.4**

A company producing ball bearings has a total production lead time of 2 weeks and a procurement lead time of 1 week for raw materials. A customer of this company sends daily orders to the company, with a required delivery time of 2 weeks. On top of that, the customer also provides forecasts: each month a new forecast is given, showing the expected demand over the next 30, 60, 90, and 180 days. Each forecast for a longer horizon consists of the forecasted amount for the shorter horizon plus a forecast for the extra days. The level of uncertainty increases with the horizon. The forecast reliability of the last 90 days of the 180-day forecast is low.

a What can the company do with the forecast with a 30-day horizon? Which decisions ("taps") may be affected by that forecast?

b What can the company do with the forecast with a 180-day horizon? Which decisions ("taps") may be affected by that forecast?

**ANSWERS**

**Theory**

**Exercise 10.1.1**

(production/supply) order release

(order) sequencing

(station) capacity allocation

**Exercise 10.1.2**

See page 167.

**Exercise 10.1.3**

z=1.04

**Exercise 10.1.4**

Nr.products/hr

**Answers**

**Basic exercises**

**Exercise 10.2.1**

a 4.20

b 1.92

**Exercise 10.2.2**

a Waiting times

Utilization rate of workstations

b Material availability at workstations

Order release cf. cycle time of line

c Set-up times needed

Batch sizes

d Capacity planning

Material planning

e DPC releases orders for Units > impact on the workload in unit

PUC prioritizes orders (sequencing) > impact moment orders are ready

f Order sequencing (prioritization)

Capacity allocation (to workstations)

g First: allocation to a unit, not yet to a workstation

Second: allocation to a workstation

**Exercise 10.2.3**

z(93%)=1.475; L(plan)=40 (rounded)

**Exercise 10.2.4**

15.87%

**Exercise 10.2.5**

a 23.46 hrs

b 4.93 hrs

c 32 hrs

**Exercise 10.2.6**

160

**Exercise 10.2.7**

6 days

**Exercise 10.2.8**

Volume flexibility: the ability to vary periodically the number of products produced (or hours worked). This can be achieved by working with for instance flexible contracts, using overtime, etc.

Mix flexibility: determines to what extent the mix of products, given the volume, can be varied. This can be achieved for instance by modular designs; the work stays the same only the components may differ.

**Exercise 10.2.9**

a

**Exercise 10.2.10**

a

**Exercise 10.2.11**

c

**Exercise 10.2.12**

To have short throughput times

To have a high delivery reliability

To have as low costs as possible

**Answers**

**Complex exercises**

**Exercise 10.3.1**

a Project-based production.

b Lead time determination, capacity utilization, throughput time control, material control

**Exercise 10.3.2**

a Process-based, somewhat leaning towards mass assembly;

Focuses: capacity planning, utilization planning, and changeover time control

b Work order release, capacity allocation, order detail planning, and sequencing

Target quantities: speed, reliability, and efficiency

c Production level, desired cycle time, and desired stock level, aimed at speed, efficiency, and reliability respectively.

**Exercise 10.3.3**

a Line assembly

b Material availability(supply) at work stations

Order release cf. the line cycle time

c Batches differ (processing batches are needed at painting)

Set-up times are different

**Exercise 10.3.4**

a Procure raw materials

b Aggregate planning on capacity (like nr. shifts)

Checks with suppliers on volume and/or mix

**11 Production Control for Deterministic, Static Production Situations**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

*- Algorithm of Hodgon*

*- Johnsons rule*

*- Rule of Campbell, Dudek and Smith*

*- Algorithm of Wilkinson-Irwin*

*- Deterministic sequencing problem*

*- Throughput time*

*- Due date*

*- Dynamic sequencing problem*

*- Earliest Due Date*

*- Static sequencing*

*- SPT*

*- Lateness*

*- Tardiness*

*- Makespan*

*- Work-in-Process*

*- Stochastic sequencing problem*

*- Weighed SPT*

**Theory**

**Question 11.1.1**

What is the relationship between lateness and tardiness?

**Question 11.1.2**

Give for the sequencing problem 6 performance measures that are relevant from a logistic control point of view.

**Question 11.1.3**

Describe the relationship between throughput time and work-in-process.

**Question 11.1.4**

Use the relationship between throughput time and work-in-process to explain why the SPT rule minimizes the average throughput time.

**Question 11.1.5**

Explain why for a deterministic, static production situation with 1 machine, SPT not only the average throughput time but also the average lateness minimizes.

**Question 11.1.6**

If a certain sequence leads to the minimum average lateness does that same sequence then also minimize the average tardiness?

**Question 11.1.7**

Why is, in the algorithm of Hodgson, placing the largest order among the first *k*-orders (second step) a wise decision?

**Question 11.1.8**

Using the algorithm of Wilkinson and Irving one implicitly has several assumptions. Which of the following assumption(s) is (are) true:

a Each customer is equally important.

b Every customer must be delivered on time.

c Better some customers a little bit late than one customer much too late.

d As less possible customers have to be delivered too late.

**Question 11.1.9**

Why is in the situation of minimizing the makespan for a group of orders and parallel machines, the sequence of the orders at the different machines not relevant?

**Question 11.1.10**

Why is it when using the rule of Campbell, Dudek, and Smith necessary to determine the

makespan of the original *m*-machine problem instead of the makespan of the artificially created two-machine problem?

**Basic Exercises**

**Exercise 11.2.1**

A construction company has to execute 10 projects. If a project is delivered too late, a fine has to be paid. This fine is directly proportional to the number of days the project I delivered too late. The company can only execute one project at the same time Which rule has to be used to determine the sequence in which the projects have to be executed such that the total fine is minimized?

**Exercise 11.2.2**

At time t = 0, there are six orders (A, B, C, D, E, and F) available to be processed on machine 1. Table 11.1 shows the processing times on machine 1 and the requested delivery times of the orders.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | A | B | C | D | E | F |
| Processing time | 7 | 6 | 4 | 3 | 5 | 2 |
| Delivery time | 9 | 15 | 24 | 12 | 16 | 11 |

**Table 11.1** The processing times and delivery times for six orders.

The orders are processed in an order where the performance criterion is: 'as few orders as possible late'.

What is the average throughput time given that order?

**Exercise 11.2.3**

Consider the situation in exercise 11.13. However, the orders are now processed in an order where the performance criterion is: 'minimizing the average delivery time deviation'.

What is then the average tardiness?

**Exercise 11.2.4**

Orders A, B, C, D, and E must undergo two operations in sequence on machine 1 and machine 2. For each machine, the utilization times per order are as follows are given in Table 11.2.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | A | B | C | D | E |
| Processing time machine 1 | 1 | 6 | 6 | 5 | 7 |
| Processing time machine 2 | 5 | 3 | 6 | 4 | 8 |

**Table 11.2** The processing times on the two machines for the 5 orders.

Which sequence gives the minimal makespan?

**Exercise 11.2.5**

At 11:00 h in the morning orders A, B, C, D, and E still have two operations to go. The first operation is on machine M1, and the second operation is on machine M2. Table 11.3 shows the processing times required on these machines (times in minutes), including the moment the jobs have entered the queue in front of machine M1:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Order | A | B | C | D | E |
| Processing time M1 | 10 | 40 | 60 | 80 | 70 |
| Processing time M2 | 50 | 30 | 60 | 40 | 80 |
| Arrival time at M1 | 08:00 | 08:30 | 09:15 | 10:30 | 10:45 |

**Table 11.3** The arrival time of the 5 orders at machine 1, and the processing times at the two machines for 5 orders.

a Determine the sequence of these jobs according to Johnson's rule.

b Determine the sequence of these jobs when using a FIFO sequence.

c Determine the sequence of these jobs when using the SPT rule for the operation time required on M1.

d Determine the total throughput time (=makespan) for these jobs for all three sequences.

e Determine the average throughput times for all three sequences.

f Is the schedule that minimizes the total throughput time (=makespan) for these jobs the same schedule as the one that minimizes the average throughput time?

**Exercise 11.2.6**

For orders A, B, C, D, and E, successively three operations have to be performed at machines 1, 2, and 3. The processing times are given in Table 11.4.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | A | B | C | D | E |
| Processing time machine 1 | 3 | 1 | 5 | 2 | 6 |
| Processing time machine 2 | 4 | 6 | 3 | 2 | 4 |
| Processing time machine 3 | 5 | 4 | 2 | 6 | 3 |

**Table 11.4** The processing times at the three machines for 5 orders.

Which sequence gives the minimal makespan?

When determining the size of a given order, use a table known as a completion table, i.e. a table in which the columns are formed by the orders in the sequence question and the rows by the completion times of each order at the machine in question. In that case, *Cij = max(Ci,j-1, Ci-1,j)* + *pij* (with *Cij:* the completion time for order i on machine j; *Cij*; = 0 if i and/or j do not exist).

**Complex Exercises**

**Exercise 11.3.1**

The company Asus makes custom-made parts. The production process consists of 3 steps which must take place one after the other (first drill, then mill, then assemble). The orders booked for the coming days are shown in Table 11.5; none of these orders have been worked on yet and all machines are available now.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Job | Drilling  (hours) | Milling  (hours) | Assembly  (hours) | Delivery time  (hours) | Arrival Time  (hrs. vs. now) |
| A | 2 | 1 | 3 | 6 | -2.50 |
| B | 2 | 3 | 2 | 10 | -2.25 |
| C | 1 | 1 | 1 | 8 | -2.00 |
| D | 2.5 | 2.5 | 1.5 | 9 | -1.50 |
| E | 3 | 1 | 3 | 10 | -1.00 |

**Table 11.5** The different processing times, the delivery time, and the arrival time for 5 orders.

a At what moment will Job E be completed if jobs are processed in the sequence they came in (FCFS)?

b After the acquisition of a new machine, the two processes Drilling and Milling can be combined into one process. The processing time of this new machine for the individual jobs is equal to the sum of the current processing times for Drilling and Milling. Draw up a new Gantt chart with the 2 workstations if Johnson's rule is used.

c Is the investment in the new machine justified if you look at the average tardiness of these five orders? Explain your answer.

**Exercise 11.3.2**

The company “Candyfleet” in Den Helder makes machines for candy manufacturers. The required last step before delivery is to test the machines. The orders have been placed by different customers; they are delivered as soon as they are ready.

a What are the average throughput time and the average work-in-process (WIP) if the orders given in Table 11.6 are processed according to SPT? Show your calculation.

|  |  |
| --- | --- |
| Order | Processing time (hours) |
| I | 9 |
| II | 10 |
| III | 6 |
| IV | 7 |
| V | 3 |
| Total | 35 |

**Table 11.6.** The processing time of 5 different orders.

Up until now, the testing has been done by one employee. Management is considering having the testing done in two consecutive steps, by two employees (in other words two workstations).

The first employee (workstation 1) prepares the test set-up, and the second employee (workstation 2) performs the actual test. The processing times of the two stations are given in Table 11.7.

b What is the average throughput time and average work in process (WIP) if the orders are processed in a sequence minimizing the makespan? Show your calculations.

|  |  |  |  |
| --- | --- | --- | --- |
| Order | Processing time Station 1 (hours) | Processing time Station 2 (hours) | Total Processing Time (hours) |
| I | 4 | 5 | 9 |
| II | 4 | 6 | 10 |
| III | 4 | 2 | 6 |
| IV | 3 | 4 | 7 |
| V | 2 | 1 | 3 |
| Total | 17 | 18 | 35 |

**Table 11.7.** The processing times at the two stations for 5 orders.

**Exercise 11.3.3**

A certain machine can process orders without the necessary presence of an operator. Therefore it is possible to use this machine at night (outside operating hours). The orders that are processed outside the operating hours we will call night-orders. The available time at night during 24 hours is 16\*60 = 896 minutes. Before an order, that consists of a series of products, can be processed, it first has to be prepared, that is, the individual products of a series of products need to be placed on a product carrier and the control of the machine has to be programmed for processing the products. The preparation takes place during the day shift by certain operators (preparers) who also have to do other activities. During the day shift the orders that need the presence of an operator while being processed are processed.

Suppose at the beginning of each day several night-orders are available to be prepared and for each order, the preparation time and the due date are known. The company wants that outside the day shift the machine is used as much as possible. Table 11.8 gives the night orders that are available at the beginning of day 1, per order the preparation time and the processing time (both in minutes), and the due date (in days). An order is assumed to be finished if it is completely taken off the machine (which only can take place during the day shift of course).

|  |  |  |  |
| --- | --- | --- | --- |
| Order identification | Preparation time | Processing time | Due date |
| A | 20 | 40 | 3 |
| B | 40 | 80 | 2 |
| C | 10 | 50 | 3 |
| D | 50 | 100 | 2 |
| E | 60 | 70 | 3 |
| F | 20 | 50 | 2 |
| G | 30 | 50 | 2 |
| H | 40 | 60 | 2 |

**Table 11.8.** The preparation time, processing time, and due date for 8 different orders,

*Note:* if the preparation activities for an order are started on day *t* and only partial can be executed, the remaining activities can be finished the next day. It may be assumed that of the interrupted order a proportionate part of the products can be processed at night.

a Which orders have to be prepared on the first day if the goal is to maximize the use capacity of the next night?

b In which sequence have the orders to be prepared if the goal is to deliver as many as possible orders from the available orders? How many orders are then late?

c In which sequence have the orders to be prepared if the goal is to minimize total tardiness? What is then the total tardiness (in days)?

**Exercise 11.3.4**

On a certain day, several airplanes that are heading for Schiphol have to divert to Maastricht due to bad weather. These will arrive in about 30 minutes. Assume that they all enter the airspace of Maastricht at the same time. Table 11.9 gives the flight numbers and the remaining flight time (due to the fuel) each of the airplanes still has. The landing time differs per airplane and is also given in Table 11.9. An airplane can only start with the landing procedure if the previous airplane has

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Airplane | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Flight number | Kl  343 | Twa  15 | Pa  344 | Kl  654 | Uk  489 | Vz  456 | Sa  345 | Al  154 | Sy  764 | Ca  342 |
| Remaining  time | 14 | 80 | 19 | 80 | 20 | 80 | 80 | 80 | 80 | 80 |
| Landing time | 11 | 15 | 5 | 6 | 5 | 7 | 6 | 9 | 7 | 6 |

**Table 11.9.** The remaining flight time and landing time for 10 different airplanes.

finished its landing. If an airplane can not land in time it has to go to a, more or less abandoned, nearby Airforce airport (which of course is not preferred).

a In which sequence have these airplanes to land and which airplanes have to go to the Airforce airport?

Suppose that the remaining times for flights 1, 3, and 5 are not as in Table 11.9, but 140 rep. 190 resp. 200 and that an airplane can only start with the landing procedure if the previous airplane has finished its landing and all passengers have disembarked. The disembarking times depend on the type of airplane and the number of passengers and are given in Table 11.10. Disembarking can start as soon as the plane has landed.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Airplane | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Disembarking  time | 10 | 10 | 10 | 5 | 12 | 7 | 10 | 8 | 15 | 4 |

**Table 11.10.** The disembarking time for the 10 different airplanes.

b In which sequence have the airplanes to land such that the total processing time (landing and embarking) is minimized?

Suppose that there is only one baggage belt available and that the baggage processing times are given as in Table 11.11.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Airplane | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Baggage processing time | 6 | 5 | 6 | 7 | 6 | 5 | 8 | 6 | 10 | 5 |

**Table 11.11** The baggage processing time for the 10 different airplanes.

c In which sequence have the airplanes to land such that the last passenger gets his baggage as soon as possible?

**Exercise 11.3.5**

In the assembly department of WAHAS, not only do assembly processes take place but the modules are also packaged and prepared for transport. On a certain day, at 07.00 in the morning, there are six orders at the packaging place waiting to be packaged. These orders require a packaging time as given in Table 11.12.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Order | 1 | 2 | 3 | 4 | 5 | 6 |
| Packaging time | 8 | 12 | 16 | 10 | 14 | 18 |

**Table 11.12** Packaging time per order (in minutes) for 6 different orders.

After being packaged, each order is, using an automatic transportation line, sent to the place where for each order a (separate) truck is waiting to be loaded. Table 11.13 gives the time for transporting the system from the packaging place to its loading place. This time is independent of the number of systems already present at the transportation line (as with a moving belt).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Order: | 1 | 2 | 3 | 4 | 5 | 6 |
| Transportation time | 7 | 4 | 1 | 3 | 2 | 1 |

**Table 11.13** Transportation time per order (in minutes) for 6 different orders.

Table 11.14 gives the times at which the drivers would like to start loading. This table also gives the loading time for each order (and thus per truck); the planned start time plus loading time gives the planned departure time.

Each driver that can not depart at the planned departure time gets a compensation of €1000 from WAHAS Europe BV.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Order: | 1 | 2 | 3 | 4 | 5 | 6 |
| Planned starting time | 07.37 | 07.22 | 07.47 | 07.17 | 07.28 | 07.59 |
| Loading time | 5 | 4 | 8 | 2 | 3 | 4 |

**Table 11.14** Planned starting times and loading times (in minutes) for 6 different orders.

Question: What is the minimum (total) compensation that WAHAS has to pay? Motivate your answer.

**Exercise 11.3.6**

At the University each student gets a laptop at the beginning of the study year. To get such a laptop 3 service counters have to be visited. At the first encounter, the student gets the contract that has to be signed; here several personal data are filled in and it is checked whether the student has paid the enrollment fee. Moreover, the contract between the student and the University is signed and questions of the students are discussed. The second counter is necessary to arrange the financial contract and this contract between the student and the bank is signed. Finally, at counter 3, the laptops are handed over to the students with a short introduction. Each student has to visit these counters in this sequence.

Table 11.15 gives for each counter the number of persons that work there (parallel)

|  |  |  |  |
| --- | --- | --- | --- |
| Counter | 1 | 2 | 3 |
| Number of workers | 1 | 1 | 8 |

**Table 11.15** Number of workers per counter.

To handle the influx, some methods are being considered. One of these methods, method I, works as follows: In front of counter 1 a small waiting room, where 4 students can wait (excl. the student that is being served at counter 1), is constructed. As long as not all places in this waiting room are occupied, students are accepted. If all places are occupied, new arriving students are asked to come back at another moment in time. Accepted students are being served in FCFS (FIFO) sequence and at the other counters there are unlimited waiting rooms.

The average processing times for each counter can be based on the times for the 8 students given in Table 11.16.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| stud. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| p(1) | 5 | 3 | 4 | 4 | 5 | 8 | 7 | 4 |
| p(2) | 4 | 7 | 3 | 1 | 7 | 2 | 2 | 5 |
| p(5) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| dd | 15 | 30 | 30 | 60 | 15 | 30 | 45 | 45 |

**Table 11.16** Data of the students in the group that starts at t=0 (times in minutes); p(i) is processing time at counter i.

An alternative to method I is method II.

* Using FCFS (FIFO) students are divided into groups of 8. Once a group is formed, this group can go to the first counter.
* The whole group has to be completed at all counters before a new group can start at counter 1

At a certain point in time (say t=0) there is a group of 8 students with data as given in Table 11.15. For each student in this group, this table gives the processing time per counter and the time at which the next class of this student starts (dd).

a In which sequence have these 8 students to be processed such that one can start as soon as possible with the next group?

b How long does it take to process this group?

**ANSWERS**

**Theory**

**Question 11.1.1**

Tardiness = max(0, Lateness)

**Question 11.1.2**

Average throughput time

Average lateness

Average number of orders

Makespan

Maximum throughput time

Average tardiness

**Question 11.1.3**

**Question 11.1.4**

By using the SPT rule the number of jobs is minimized (all the jobs leave the shop as soon as possible), thus also the average number of jobs. Given the relationship between throughput time and work-in-process also the average throughput time is minimized.

Note: It can also be proven by contradiction: assume that we have a non-SPT sequence that is optimal. Since the sequence is non-SPT there must be a pair of adjacent jobs *i* and *j,* with *j* following *i,* such that service time job *i* > service time job *j.* Now interchange jobs *i* and *j* and look at the total throughput time in the old and the new situation. It is then easy to show that the total throughput time in the new situation is smaller than in the old situation (see K.R. Baker (1974): Introduction to Sequencing and Scheduling).

**Question 11.1.5**

where is the average lateness

is the average flow time (or throughput time)

is the average due date

**Question 11.1.6**

No.

**Question 11.1.7**

r(i): ready time order i; dd(i): duedate order i; p(i): proc.time order i

For first k orders: dd(k)>r(k-1); if the order with max p(i) is removed, then for all orders following that order the r(i) is decreased to a maximum (with max p(i)).

For the new ready time, we know:

r’(k)<=r(k-1)<dd(k), so all of the first (k-1)-orders remaining from the first set of k-orders, are guaranteed on time. The max. reduction of the ready times makes the best chance of being on time for all orders.

**Question 11.1.8**

a and c.

**Question 11.1.9**

The time to complete a given set of orders on a machine is independent of the sequence in which the orders are processed.

**Question 11.1.10**

Because when using artificially created two-machine problems, not all machines are taken into account.

**Answers**

**Basic exercises**

**Exercise 11.2.1**

Wilkinson/Irwin

**Exercise 11.2.2**

Average throughput time per job: 13.5

**Exercise 11.2.3**

Average tardiness is 3.83

**Exercise 11.2.4**

Sequence: A-C-E-D-B (also correct: A-E-C-D-B)

**Exercise 11.2.5**

a a-c-e-d-b

b a-b-c-d-e

c a-b-c-e-d

d 290-340-300

e 288-274-272

f no

**Exercise 11.2.6**

Sequence: DABEC

**Answers**

**Complex exercises**

**Exercise 11.3.1**

a 15.00

b

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1 | a | a | a | a | a | a | e | e | e | e | e | e | e | e | b | b | b | b | b | b | b | b | b | b | d | d | d | d | d | d | d | d | d | d | c | c | c | c |  |  |
| 2 |  |  |  |  |  |  | a | a | a | a | a | a |  |  | e | e | e | e | e | e |  |  |  |  | b | b | b | b |  |  |  |  |  |  | d | d | d |  | c | c |
|  |  | 1 |  | 2 |  | 3 |  | 4 |  | 5 |  | 6 |  | 7 |  | 8 |  | 9 |  | 10 |  | 11 |  | 12 |  | 13 |  | 14 |  | 15 |  | 16 |  | 17 |  | 18 |  | 19 |  | 20 |

c No

**Exercise 11.3.2**

a 17.6 hr resp. 2.5 orders

b 15.8 hr resp. 3.8 orders

**Exercise 11.3.3**

a First night CFDA; second night: rest.

b F, G, H, A, C, and E. 2 orders are too late.

c Sequence: F, G, H, B, D, C, A and E. Four orders are each one day too late (B, D, A, and E).

**Exercise 11.3.4**

a 1, 3, 5, 2, 4, 6, 7, 8, 9, 10. Only airplane 5 can not land in time.

b 3, 5, 7, 6, 9, 1, 2, 8, 4, 10

c So optimal sequence: 3-5-4-7-9-1-8-2-6-10

**Exercise 11.3.5**

The total compensation WAHAS has to pay is: €2000,=.

**Exercise 11.3.6**

a The optimal sequence is 2-5-8-1-3-4-6-7

b 47 (incl. counter 3) minutes.

**12 Flow Process Production**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *Aggregate stock*

*- Capacity stock*

*- Cycle length*

*- Cycle time*

*- Changeover order*

*- (Pure) rotation cycle*

*- Run out-time*

*- Batch size stock*

*- Tact time*

*- Safety stock*

###### **Theory**

**Question 12.1.1**

What is meant by cycle time in flow process manufacturing and what is the difference with the throughput time?

**Question 12.1.2**

What is the fundamental consideration when choosing a cycle length for a product?

**Question 12.1.3**

Why is it wise, if there are no changeover costs, to make the cycle time for products as short as possible (provided that there is still enough capacity left for actual production)?

**Question 12.1.4**

What are the advantages and disadvantages of a fixed cycle time per product in flow process manufacturing?

**Question 12.1.5**

Why does a check have to be carried out after, from a cost point of view, the optimal cycle time has been determined?

**Question 12.1.6**

Why is there a principled choice for the same, fixed cycle time for all products? Under what conditions can this principle be deviated from without leading to variations in the cycle time for a product?

**Question 12.1.7**

What is the difference between an aggregate inventory and the inventory per product? When is aggregate stock important?

**Question 12.1.8**

What is the reason for using safety time when calculating the maximum cycle time for a product?

##### **Basic Exercises**

**Exercise 12.2.1**

A producer of plastic knows that the demand for a specific industrial plastic is 1500 tonnes per year. If he did not have to produce any other plastic, he could produce 300 tonnes per week (50 weeks in a year). However, because other plastics also have to be produced, the producer uses a batch size of 30 tons.

How large is the average batch size stock, assuming that a batch is only produced when there is a need?

**Exercise 12.2.2**

The production speed of an injection molding machine producing type *i* plastic is 3000 kilos per day. The annual demand (a year has 250 days) for this type of plastic is 100 000 kilos. Keeping 1 kilo of plastic in stock costs €0.15 on an annual basis. The changeover costs are € 5000 per changeover.

What is the optimal cycle time for product *i* from a cost point of view (rounded to whole days)?

**Exercise 12.2.3**

A company produces 5 products with data as in Table 12.1. Production is done in a pure rotation cycle.

a Determine the cost-optimal cycle time.

b Determine the total average batch size inventory at this optimal cycle time.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Product | Set up costs  (€ per set up) | Inventory holding costs  (€ /piece/day) | Production speed (pieces/day) | Demand (pieces/day) |
| 1 | 25 | 0.0050 | 1500 | 200 |
| 2 | 40 | 0.0048 | 2500 | 300 |
| 3 | 30 | 0.0056 | 1000 | 240 |
| 4 | 80 | 0.0024 | 2000 | 210 |
| 5 | 90 | 0.0060 | 3000 | 200 |

**Table 12.1** Data for the 5 products.

**Exercise 12.2.4**

A company produces 5 products with data as in Table 12.2. Production is done in a pure rotation cycle. Assume that a day consists of eight hours.

a Determine the minimum cycle time at which the average demand can still be met.

b Items 1 to *5* in this question are the same products as the items in the previous question. Using the answer to question 12.16, now determine the optimum cycle time from the point of view of cost while still meeting the demand.

|  |  |  |  |
| --- | --- | --- | --- |
| Product | Set up time  (hours/set up) | Production speed (pieces/day) | Demand  (pieces/day) |
| 1 | 1.25 | 1500 | 200 |
| 2 | 2.00 | 2500 | 300 |
| 3 | 1.50 | 1000 | 240 |
| 4 | 2.50 | 2000 | 210 |
| 5 | 4.50 | 3000 | 200 |

**Table 12.2** Data for the 5 products.

**Exercise 12.2.5**

A certain company produces polyethylene in three different grades: A, B, and C. The conversion plant can be considered as one machine. The installation runs continuously at a speed of 20 tonnes per hour for grades A and B and at 15 tonnes per hour for grade C, except when changing grades (this takes 7 hours per change). Assume that the line is available 365 days a year 24 hours a day. The following costs are involved:

Exchange costs € 10 000 per product change (identical for all changes)

Inventory costs € 120 per tonne per year (identical for all products)

The annual demand is 90 000 tonnes (for grade A), 50 000 tonnes (for grade B), and 20 000 tonnes (for grade C).

a Give a brief definition of a pure rotation cycle.

b Explain in words how to determine an optimal pure rotation cycle time, and why it is both the lowest cost and implementable.

c Calculate the optimal pure rotation cycle time (in hours) for the above polyethylene operation.

d Suppose the company decides to implement this pure rotation cycle and strives to realize this cycle operationally as much as possible, then name two potential benefits that the use of a pure rotation cycle can bring from a human resource management perspective.

**Complex exercises**

**Exercise 12.3.1**

The company Peent & Pek produces and sells paint in different colors and packaging shapes. The production process consists of a paint mixing line and a packaging line. The paint mixing line has changeover times for a color changeover. These changeover times depend on the order. Table 12.3 shows the changeover times for the different colors (in hours).

Immediately after paint mixing, the paint is fed through to the packaging line and processed. The storage option between the paint mixing line and packaging line is therefore very limited. The packaging line is very flexible and has a changeover time of 2 minutes, both in terms of color and packaging form. The packaging line can pack at a speed of 2 tons per hour. The paint mixing line can produce at a speed of 1 ton per hour (regardless of the type of paint).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | To color: | | | | | | | | |
| 1 | 2 | 3 | 4 | *5* | 6 | 7 | 8 | 9 |
| From color: | 1 | 0 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 2 | 4 | 0 | 1 | 2 | 3 | 4 | 1 | 2 | 3 |
| 3 | 3 | 4 | 0 | 1 | 2 | 3 | 4 | 1 | 2 |
| 4 | 2 | 3 | 4 | 0 | 1 | 2 | 3 | 4 | 1 |
| *5* | 1 | 2 | 3 | 4 | 0 | 1 | 2 | 3 | 4 |
| 6 | 4 | 1 | 2 | 3 | 4 | 0 | 1 | 2 | 3 |
| 7 | 3 | 4 | 1 | 2 | 3 | 4 | 0 | 1 | 2 |
| 8 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 0 | 1 |
| 9 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 0 |

**Table 12.3** Changeover times in hours on the paint mixing line.

The regular demand per color per week may be considered as a random draw from a normal distribution with average and standard deviation as mentioned in Table 12.4. In addition to the regular products listed in Tables 12.3 and 12.4, orders for specific products are also accepted from time to time. The marketing and production departments agree that the factory should in principle have 10% capacity left over per week for those specific products.

Each color is packaged in four packaging forms, each of which has an equal expected demand and standard deviation of the demand per week (which are independent of each other). Within a cycle of a color, the paint is first filled into the first form of packaging, then into the second and third, and finally into the fourth.

The factory produces 16 hours a day for *5* days a week and 50 weeks a year. The company produces the regular products to stock. The company wants to be able to supply 95% of the demand per week for regular products from stock and also to work with minimal stocks.

|  |  |  |
| --- | --- | --- |
| Color | Average demand | Standard deviation demand |
| 1 | 12.6 | 2.0 |
| 2 | 11.2 | 1.8 |
| 3 | 9.8 | 1.5 |
| 4 | 8.4 | 1.2 |
| *5* | 7.0 | 1.0 |
| 6 | 5.6 | 0.9 |
| 7 | 4.2 | 0.5 |
| 8 | 2.8 | 0.3 |
| 9 | 1.4 | 0.2 |

**Table 12.4** Average and standard deviation of the demand per week (in tonnes).

a Determine a sensible production schedule and the minimum cycle time and production batch sizes associated with that schedule for the regular products.

b Determine the necessary safety stock for the regular packaged products.

c Determine the average total stock of the regular products (in tonnes) given the calculated minimum cycle time.

**Exercise 12.3.2**

Medkouws, established in Disies (England), produces various types of mixed animal feeds, mainly intended for the local market. The total range includes six different mixed animal feeds, which are sold in a standard package. In the company's production department, the raw materials are mixed in a mixing machine in a certain proportion to the respective type of mixed animal feed. The exact composition and ratio of the raw materials depends on the type of mixed animal feed that is produced.

Some time is lost when converting the mixer to a different type of mixed animal feed. Table 12.5 shows the conversion time for each type of mixed animal feed to the type in question. This changeover time is order-independent. The table also indicates the speed at which the relevant types can be produced. Finally, Table 12.5 shows the expected demand per mixed animal feed for the coming year.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Mixed animal feed | 1 | 2 | 3 | 4 | 5 | 6 |
| Set up time (hours) | 6.0 | 5.5 | 5.0 | 5.5 | 5.0 | 5.0 |
| Mixing speed (tons/hour) | 2.0 | 1.0 | 1.5 | 2.0 | 1.5 | 2.5 |
| Expected demand (tons/year) | 1200 | 600 | 900 | 1200 | 900 | 1500 |

**Table 12.5** Data per mixed animal feed.

The company produces the mixed animal feeds to stock because the requested delivery time is very high. The management has decided to produce the mixed animal feeds in a fixed rotation cycle in such a way that each type is produced exactly once during a cycle. The mixing machine is available 50 weeks a year and 80 hours a week. The stock costs amount to €200,= per tonne per year (regardless of the type of mixed animal feeding). The changeover costs are € 60,= per hour

What is the cost-optimal cycle time, while also meeting the expected demand?

**Exercise 12.3.3**

A company supplies a wide variety of end products. The flow of goods is as follows:

Supplier → Pre-processing → Bottleneck → Post-processing → Customer

In principle, a stock can be built up at any location. It should be noted that the products become very bulky after processing at the bottleneck. No bottlenecks in capacity are to be expected in pre- and post-processing. For the planning, a throughput time of one week is taken into account for each of these phases.

The expensive machine (the bottleneck) is tried to occupy 100%. There are a dozen commodities. The delivery time of these raw materials is two weeks. The raw materials have a high commonality (can be used in many products) and are relatively cheap.

During the pre-processing, about twenty semi-finished products are made from these raw materials. On the bottleneck, about a hundred products are made from these semi-finished products by adding pigments. Through post-processing, the product is made completely customer-specific according to the specific customer requirements.

Customers demand a lead time of four weeks.

Planning has determined that the bottleneck runs according to a fixed production schedule. The 100 products are divided into several families. Changeover times within the families are in the order of five minutes. Changing to another family is highly family-dependent but in the size of one to two hours. The production schedule provides for the finishing of the six families in a two-week cycle.

Some data for the six families are given in Table 12.6.

a Can purchasing take place on customer order or must a stock of raw materials be kept as a decoupling stock?

b To compensate for uncertainties in the decrease and the number of changeovers within a family, planning decided to place the decoupling stock just before the bottleneck. Do you agree with this?

c How many different products do you need to distinguish when making predictions for the build-up of the decoupling stock?

|  |  |  |  |
| --- | --- | --- | --- |
| Product family | Set up time (hours) | Production speed (pieces/hour) | Average demand (pieces/week) |
| A | 1 | 100 | 500 |
| B | 1 | 75 | 450 |
| C | 2 | 150 | 300 |
| D | 1 | 35 | 210 |
| E | 2 | 10 | 50 |
| F | 3 | 110 | 550 |

**Table 12.6** Data for the six families.

The company operates 40 hours a week.

d How does the order book for A evolve?

E What is the average waiting time of an order for product A on the bottleneck machine?

f What is the average throughput time for an order if the customer order decoupling point is in front of the bottleneck?

g What is the average utilization rate of the bottleneck?

h Why is it wise to choose the average utilization rate below 100%?

i What is the utilization rate if the production cycle is reduced to one week?

j What is the minimum cycle time if we want to keep a buffer of *5*% capacity utilization at the bottleneck?

**Exercise 12.3.4**

A company produces plastic parts for various household appliances and tools. Production takes place using injection molding machines. Production takes place under annual contracts; production is done to stock, and customers are supplied from stock. Due to efficiency considerations, each of the products is made on a fixed injection molding machine. So every injection molding machine has its "own" products. Table 12.7 shows the products that are made on one of the injection molding machines. For each product, the tact time (time needed to produce one unit), the changeover time from the machine to that product, and the changeover costs (order-independent) are given. The company works 50 weeks a year, 5 days a week and 16 hours a day. Maintenance takes place outside of operating hours.

|  |  |  |  |
| --- | --- | --- | --- |
| Product | Tacttime  (in minutes) | Setup time  (in minutes) | Setup costs  (in €) |
| 1  2  3  4  5 | 1  2  1  3  2 | 300  400  300  400  200 | 60  75  60  80  70 |

**Table 12.7** Various times and costs per product.

Table 12.8 shows the demand for products as laid down in the annual contracts. You can assume that the actual demand on an annual basis is uniformly divided between the indicated boundaries. The customers order their need for parts every week and expect immediate delivery from stock. The cost of stocking is € 1.00 per piece per year for each of the products.

a Determine the expected costs of stock keeping and changeovers per year, based on the minimum cycle time on the injection molding machine for the situation where the

|  |  |  |
| --- | --- | --- |
| Product | Lower bound demand per year | Upper bound demand per year |
| 1  2  3  4  5 | 60 000  20 000  30 000  8.000  4000 | 70 000  25 000  40 000  10 000  5000 |

**Table 12.8** Demand data by product.

products are produced in a pure rotation cycle and the company wants to be able to produce the agreed annual deliveries for all customers with 100% certainty.

b Would the costs of stockholding as calculated in question 1a.iIncrease, remain the same or decrease if it turned out afterward that the demand per product is equal to the lower limit? Argue your answer (you don't have to quantify it).

c Determine the cycle time of a pure rotation cycle where the sum of inventory costs and changeover costs is minimal, assuming an expected demand per product.

d Based on the cycle time determined in question c, could the sum of inventory costs and changeover costs be reduced even further by abandoning the requirement of a pure rotation cycle? Argue your answer (you don't need to quantify it).

**Exercise 12.3.5**

A factory mixes supplied leaves and pipeweed into well-known blends such as Tonlip and Wickpick. A total of 6 blends are distinguished. Table 12.9 shows some demand characteristics of the blends. For each blend, there are 3 forms of packaging, namely the tin box, the well-known spice bag, and the piping bag. Each packaging form always contains exactly 1 pound of blend per packaging unit. The spice bag is on average twice as popular as the pipe bag; the tin box is requested on average as often as the pipe bag. The coefficient of variation of the demand per week for each of the three forms of packaging is the same for all three forms. You may consider the demand per week for a certain blend in a certain packaging form as an independent draw from a normal distribution.

The packaged blends are made on one production line in the factory. In between the production of the blends, the line must be thoroughly cleaned, with the time required for cleaning strongly depending on the ingredients used and to be used. Table 12.10 shows the required cleaning times. In addition, the line must be changed if the packaging is changed; This always takes 10 minutes. If you change the blend and the packaging form, the required

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Melange: | 1 | 2 | 3 | 4 | 5 | 6 |
| Average demand | 20 000 | 18 000 | 16 000 | 14 000 | 10 000 | 6000 |
| Standard deviation demand | 5000 | 4500 | 4000 | 3500 | 2500 | 1500 |

**Table 12.9** Demand characteristics of blends (in kilos per week).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| to  from | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 0 | 30 | 20 | 30 | 25 | 15 |
| 2 | 25 | 0 | 30 | 40 | 15 | 30 |
| 3 | 15 | 40 | 0 | 30 | 30 | 30 |
| 4 | 25 | 20 | 15 | 0 | 30 | 30 |
| 5 | 40 | 30 | 25 | 15 | 0 | 30 |
| 6 | 30 | 15 | 25 | 25 | 30 | 0 |

**Table 12.10** Cleaning times required between blends (in minutes).

changeover time for packaging can easily be achieved within the required cleaning time.

The factory is in operation 4 days a week, 24 hours a day. The production speed of the line is the same for all blends in all packaging forms, namely 1000 kilos per hour.

The planner has indicated that production must be carried out following two guidelines:

1 In the order 1-2-3-4-5-6 with the order in packaging forms per blend: spice bag -pipe bag-tin box;

2 To ensure that capacity demand can be met in at least 93.75% of cycles, capacity should only be occupied up to 93.75% on average per cycle.

a Given these guidelines, what is then the minimum cycle time at which the average demand can still be met?

b What do you think of the minimum cycle time given guideline 1? Substantiate your answer quantitatively.

To answer the next two questions, assume a cycle time of two weeks (this is not necessarily the correct answer to questions a and b).

c What do you think of guideline 2 given the requirement that the demand for capacity must be met in at least 93.75% of the cycles? Substantiate your answer quantitatively.

**ANSWERS**

**Theory**

**Question 12.1.1**

Cycle time is the time between two successive production moments of a certain product.

**Question 12.1.2**

To have as little setup time as possible (maximizes the time for production).

**Question 12.1.3**

This leads to as low as possible inventory costs.

**Question 12.1.4**

Advantage: we know how much to produce

Disadvantage: less flexibility

**Question 12.1.5**

In determining the optimal cycle time only the capacity is considered; costs are not taken into account which might lead to too many set-ups.

**Question 12.1.6**

That we have stable cycle times. Given the fact that in inventory control systems the costs are not very sensible for deviations in the optimal bath size, this leads to the use of the same, fixed cycle time for all products.

**Question 12.1.7**

Aggregate inventory: Sum over all items of batch size inventories, safety stocks (and capacity inventories).

Inventory per product: batch size inventory + safety stock

**Question 12.1.8**

To absorb (small) fluctuations in demand.

**Answers**

**Basic exercises**

**Exercise 12.2.1**

Average batch stock size = 13.5

**Exercise 12.2.2**

*C\* =* 219 days

**Exercise 12.2.3**

a 10 days

b In total 4958 pieces per cycle.

**Exercise 12.2.4**

a Minimal cycle time: 11.75/2.68 = 4.38 days.

b Cost-optimal cycle time: 10 days (= max(Copt,Cmin) )

**Exercise 12.2.5**

a Cycle in which all products occur exactly once in a fixed order

b Optimal cycle time = max(Cost-C, Capacity-C)

Cost-C minimization takes all relevant costs (inventory costs and changeover costs) and minimizes them.

Capacity-C checks whether everything fits within the available capacity.

Because it is a rotation cycle, it is possible to plan in detail.

c The optimal pure rotation cycle = 631 hours.

d - Easier scheduling of maintenance teams through predictable changeover times

* More stable work pattern and therefore better execution of tasks
* Fixed sequence and therefore stronger learning curve during changeovers

**Answers**

**Complex exercises**

**Exercise 12.3.1**

a Production schedule: 1-2-3-4-5-6-7-8-9- back to 1. (also good: 1-6-2-7-3-8-4-9-5-1- etc.).

Cmin = 9/9 = 1 week.

Batch size per product is equal to the average demand per week (see Table 12.4).

b See Table 12.11.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| color | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Safety stock (tonnes/ color/packaging) | 1.65 | 1.48 | 1.23 | 0.99 | 0.82 | 0.74 | 0.41 | 0.25 | 0.16 |

**Table 12.11** The required safety stock for each of the items.

c The total average stock is: 61.5 tons.

**Exercise 12.3.2**

The optimal cycle time (while also meeting expected demand) is 4 weeks.

**Exercise 12.3.3**

a Stock is needed.

b Yes.

c Less than 100. probably only 6!

d Rises in the non-production period and decreases very rapidly in the production period.

e It will take an average of one week before a product can be produced (maximum 2 weeks).

f The average throughput time is 65 hours.

g The utilization is 85%.

h Because otherwise there is no longer any slack for irregularities.

i 97.5 %

j Cmin = 1.11 weeks.

**Exercise 12.3.4**

a The costs of changeovers per year are €8625,=.

The costs of stock-keeping per year are (with C=1/25 years):

b If the actual demand is lower than the upper bound, there will be a higher-than-expected inventory of each product at the start of a new production. The inventory costs are therefore higher.

c The rotation cycle time at which the cost of holding inventory and changeover is minimal is equal to:  *=* 4 weeks

d It is certainly lucrative to let go of the pure rotation cycle.

**Exercise 12.3.5**

a Cmin = 5/6 week

b The sequence 1-6-2-5-4-3 gives a cleaning time of 6×15 (min.). This reduces the changeover time per cycle to 3.5 (h.). This makes Cmin = 3.5/6 weeks, which is a lot better.

c (C = 2 weeks!)

For reliability of 93.75% (normal distribution), a k-value of 1.55425 applies (based on interpolation of the table in Appendix 6.A in the book). In other words, the reserve capacity per cycle should be 19.89 (h.). That is 10.36% of the capacity per cycle.

The guideline should be: the capacity may only be occupied for 89.64% (on average).

**13 Mass Assembly Production**

**Note:** In the book and in the exercises we use the words work center and (work) station. These are interchangeable and mean the same: a place with one or more (similar) resources to perform a task, operation, or activity (the latter three are also interchangeable).

There is a small typo in the book (1st edition) on page 203.:

1.45 \* 1.98 should be 1.65 \* 1.98.

In designing flow production (or line assembly) systems, efficiency often plays an important role. Efficiency is defined as the ratio between expected offers and actual offers, where offers can be time, money, etc. (see for instance The Delft Systems Approach [2010] by Veeke, Otjes, and Lodewijks).

For a flow line, the expected offers are determined by the processing times of the tasks, and the actual offers are determined by the number of stations and the tact times. In formula:

Efficiency of a flow line =

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *Takt time*

- *Throughput time*

- *Processing time*

- *Lead time*

- *Workstation*

*- Buffer*

- *Line balancing*

- *Precedence relation resp. precedence restriction*

- *Precedence diagram; precedence graph*

*- Blocking*

*- Mixed-model production*

*- Redundancy*

- *Station efficiency*

- *Line efficiency*

*- Cross training*

*- Cherry picking*

*- Skill chaining*

*- Bucket brigade*

*- Factory flow analysis*

*- Pure flow production*

*-- Multi-model production*

*-- Starving*

##### **Theory**

**Question 13.1.1**

Why is there little or no waiting time in pure flow production?

**Question 13.1.2**

What is meant by tact time within flow production?

a The time between the production of two consecutive products of the same type.

b The delivery interval.

c The total processing time of a single product.

d The average processing time of a product per station.

e The minimum residence time of a product in a production system.

**Question 13.1.3**

What obstacles cause a deviation from the concept of pure flow production?

**Question 13.1.4**

Name two methods to absorb interference/disturbances in a line.

**Question 13.1.5**

Why will a system where three lines use the same machine require a buffer before and after the machine?

**Question 13.1.6**

What is the difference between 'starving' and 'blocking' of a line?

**Question 13.1.7**

Name five reasons why buffers may be desirable in flow production.

**Question 13.1.8**

How can the models for two-station lines be used as an approximation for lines with more than 2 stations?

**Basic Exercises**

**Exercise 13.2.1**

A working day has 8 working hours. The demand for products from a production line is 3200 per day. What is the takt time for that line?

**Exercise 13.2.2**

A line consists of 4 workstations with the following operation times:

Station 1 35 sec.

Station 2 40 sec.

Station 3 28 sec.

Station 4 38 sec.

a Determine the average cycle time for these 4 stations.

b Determine the maximum cycle time for this line.

c Determine the throughput time of a product going through this line assuming the speed of the line cycle time.

d Determine the throughput time of a product going through this line assuming the speed of the takt time.

e Given a tact time of 45 sec., determine the efficiency of station 3.

f Given a tact time of 45 sec., determine the efficiency of the line.

**Exercise 13.2.3**

Draw the precedence graph for the situation given in Table 13.1.

|  |  |
| --- | --- |
| Operation | Predecessor |
| 1 | - |
| 2 | 1 |
| 3 | 1 |
| 4 | 2, 3 |

**Table 13.1** Predecessors of the 4 operations.

**Exercise 13.2.4**

To produce X (in several steps) in total 70 min. of operation time is needed. The takt time for the department producing the part is 120 sec. How many workstations are required at least in this department to meet the takt time?

**Exercise 13.2.5**

The activities given in Table 13.2 are carried out on an assembly line:

|  |  |  |
| --- | --- | --- |
| Task | Operation Time | Preceded by |
|  | (sec/product) |  |
| A | 20 | - |
| B | 15 | - |
| C | 8 | A |
| D | 15 | B, C |
| E | 25 | C |
| F | 15 | D, E |
| G | 15 | F |

**Table 13.2** Operation times and the predecessors of the different tasks.

The number of hours available per day is 7. The demand for products equals 840 per day.

a Determine the takt time

b What is the minimum number of workstations required for the line to meet the demand?

c Draw the precedence diagram for the tasks.

d Balance the line taking into account the precedence relations, by using the *most succeeding operations* rule; if that number would be equal use the *longest operation time* rule as the second rule.

**Exercise 13.2.6**

De candy factory Brosser produces all types of chocolate energy bars. The production process for one of the delicious energy bars follows the following steps:

- melted chocolate is poured into molds;

- the molds with chocolate are transported to a fill station where the additional content ("fillings") is added;

- then the bars are shaped in their final shape, decorated, and covered with an attractive coating;

- finally, the bars are wrapped individually and put in boxes.

This production line runs 5 days/week, 8 hrs/day. Every week the demand for these bars is 3000 boxes.

The production and packing of the bars for one box consists of the 13 activities given in Table 13.3.

|  |  |  |
| --- | --- | --- |
| Activity | Operation Time [sec] | Preceded by |
| 1 | 6 | - |
| 2 | 8 | 1 |
| 3 | 9 | 2 |
| 4 | 11 | 2 |
| 5 | 12 | 2 |
| 6 | 14 | 3, 4, 5 |
| 7 | 9 | 1 |
| 8 | 5 | 7 |
| 9 | 12 | 8 |
| 10 | 8 | 9 |
| 11 | 9 | 6 |
| 12 | 12 | 10. 11 |
| 13 | 9 | 12 |

**Table 13.3** Operation times and the predecessors of the different tasks.

a Draw the precedence diagram.

b What is the takt time?

c Combine activities on a workstation using the longest operation time rule, taking into account the precedence relations.

d What is the efficiency of the line?

**Complex Exercises**

**Exercise 13.3.1**

For an assembly line, the required output per day is 360 products. The line runs for 450 minutes per day. Table 13.4 gives information on the time per task and the successor relations between the tasks for the product to be assembled, i.e. the last column of the table shows which tasks can only be done after the task concerned is done.

|  |  |  |
| --- | --- | --- |
| Task | Operation Time (sec) | Preceding |
| A | 30 | B, C |
| B | 35 | D |
| C | 30 | E, F |
| D | 35 | H |
| E | 15 | G |
| F | 65 | G |
| G | 40 | H |
| H | 25 | - |

**Table 13.4** Operation times and the predecessors of the different tasks.

a Balance the line using the *most-succeeding-tasks*-rule; is that number equal use the *longest-operation-time-*rule as the second rule.

b Is it possible to increase the efficiency of this line even further? If so, show how. If not, explain why not.

**Exercise 13.3.2**

Factory De Trekker produces different types of trailers. Producing a trailer requires ten tasks to be performed. These ten tasks are shown in Table 13.5 (listed from the smallest task time to the longest task time).

The production line for these trailers runs 5 days/week. Each day two shifts work on the line; each shift lasts for 9 hours. The demand per working day is 60 trailers.

a Balance the line taking into account the precedence relations and using the longest-operation-time rule.

b Determine the efficiency of workstation 2.

|  |  |  |
| --- | --- | --- |
| (Task)Time (min) | Task | Preceded by |
| 4 | 2 | - |
| 4 | 5 | 3, 4 |
| 4 | 9 | 6, 7 |
| 7 | 1 | - |
| 8 | 3 | - |
| 10 | 8 | 3 |
| 12 | 4 | 1, 2 |
| 14 | 7 | 5 |
| 14 | 10 | 8, 9 |
| 18 | 6 | 4 |

**Table 13.5** Task times and the predecessor of the different tasks.

c Assume the demand rises to 84 trailers per working day. What are the consequences for the theoretical minimum number of workstations required? (Show the calculations).

d Assume that demand remains at 60 trailers a day, but the number of hours per shift is reduced to 8 hrs. What are the consequences of this change for the production line, assuming again the longest-operation-time rule? (Show the calculations).

**Exercise 13.3.3**

The production of product XYZ requires ten operation steps. Table 13.6 shows these steps and the operation time required per step.

|  |  |
| --- | --- |
| Operation Step | Operation time (sec) |
| A | 25 |
| B | 12 |
| C | 34 |
| D | 15 |
| E | 18 |
| F | 22 |
| G | 78 |
| H | 16 |
| I | 20 |
| J | 12 |

**Table 13.6** Operation times of the different operation steps.

Some of these operation steps have a precedence relation, i.e. some steps can only be started after one or more other steps have been finished. Table 13.7 shows these precedence relations between the operation steps in terms of which tasks are required to be done before some other tasks can be started.

|  |  |
| --- | --- |
| Operation Step | Preceding |
| A | D, E |
| B | F |
| C | E |
| D | F, H |
| E | H, J |
| F | G |
| G | I |
| H | I |
| I | J |
| J | - |

**Table 13.7** The predecessors of the different operation steps.

The production department works 8 hrs/day and is supposed to produce 720 products per day.

a Taking into account the takt time, one of the operation steps will give issues when determining workstations. Which operation step would that be and how could the issue be solved without changing the operation step itself?

b What is the efficiency of the line if the line is balanced using the longest operation time rule while applying the solution for the issue mentioned in a.?

**Exercise 13.3.4**

Joh. Hengelo produces securities like shares and stamps. In the packaging production unit, the printed products are packed in sales- and transport packaging. Each day of 12 hours, this department gets on average 324 orders. The number of orders follows a Poisson distribution.

Recently the company has invested in an automated packaging line. This line, part of the sub-unitAutomatic Packaging, consists of three stations (resp. 1, 2, and 3) on which the orders subsequently are processed. Each station *i* (*i* = 1, 2, 3) has one machine preceded by a buffer that can contain all materials for *Zi* orders at the same time. As soon as an order is started, all the material required for that order is taken out of the buffer and the material for a new order (if present) can be stocked in the buffer. Table 13.8 gives the average processing times per order per machine. Since the orders vary in size, the processing times follow (approximately) a negative exponential distribution. Ideally, each order is upon arrival immediately released to the sub-unit Automatic Packaging, and the required materials for this order are placed in the buffer of station 1. However, if upon release the buffer of station 1 is full, then the order is released to the sub-unit Hand Packaging.

|  |  |  |  |
| --- | --- | --- | --- |
| Station: | 1 | 2 | 3 |
| Processing time: | 2.0 | 2.2 | 1.8 |

**Table 13.8**  Average processing time per station (in minutes).

a What is given the order arrival pattern the average number of orders that will be processed per hour by the sub-unit Automatic Packaging, given that *Z1* = 4 and *Z2* = *Z3* = ∞?

After some time, it turns out that the machines of stations 2 and 3 regularly break down. Detailed analysis shows that the machine at station 2 on average every 60 minutes fails, independent of whether it is used or not. A breakdown takes on average (repair included) 10 minutes.

The machine at station 3 fails on average every 100 minutes (also independent of whether it is used or not) and a breakdown on average takes 2 minutes (repair included).

bIs the throughput as calculated in question a. still achievable given this breakdown behavior?

Give a quantitative answer.

c Is it necessary to change to order release rule for the sub-unit Automatic Packaging?

Those orders that do not go through the sub-unit Automatic Packaging line are packed in the "Manual Packaging" sub-unit. This sub-unit consists of a packaging line with four stations, with each station manned by one person. An order must go through all stations in the order 1-2-3-4. Of all orders supplied, six orders are always taken together on a FIFO basis. This group of six orders is first completed in full by all four stations of the line before the first station starts with the first order of the next group of six. The six orders are ordered in such a

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Order: | I | II | III | IV | V | VI |
| Station 1: | 2 | 3 | 1 | 5 | 6 | 2 |
| Station 2: | 2 | 2 | 2 | 1 | 2 | 3 |
| Station 3: | 4 | 2 | 2 | 1 | 3 | 4 |
| Station 4: | 1 | 2 | 4 | 4 | 3 | 3 |

**Table 13.9** A representative group of orders with occupancy time per station (in min.).

way that the capacity of the line is used as well as possible. Table 13.9 gives a representative example of such a group of six orders.

d If you can assume that the utilization rate of the line to be achieved can be deduced from the data of the representative group, given the method outlined, what is then the maximum capacity of the line (expressed in the number of orders per hour)?

**Exercise 13.3.5**

An assembly line in the computer industry contains four workstations. A buffer has been placed between each of the four stations. The first buffer and the third buffer (i.e. for the second and fourth workstations) are placed in the same cleanroom and are limited in size because the costs of space in the cleanroom are high. The second buffer (i.e. for the third workstation) has no cleanroom requirements. The buffer capacity of this second buffer is virtually unlimited in practical terms.

The line is a mixed model line. Especially at the first two stations, this leads to quite a variation in processing times between the different products, although the exact processing time is known in advance for each product.

The average processing time at the first station is 1 minute per product. The first two stations are fully balanced. Both processing times are distributed exponentially.

At the last two stations, there is no variation in processing times between the products. If the machines are operating at these stations, the processes are carried out at a constant speed. The third station produces 1 product every minute, while the fourth station is slightly slower and only produces 50 pieces per hour. However, the third station is subject to malfunctions. If the machine is running, it will break down after an average of 2 hours. The repair usually doesn't take very long (about 24 minutes on average), but just like the uptime, the downtime is also exponentially distributed.

a Explain what a mixed model line is, and why this can lead to variations in processing times, given that the processing times for each type of product are deterministic.

b How large should the first buffer be so that an average of 50 computers per hour can be produced on the first part of the line (up to the second buffer)?

c How big should the third buffer be so that the net line speed of the entire line is at least 45 computers per hour?

d There is room in the company for an investment that can lead to an extra buffer space OR a reduction of the average downtime by 10%. Calculate which choice you make from both options so that the net line speed is increased the most. For this question, assume that the current capacity is equal to the sum of the number of buffer places calculated under b and c.

**Exercise 13.3.6**

In one of the assembly departments of LAMS, producer of Wafer Steppers, fans are produced. This requires 6 actions A, B, C, D, E, and F in exactly this order. The company combines several actions at a so-called workplace with one employee at each workplace. Products cannot be stored between the workstations and have to wait until they can move to the next workstation (i.e. when the latter has finished its operations) when all actions have been carried out at a certain workstation. Action A lasts 1 hour, B 0.5 hours, C 0.5 hours, D 1 hour, E 0.25 hours, and F 0.5 hours. The company has a choice of:

1 To perform all actions separately; so 6 workplaces;

2 To combine A, B, and C and combine D, E, and F; so 2 workplaces.

a Determine the throughput time and takt time for each of the two configurations if you can assume that the machining times are constant.

b What else plays an important role in the choice of one of the two configurations besides takt time and throughput time?

Suppose the company opts for the configuration with two workstations. After some time, it turns out that the processing times are not constant, but more or less follow a negative-exponential distribution. It turns out that on average, two orders for a fan arrive every 1.5 hours; The interarrival time also appears to be negatively and exponentially distributed. LAMS can outsource an order for a fan without any significant time delay, but this costs €10,= per fan. It is decided to have a maximum of 5 orders waiting for the 1st workplace. If there are already 5 orders waiting for a new order when it arrives, it will be outsourced.

c What percentage of orders should be outsourced?

In one of the other departments, the so-called foundation is produced. To do this, several actions must be carried out in a fixed order at several workplaces. Each workstation has one machine. This department expects about 120 orders in the coming year. The department also carries out work for other companies. The orders are expected to come in very randomly following a Poisson arrival process. Processing times on the first machine are highly dependent on the product design and are expected to be distributed negatively exponentially with an average of 19 hours. The department now works 50 weeks a year, 6 days a week, 8 hours a day. For the first workplace in the department, there is a limited storage space where the materials needed for one order can be stored. There are no restrictions for the other machines in the department. If there is no room at this machine at the time an order comes in, the order will be outsourced for the sake of delivery performance. However, this outsourcing costs € 400,= per order, mainly due to the transport costs. It turns out that the storage space can also be expanded, which requires an additional investment of € 40 000,= per storage place of the materials for one order. The payback period for any expansion of the storage capacity must be one year.

d What is the optimal number of additional storage locations from a cost point of view and is this investment profitable?

**ANSWERS**

**Theory**

**Question 13.1.1**

If we have pure flow production, the interarrival times are constant (at each work center) and the service times are also constant. Therefore we have no waiting time phenomenon.

**Question 13.1.2**

The delivery interval.

**Question 13.1.3**

Different processing times.

Variable processing times.

Different products.

Disturbances at the work centers.

No availability of efficient technology.

**Question 13.1.4**

Use of buffers.

Having redundant machines.

**Question 13.1.5**

Because the arrival (at the single machine) of the products of the 3 lines generally are not synchronized.

**Question 13.1.6**

Starving: The work center becomes idle due to a lack of products.

Blocking: The product can’t leave the work center, and therefore the work center has to stop producing.

**Question 13.1.7**

Reasons for buffering in a flow line:

- preventing starving/blocking in case of short breakdowns,

- preventing starving/blocking in case of set-up times,

- preventing starving/blocking in case of variation in processing times (due to uncertainty in processes or to change in product type),

- preventing starving/blocking before or after a station with multiple servers,

- allowing for routing variation.

**Question 13.1.8**

By approximating this line by a set of two-machine lines (page 218).

**Answers**

**Basic exercises**

**Exercise 13.2.1**

9 seconds

**Exercise 13.2.2**

a 62.2 %

b 78.3 %

**Exercise 13.2.3**

See Figure 13.1.

1

2

4

3

**Figure 13.** The precedence graph.

**Exercise 13.2.4**

35

**Exercise 13.2.5**

a 30 seconds

b4

c See Figure 13.2.

A

B

E

C

F

D

G

**Figure 13.2** The precedence diagram.

d Station 1: A and C

Station 2: E

Station 3: B and D

Station 4: F and G

**Exercise 13.2.6**

a See Figure 13.3.

A black background with yellow squares

AI-generated content may be incorrect.

**Figure 13.3** The precedence diagram.

b 48 seconds

c Station 1: 7, 1, 2, 5, 4

Station 2: 3, 6, 11, 8

Station 3: 9, 10, 12, 13

d 86.11 %

**Answers**

**Complex exercises**

**Exercise 13.3.1**

a work center (station) 1: tasks a, c, and e

work center (station) 2: task f

work center (station) 3: tasks b, and g

work center (station) 4: tasks d, and h

b No. We use 4 work centers and the minimum number of work centers required is 4.

**Exercise 13.3.2**

a

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Work center | Candidates | Assigned | Cumulative processing time | Idle time |
| 1 | 1, 2 and 3 | 3 | 10 | 8 |
|  | 1 and 2 | 1 | 17 | 3 |
| 2 | 2 and 8 | 8 | 10 | 8 |
|  | 2 | 2 | 14 | 4 |
| 3 | 4 | 4 | 12 | 6 |
| 4 | 5 and 6 | 6 | 18 | 0 |
| 5 | 5 and 7 | 7 | 14 | 4 |
|  | 5 | 5 | 18 | 0 |
| 6 | 9 | 9 | 4 | 14 |
|  | 10 | 10 | 18 | 0 |

b 0.778

c 8

d 2 stations for the work center for operation 4 are now required.

**Exercise 13.3.3**

a Operationstep G. Two stations for task G (in this way it seems that the processing time at this work center is 39 seconds).

B The efficiency of the line is

**Exercise 13.3.4**

aλ' = 23.6 per hour.

b1 No.

b2 Yes.

c 6 orders can be processed in 25 minutes or 14.4 per hour.

**Exercise 13.3.5**

a p 211

b 4.

c 14.

d Reducing downtime.

**Exercise 13.3.6**

a Configuration1: 6

Configuration2: 4

b Number of operators

c 1.265 orders.

d 1 Additional storage location.

Not profitable.

**14 Small Series Production (Job Shop)**

Notes: The variance in the application in the book should be 5197.28 instead of 6196.93; the coefficient of variation hardly changes.

The Pollaczek formula can not always be used to calculate the average waiting time. It certainly can be applied in situations where:

* The number of arrivals per period is (very) irregular (following a Poisson distribution).
* The service times strongly vary (negatively exponentially distributed).
* Machines are available without disturbances for the (daily) operating time.
* An operation that has been started is not interrupted to start another operation (non pre-emptive).

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

- *Utilization rate*

*- Service time*

*- Bottleneck*

*- Due date*

*- Completion (waiting) time*

*- Throughput time*

*- Job shop*

*- Work-in-process*

*- Transition matrix*

*- Priority rule*

*- Waiting time*

*- Operation due date*

*- External due date*

*- Functional layout*

*- Lead time*

*- Delivery reliability*

*- Internal due date*

*- Tardiness*

*- Lateness*

*- Due date determination rule*

*- Customer-dependent lead time*

*- Order-dependent lead time*

*- Constant lead time*

*- Workload-dependent lead time*

###### **Theory**

**Question 14.1.1**

What structural measures can be taken to reduce the average throughput time?

**Question 14.1.2**

Where in Pollaczek’s formula are changeover times taken into account?

**Question 14.1.3**

Where in Pollaczek's formula is the batch size of an order taken into account?

**Question 14.1.4**

What control measures are available to us to influence the throughput time of orders?

**Question 14.1.5**

For each of the following statements, please indicate whether they are true or not and why:

a Immediate transfer of operators in the event of a vacancy of a workstation gives a large reduction in both the average and variance of the throughput time.

b Delay in the transfer of operators after the end of an operation has only a minor effect on the gain to be achieved in throughput time.

c In any environment, the use of multi-skilled operators makes sense.

d Only with a large number of alternative machines for each operation, a significant throughput time reduction is possible.

e The use of SPT makes more sense in an environment without alternative machines than in an environment with alternative machines.

**Question 14.1.6**

A woodworking department consists of four workstations, namely: drilling (B), sanding (S), sawing (Z), and painting (L). Work orders A to E are all suborders and are awaiting the release of capacity. Suborders A, C, and D belong to order I, which was released on 1 October. Suborders B and E belong to order II, which was released on October 3.

The revolving routing of the suborders across the various workstations is as follows:

A and E: B – S – Z

B and C: S – Z

D : L

Assess the correctness of the following statements.

a When priority NUB is applied, sub-order A has priority over sub-order E at workstation B.

b When applying the priority rule FASFS, suborder B takes precedence over suborder C at workstation S.

**Question 14.1.7**

Explain the findings (in Appendix 14.B in the textbook) on the differences in order throughput times between fixed and dynamic batch sizes for production runs.

**Question 14.1.8**

What is the difference between delivery time (due date), throughput time, and lead time?

**Question 14.1.9**

In addition to an internal delivery date, an external delivery date is also used. What is the difference between these two types of delivery dates? Why is this distinction important?

**Question 14.1.10**

When do due date-oriented priority rules affect the average throughput time?

Explain why due date-oriented priority rules in general will affect the standard deviation of the lateness.

**Question 14.1.11**

Indicate the formal rule that applies to the lead time determination rule used according to:

a TWK

b NOP

**Question 14.1.12**

Explain why order-dependent lead time determination rules in general have a reducing effect on the standard deviation of the lateness.

**Question 14.1.13**

With workload control, orders are held back for order release. This has a detrimental effect on the average order throughput time. What positive consequences of this deliberate blocking of orders do you see when you consider the decomposition of the logistical control problem into goods flow (decoupling point) control and production unit control?

**Question 14.1.14**

What are the two ways of controlling the workload?

**Question 14.1.15**

Explain why, if the efficiency of production depends on the amount of work in progress, a work order release function appears to be a successful control tool.

**Basic Exercises**

**Exercise 14.2.1**

A work center consists of one machine. The work orders for this workstation can be classified into three classes, namely inventory orders, customer orders, and rush orders. When choosing an order from the queue at the workplace, one always chooses the rush orders first, then the customer orders, and finally the stock orders. When choosing more orders from the same category, the FIFO rule is used. The order processing times are distributed negatively exponentially with an average of three hours. The average inter-arrival time of inventory orders is twelve hours, while on average a customer order arrives every ten hours and a rush order every eight hours. The inter-arrival times of orders at the workplace follow approximately a negative-exponential distribution. The machine can be used five days a week and eight hours a day.

What is the average throughput time per type of order?

**Exercise 14.2.2**

The car service company 'Wheel-Fit' wants to attract a new mechanic for changing tires. The company has a choice of two candidates. Candidate 1 still has to be trained and can help an average of two customers per hour; Candidate 2 is experienced and can help an average of three customers per hour. An average of two customers arrive per hour to have their tires changed. The inter-arrival times and the service times may be considered to be negative- exponentially distributed.

a How much is the average waiting time of a customer if one decides to hire candidate 2, assuming that customers are served in order of arrival?

b Suppose candidate 1 is much cheaper than candidate 2. What would you advise the company?

**Exercise 14.2.3**

A mail-order company specializes in sending 'Bonsai trees'. This is a difficult job and they only have one employee who can do this well. This employee can take care of 20 orders per week (a week has five working days of eight hours). Because 'Bonsai trees' are quite different from each other, they also require different service times. Research has shown that the order service time is normally divided by an average of 15 minutes. Every week, 18 requests for 'Bonsai trees' are received, following a negative-exponential distribution.

What is the average throughput time of an order, assuming it is handled in a FIFO sequence?

**Exercise 14.2.4**

Electrical components that have to be tested, arrive in an electronic test department according to a Poisson process. Four all-round testers work in the test department. Research has shown that the utilization rate is 95%. Research also shows that the test times per application are divided negatively exponentially. The average turnaround time for a test application is 4.6 hours.

What is the average service time per test request?

**Exercise 14.2.5**

Peentit specializes in printing on textile products. The product package with operations on the dyeing machine can be divided into several product groups based on color. All products within a group use the same machine setting. A changeover time is required between the production of products from different product groups. For capacity and economic reasons, work orders that arrive at the machine are bundled into so-called production runs in such a way that only orders are produced within a run with products from the same product group. A production run for product group *i* always consists of exactly five orders. The average frequency of arrival of orders from Group *i* is one per two days. The interarrival times of orders from group *i* at the machine can be calculated as independent draws from a probability distribution.

What is the average completion waiting time of a Group *i order*?

**Exercise 14.2.6**

The throughput time by a certain production department appears to be (approximately) normally distributed with an average of 25 days and a standard deviation of 6 days. The production management wishes to keep the planning of work orders simple and therefore to work with only one lead time to be issued.

a What lead time should be used to achieve an average lateness of 0?

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Order | Due date | Start  time | Service times at the already visited work centers | Service time at the current work center | Service times at the work centers still to be visited |
| A | 250 | 20 | 5 – 12 – 8 - 10 | 15 |  |
| B | 100 | 50 | 10 | 5 | 10 – 10 - 8 - 12 - 15 |
| C | 120 | 0 | 8 – 12 - 5 | 8 | 4 |
| D | 300 | 100 |  | 10 | 5 -10 - 5 |

**Table 14.1** Orders at a workstation at time = 100 and their characteristics.

b What percentage of orders are late to the lead time determined in question a?

c What lead time should be used to ensure that 95% of orders will arrive on time?

**Exercise 14.2.7**

Consider the queue of orders at a workstation at time t = 100 as given in Table 14.1.

Determine the order in which the orders are processed if the priority rule is:

a SPT

b DD (Due Date)

c RS (Remaining Slack)

d RSO (Remaining Slack per Operation)

e ODD (Operation Due Date), where you can assume that when determining the operation due dates, at release the slack is evenly distributed over the operations.

**Exercise 14.2.8**

Comment briefly on each of the statements:

a To minimize the standard deviation of the lateness, one should use long internal lead times (i.e. lead times with a lot of slack) and a due date-oriented priority rule.

b Workload-dependent lead times are especially interesting in environments with high utilization rates.

c If lead times for an order *i* are issued according to the following rule:



whereby:

*α* constant

*r* total number of work centers in the department

*pgem* average service time per work center (across all operations, orders, and work centers)

*pi,j*  service time of order *i* at work center *j*

then applying a priority rule that takes into account the remaining slack of an order leads to a decrease in the average throughput time compared to the priority rule 'FIFO'.

**Complex Exercises**

**Exercise 14.3.1**

A certain company produces a large number of products. The products can be divided into several Main Products. A characteristic of a Main Product is that the products that fall within the same Main Product category all have the same routing and the same average service times at the various work centers. The production has all the characteristics of a job shop.

One of the work centers has a high utilization rate and a rather considerable changeover time between the Main Products. Therefore, they work with production runs of ten orders, i.e. they wait to change to another Main Product until there are ten orders at that work center for products that fall within that Main Product.

a What is the average completion (-waiting) time for a work order under this production run policy, assuming an arrival intensity of *λ*?

At work center three, there are three machines, each with its permanent operator. For all products at this work center, the processing time per piece is distributed negatively exponentially with an average of seven minutes. There are three Main Products that have to be processed at this work center and all products within these Main Products have a fixed batch size of 50 pieces from the time of order release (with only identical products per order). Orders are handled in random order at the work center. The machines have a fixed set-up time of sixty minutes. After a series has been processed on a machine, some manual actions must be carried out by the operator before the series can continue; The machine remains idle during these operations. The manual operations take an average of thirty minutes with a standard deviation of ten minutes (independent of the order characteristics). The arrival process of each of the three Main Products can be seen as a Poisson process. The frequency of arrival of the Main Products at this workstation is shown in Table 14.2. The company works 8 hours a day, 5 days a week, and 45 weeks a year.

|  |  |  |  |
| --- | --- | --- | --- |
| Main Product | I | II | III |
| Arrivals per day  (average) | 1.5 | 0.5 | 1.2 |

**Table 14.2** The average number of orders arrivals per day at work center three for each of the three main products.

b What is the average number of orders at work center three (on or in front of the machines)?

Suppose the customers place orders for combinations of products and expect that the ordered combination is delivered as a whole. Management is therefore considering using SPT instead of FIFO.

c Indicate the performance of this priority rule in the case of small combinations (i.e. few different products per combination order) and in the case of large combinations (many different products per combination order).

**Exercise 14.3.2**

A job shop manufacturing company makes parts for manufacturers of capital goods. The job shop consists of 5 work centers: A, B, C, D, and E. Each work center consists of several identical machines and production employees who use the machines to carry out operations for the production of the parts. The job shop works 8 hours a day, 5 days a week, 50 weeks a year.

Table 14.3 shows the number of identical machines per work center, and the mean and standard deviation of the service time per order. The production orders are placed by the customers, with whom a standard lead time of 8 weeks has been agreed. When planning their production processes, these customers therefore take into account a parts lead time of 8 weeks.

|  |  |  |  |
| --- | --- | --- | --- |
| Work center | Number of machines | Average service time  per order (in hours) | The standard deviation of the service time per order (in hours) |
| A | 2 | 8 | 8 |
| B | 1 | 4 | 3 |
| C | 3 | 13 | 10 |
| D | 2 | 7 | 4 |
| E | 1 | 4 | 4 |

**Table 14.3** Characteristics of several workplaces.

The interarrival time of production orders is distributed negatively exponentially with an average of 4.5 hours. Each of the 5 work centers has an equal chance that an upcoming production order will need to be processed there first at that work center. The number of operations and the routing of the production orders are such that an order that has been processed at a certain work center will go to one of the other work centers with an 80% chance and will be finished with a 20% chance, where each of the other work centers or the exit is as likely as being the next destination. The orders are processed at the work centers in the order First Come, First Served. You can assume that the interarrival time of production orders at each of the work centers is distributed negatively exponentially.

a Determine the average throughput time for each of the five work centers.

b Determine the expected throughput time of any order with two operations.

c Given the standard deviations of throughput times per work center as given in Table 14.4, determine the probability that any order with routing {B, C, A, D, E} will be delivered on time. You can assume that for orders with 5 operations, the total throughput time can be

considered as normally distributed.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Work center: | A | B | C | D | E |
| std.dev. throughput time (in hours) | 30 | 25 | 80 | 10 | 36 |

**Table 14.4** Standard deviations of the throughput times.

d Will the chance of on-time delivery increase if the priority rule SPT is used instead of FCFS? Argue your answer.

e Will the average lateness decrease if the priority rule EDD is used instead of FCFS? Argue your answer.

**Exercise 14.3.3**

VLO-SJOP is a producer of a wide range of metal goods. In terms of production, the range can be divided into four streams:

- stream A, which enters work center I, goes to work center II, then goes to work center III, and then leaves the production floor;

- stream B, which enters work center II, goes to work center III, and then leaves the production floor;

- stream C, which enters work center II, goes to work center IV, and then leaves the production floor;

- stream D, which enters work center III, then goes to work center IV, and then leaves the production floor.

There is one machine at work center 1 and the processing time there is constant and equal to 10 minutes per product. There is also one machine at work center II and the processing times per product are approximately normally distributed; the standard deviation in the operation time is 1/3 of the average operation time. The average processing time is 4 minutes for products of flow A, 3 minutes for products of flow B, and 1.5 minutes for products of flow C. At work center III there are three identical machines and the processing times are constant and equal to 4 minutes per product. At this work center, the machine has to be reset every time a new series is put into operation. This set-up time is distributed negatively exponentially with an average of 10 minutes. At work center IV there is one machine with a constant processing time of 0.5 minutes per product.

Customer orders are always orders for 20 (identical) products. Therefore, within each flow, orders of 20 pieces are used. It turns out that for flow A, an order comes in exactly after 4 hours every time. For flow B, an average of 3 orders per day come in, for flow C, an average of 4 orders come in per day and for flow D, an average of 10 orders come in per day. You can assume that an approximate Poisson distribution applies to the mix of arrivals at work centers II and III.

At each work center, orders are processed in order of arrival. VLO-SJOP works 8 hours a day, five days a week.

a One of the logistics employees suggested the idea of working at work center II with two classes: a class K1 that contains orders from flow A and a class K2 that contains orders from flows B and C. Orders from class K1 will be given priority over orders from class K2. Within a class, orders are processed in order of arrival. Does this affect the average turnaround time? Please explain your answer (you do not need to quantify it).

b For the time being, it is decided to continue without division into classes.

What is the average throughput time of orders in flow A? Substantiate your answer.

c Suppose the average throughput time is equal to 4 days at work center I, 15 days at II, 10 days at III, and 6 days at IV. If one wants to use the TWK lead time determination rule (with FIFO as the priority rule) with the same parameter value for each flow, how large should this parameter value be if one wants to minimize the standard deviation in the lateness?

**Exercise 14.3.4**

A production company makes a fixed range of products in several processing steps. There are five product types. Each of the product types is requested equally often on average. Customers place orders in a series of 100 pieces (of the same type). The order arrival process can be characterized as a Poisson process with a (total) average of 6 order arrivals per day. At each of the work centers, the orders are processed in order of arrival.

Before the first operation can begin, the machine operator must first collect material (per order). The collection time is the same for all products and takes exactly 10 minutes per order. The processing time is the same for all products in one order. Table 14.5 shows the processing time per product for the various product types.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Product type | A | B | C | D | E |
| Production time | 0.40 | 0.50 | 0.65 | 0.80 | 0.90 |

**Table 14.5** The production time per product (in minutes) for each of the five types.

Aggregated over the entire range, it appears that the processing time per order is normally distributed with a standard deviation that is approximately equal to 1/3 of the mean.

When 20 pieces of an order are ready, they are transported to the next workplace (transport order).

The company works 8 hours a day, 5 days a week, and 45 weeks a year.

a In this question, we only consider the first work center. What is the average throughput time of one product from an order (from arrival at the first workstation to arrival at the next workstation)?

There are many work centers in this production company. At one of the work centers, W (consisting of one machine), in the order routing, the orders arrive in a series of 100 pieces. The orders arrive according to a Poisson process with an average of 6 orders per day. The processing time is distributed negatively exponentially, and the utilization rate is 90%

There is little space at work center Z (also one machine) that comes after work center W (and where an operation is carried out that all orders have to undergo after work center W) and therefore only a limited number of products can be placed. If there is no more room for a new series of products, it will go to another department where the relevant processing is also can be carried out, instead of to Z. However, this entails extra costs of €10,= per series that has to go to the other department. At the moment, there is room for a maximum of 600 products at Z. The processing time at workplace Z is distributed negatively exponentially with an average of 96 minutes per order.

b What are the expected extra costs per week?

In contrast to the number of operations, the work content (number of hours of production time required) appears to differ considerably per type of product. An analysis of the work content shows that it has an average of 25 hours with a standard deviation of 15 hours. At the moment, all orders are given the same external lead time that is based on the average throughput time of an order and leads to a delivery reliability of 95%. The company wants to work with shorter external lead times, but these must be at least as reliable as the current lead times.

c Give two methods that the company can use to achieve this goal and give an example of each method (also indicate how the parameter value(s) can be determined).

**Exercise 14.3.5**

COMPRO manufactures composite products. The parts are partly purchased and partly made in their production department. The parts are made in series. A total of 30 different parts are made in the company's production department. The production orders are generated weekly using an MRP system.

The production department is functionally organized and consists of several work centers. The production orders have widely varying routing, both in terms of order and number of operations. Each work center consists of several identical machines, with a permanent employee per machine. In the production department, First Come First Served is used as a priority rule for each work center. Table 14.6 shows the throughput time distribution of the orders.

a What is the average and standard deviation in the lateness and the percentage of late orders, if all orders get the same lead time of 7 weeks?

b Suppose that the requested lead times of the orders are characterized as a random draw from the frequency distribution given in Table 14.7 and suppose that the production department always accepts the requested lead time of the order. Determine the mean

|  |  |
| --- | --- |
| Throughput time | % Orders |
| 2 | 5 |
| 3 | 10 |
| 4 | 15 |
| 5 | 25 |
| 6 | 20 |
| 7 | 10 |
| 8 | 7 |
| 9 | 5 |
| 10 | 3 |

**Table 14.6** Throughput time distribution (throughput time in weeks).

|  |  |
| --- | --- |
| Lead time | % Orders |
| 5 | 10 |
| 6 | 20 |
| 7 | 40 |
| 8 | 20 |
| 9 | 10 |

**Table 14.7** Lead time distribution (lead time in weeks).

and standard deviation in the lateness and the percentage of orders that are delivered late under this lead time determination rule.

c The production manager wants to increase the delivery reliability. He is particularly interested in reducing the standard deviation of the lateness. Give two measures that can achieve this.

d The production manager has decided to use the priority rule Earliest Due Date. He then considers making the lead time of a production order dependent on the batch size. The average lead time issued over the flow of production orders remains the same as for the lead times in Table 2. What effect(s) will this have on:

* + 1. The average lead time;
    2. The average lateness;
    3. The number of late orders.

You may assume that the batch size of a production order does not depend on the processing time per piece.

**Exercise 14.3.6**

In the company COSA BV, complex products are made in small to medium-sized series. They are produced to stock in the assembly department. Some of the parts are produced in the parts manufacturing department. The rest of the parts are purchased.

The parts manufacturing department is functionally organized and consists of four work centers, with several identical machines per work center. An analysis of the flow of orders in parts manufacturing results in the data as shown in Tables 14.8 and 14.9.

The machines at work centers 2 and 3 have a special feature. After an order is finished on a machine, a quality inspection of the products of the order must first take place. This may only be done by the quality inspector of the department, who in addition to the inspection task of the products of these work centers also has various other tasks (such as inspection of purchased products). The inspector is available for this work throughout the operating hours.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Work center | 1 | 2 | 3 | 4 |
| Number of machines | 1 | 2 | 2 | 2 |
| Average setup time per order (in hours) | 1.0 | 0.5 | 0.5 | 1.0 |
| Average processing time per order (in hours) | 2.0 | 3.5 | 4.0 | 2.0 |

**Table 14.8** Some characteristics of the work centers.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | | To: | | | | |
| 1 | 2 | 3 | 4 | Uit |
| From: | In | 0.5 | 0.5 |  |  |  |
| 1 |  | 0.6 | 0.4 |  |  |
| 2 |  |  | 0.625 | 0.375 |  |
| 3 |  |  |  | 1 |  |
| 4 |  |  |  |  | 1 |

**Table 14.9** Transition matrix.

As long as the quality control has not yet taken place, the order remains with the machine and the machine remains unused. The processing time of quality control is negatively and exponentially distributed and with an average of 0.25 hours; Half of the jobs carried out by the inspector concern checks of orders from workplaces 2 and 3. The process of arrival of inspection jobs at the inspector can be regarded as an approximate Poisson process.

If the order is approved, it goes to the next work center, and the machine is released for a possible pending order. There is a 10% chance that an order will be rejected. In that case, the order is fully restored on the machine (i.e. the repair operation does not join the back of the queue, but is processed immediately). The repair work is not carried out by the quality inspector but by the (still waiting) operator on the machine. A restore operation takes an amount of time that is negatively and exponentially distributed, with an average of 1 hour. After a repair operation, there is no need for quality control (the order is now always good) and the order immediately moves on to the next work center.

COSA BV works eight hours a day, five days a week. There is a permanent machine operator for each machine. The orders are released according to a Poisson process, with an average of 20 orders per week. The orders are processed at the work centers according to First Come First Serve. You may assume that the time that a machine is occupied for an order (e.g. machining, setting, etc.) approximately is negative-exponential (this also applies to the 'composite processing times' at work centers 2 and 3).

a Determine the average order throughput time per work center.

Instead of keeping a machine occupied during the quality control in connection with a possible repair operation, it is considered to start the next order for work centers 2 and 3 as soon as a previous order has been processed. In that situation, the operator and machine no longer wait for quality control. The quality control remains unchanged. Because the operator and machine are no longer waiting for the outcome of the check, an order for a possible repair operation will have to be placed at the back of the queue at the work center. One of the consequences of this method is that each restore operation now also requires a setup time (which is equal to the setup time for a 'normal' order).

b In which way of working will an operation at work center 2 be finished on average the fastest? (i.e. approved or possibly restored), with the original or with the new one? Quantify the difference.

We will continue and assume the new situation as it is being considered.

c Research has shown that the standard deviation of the total throughput time of an order is a factor *of a* times the average throughput time. Indicate exactly how you would determine the internal and external lead time per order routing for the new situation, based on the average throughput time per work center.

Note: It is not the intention that you also determine the numerical values for the various routings!

d The material manager suspects that in the new situation, the external lead times are too long. Name two measures that can be taken to reduce the external lead time in the new situation, while maintaining reliability (expressed in the probability that the delivery date will not be exceeded) and utilization rates. Indicate why the measures you mentioned will have the desired effect.

**Exercise 14.3.7**

Packaging machines are developed and made in the De Velop factory. Parts are made in the OF department of the factory and are later assembled into a packaging machine in the AS department. The OF department can be characterized as a job shop, where five (main-) routings (A, B, C, D, and E) can be distinguished concerning four work centers (1, 2, 3, and 4). These routings are given in Table 14.10, together with the frequency of occurrence (both in the long and short term).

|  |  |  |
| --- | --- | --- |
| Type | Main routing | Relative frequency |
| A | 1-2-3-4 | 30% |
| B | 3-1-4-2 | 30% |
| C | 1-3-2-4 | 20% |
| D | 2-4-1-3 | 10% |
| E | 2-1-3-4 | 10% |

**Table 14.10** The five routings with the relative occurrence frequency***.***

An average of 10 orders come in per day according to a Poisson process. Processing times may be considered as drawn from a negative-exponential distribution, with averages as shown in Table 14.11 Each workstation consists of one machine. All orders will have the same lead time of eight working days. The orders are processed on each machine using First Come First Serve. The company works five days a week and eight hours a day.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Work center | 1 | 2 | 3 | 4 |
| Processing time | 20 | 45 | 30 | 35 |

**Table 14.11** The average processing time per work center is in minutes.

The company also has its development department that regularly develops new parts and new packaging machines. The development department is always keen to test the designs and therefore regularly has prototypes made. For this, it has its machinery, but it does not have a machine of the type that is at work center 3. Machine 3 is fairly specific and expensive and therefore the company only has one copy of this machine in-house. This means that the development department is dependent on the OR department for work to be carried out on the type 3 machine. As a result, machine 3 is not only used for normal production work but also for work in the development department. This work takes precedence over the normal production work, but the order that is being worked on is finished first. It turns out that on average, three development operations occur per day, and that the orders for these operations arrive according to a Poisson process. The processing time can be considered negative-exponential and the average processing time for the development operations is 50 minutes. As already mentioned in Table 2, the average processing time for normal production work is 30 minutes.

a What is the average throughput time on machine 3?

The production manager has the idea that the current working method on machine 3, where development work takes precedence, is quite disruptive to the average throughput time on machine 3.

b Is the production manager right? Substantiate your answer.

Within the holding company, of which the company is a part, there is quite a lot of concern about De Velop's financial results. Financially, the factory spends too much. It is therefore decided to appoint a new director. He believes that development work is not immediately the strong suit of the company and dissolves this department. The competitive position is also not too strong and this is mainly because the customers are not satisfied with the delivery performance: the average throughput time, which is equal to eight days for each product, is considered to be rather high and the delivery reliability also leaves much to be desired.

In a brainstorming session to come up with measures to shorten the average throughput time, one of the attendees suggests the idea of using the due date rule (DD).

c What do you think of that idea? Argue your answer.

Concerning the delivery reliability, one of the others suggests the idea of continuing to use First Come First Serve and using a different lead time determination rule.

d Which rule qualifies for this? Give the rule and argue your answer.

After a while, the order package appears to have changed, especially because the OF department has started making/repairing some parts that are needed for Service. The number of operations is not known when these types of orders are received, but each order consists of one, three, or five operations. The percentage of this type of order with one operation is 10%, with three operations 30%, and with five operations 60%. After some analysis, for each of the three types of order (with one, three, or five operations respectively), the throughput time data given in Table 14.12 are obtained, which may be considered as normally distributed for each of the three types. The lead time that is given for these orders is equal to three days for all orders.

|  |  |  |
| --- | --- | --- |
| Order type | Average throughput time | Standard deviation throughput time |
| One operation | 500 | 200 |
| Three operations | 750 | 200 |
| Five operations | 850 | 300 |

**Table 14.12** Throughput time characteristics (in minutes) for each of the three (service) types of orders.

e What percentage of these Service orders are delivered on time?

**Exercise 14.3.8**

Four employees work at a construction drawing office, each of whom can do any kind of drawing work. The orders that need to be processed arrive according to a Poisson process with an average of *9* orders per week. The orders require a processing time that is distributed negatively-exponentially with an average value of 16 hours. The orders wait for capacity after arrival and are assigned in FIFO order to the employee who has just completed a previous job. The employees are available eight hours a day, five days a week.

a Determine the average throughput time of an order.

b Determine a lead time determination rule that takes into account the order characteristics and the length of the queue in such a way that the average lateness is equal to zero.

The head of the construction office decides to invest in equipment that allows the construction work to be done in a much shorter time. This does mean that the work of each order must be split into two operations. The first operation consists of preparation, which requires 10% of the old processing time. The rest of the work on an order can now be done in 50% of the old processing time. The manager appoints one employee specifically to prepare all orders. This employee is therefore only concerned with the preparation and completes the orders in FIFO order. One employee is sent into early retirement. The other two employees then carry out the actual construction drawing work on the new equipment. After preparation, the orders wait for capacity, whereby the orders are assigned in FIFO order to the employee who finishes his job first.

c Determine the average throughput time of the orders in the new situation.

d Determine a lead time determination rule that takes into account the processing times of the order to be released and the number of orders at the two work centers at the time of release, such that the average lateness is equal to zero.

The construction manager is considering introducing SPT as a priority rule for the order preparer. The two employees for the construction drawing work continue to use FIFO as a priority rule.

e What will be the effect of this on the average throughput time? How big is that effect?

f Does it make sense with this priority rule to take into account the current amount of work in progress when issuing the lead time? Argue your answer.

**ANSWERS**

**Theory**

**Question 14.1.1**

See page 236/237

**Question 14.1.2**

In the service time; service time is (batch)processing time + set-up time +……

**Question 14.1.3**

(batch)Processing time = batch size \* item processing time

**Question 14.1.4**

See page 237

**Question 14.1.5**

a True

b Not true

c Not true

d True

**Question 14.1.6**

a True (order I has three unfinished branches; order II has 2 unfinished branches)

b Not true (order B started October 3, whereas order II started October 1)

**Question 14.1.7**

Flexible batching: see p.267 at the bottom: in case of flexible batching at moments of low utilization the (average) completion waiting time will be (much) lower, while the increase in (service) time is very limited (after all: the utilization rate at that moment is low); in case of busier periods the batch size will get closer to Qmax (and thus resemble the situation of Qfix). The latter leads to higher utilization rates(compared to the not-so-busy periods) and thus to higher (service) waiting times.

**Question 14.1.8**

Delivery time is the time promised to the customer.

Lead time is the normative throughput time.

Throughput time is the actual time from start to completion of an order.

**Question 14.1.9**

See page 248.

**Question 14.1.10**

If the due date is based on the processing times.

**Question 14.1.11**

See pages 241 and 242.

**Question 14.1.12**

These rules lead to more reliable lead times compared to customer-dependent or constant lead times.

**Question 14.1.13**

If orders can’t be released, customers can be asked to change the due date.

Goods Flow Control can change the ”priority” of the orders by changing the planned release (negotiate with PUC about the release).

**Question 14.1.14**

Holding up the release of orders.

Adjusting the capacity.

**Question 14.1.15**

Workload order release controls the amount of orders on the shop floor and thus the efficiency.

**Answers**

**Basic exercises**

**Exercise 14.2.1**

; ;

**Exercise 14.2.2**

**1** wav = 40 minutes.

**2** No.

**Exercise 14.2.3**

**Exercise 14.2.4**

*s*av = 0.97

**Exercise 14.2.5**

On average: 4 days.

**Exercise 14.2.6**

a 25 days (=average throughput time)

b 50% (normal distribution)

c 34.87 days

**Exercise 14.2.7**

a B-C-D-A

b C-B-A-D

c B-C-A-D

d B-C-D-A

e B-C-D-A

**Exercise 14.2.8**

a The rule for determining the internal lead time (such that the standard deviation of the lateness is minimized) is not correct.

The prioritization rule is correct.

b Not true.

cThat's right!

**Answers**

**Complex exercises**

**Exercise 14.3.1**

a On average: 4.5/λ

b nIII,gem = 38.07 orders.

c - Small combinations: beneficial, because combinations with small occupancy times go fast!

- Large combinations: unfavorable, because the chance of large processing times in combination is high and therefore slow! Then FIFO is better.

**Exercise 14.3.2**

##### a Applying the approximation formula for the waiting time yields:

b = 89.2 hours

c The chance that such an order will be delivered on time is



d If SPT is used, the average throughput time will decrease considerably.

e If EDD is applied, the standard deviation of the order throughput time will decrease considerably, while the average throughput time will remain the same or almost the same.

**Exercise 14.3.3**

a This way of working will increase the average throughput time.

b -Workplace I:

tav,I,A = 200 min.

-Workplace II:

tav,II,A ≈ 835 min.

-Workplace III:

tav,III,A ≈ 318 min.

Then tav,A = 1353 min.

c α is 77

**Exercise 14.3.4**

a Average transport order throughput time is 674

b The average cost per week is 65.15

c Method 1: Different lead time determination rule e.g. TWK; the parameter α is then (average throughput time)/25

Method 2: Other priority rule e.g. Operation Due Date; the value for the Slack parameter is the average wait time.

**Exercise 14.3.5**

a

*σ(l)* =1.89

Percentage of late orders: 15%

b

*σ(l)* =2.19

Percentage of late orders: 17.4%

c A priority rule such as DD (or SB) can be used.

The second measure that can be taken is to use order-dependent delivery dates, e.g. the NOP rule.

d 1 The average throughput time will decrease.

2 The average lateness decreases.

3 The fraction of late orders decreases.

**Exercise 14.3.6**

a

b

The difference is 10.1 hours in favor of the second situation.

c To minimize the standard deviation of the lateness, the average throughput time should be used for the internal lead time to be issued.

For the external lead time, we get: *lext,j* = *lint,j* +*k* \* α \*

with Gj: the routing of order *j*

the average throughput time at work center *i*

d We can reduce the external delivery data without affecting delivery reliability by either reducing the average throughput time or reducing the standard deviation of the lateness. We achieve the first via e.g. SPT or WINQ, and the second by taking into account the delivery dates when determining the sequence, e.g. via DD or SB.

**Exercise 14.3.7**

a

b Yes: LPT effect!

Since all orders have the same lead time of 8 days, the priority rule DD (and no development work) will not result in a reduction of the average lead time compared to FIFO (and no development work).

c In particular: NOP\* (dj = rj + ∑pji + βgj) or a separate estimated waiting time per workplace plus the service times of the order in question (dj = rj + ∑pji + )

d In total: 98.5% on time.

**Exercise 14.3.8**

a *tptav* = 52 hours.

b dj = rj + 16⋅nq/4 + pj

c *tptav,total* = 46.5 h.

d Assumptions:

- nq,i in such a way that workplace 2 can continue to work continuously.

* 8⋅(nq,rest+nq,prep) /2 - 1.6⋅nq,prep - pj,prep ≥0 (zal meestal wel zo zijn)

dj=rj + 4⋅(nq,rest+nq,prep) + pi,rest

e Very small (barely perceptible) decrease in the average throughput time due to the low utilization rate.

f Due to SPT, it is unclear what priority the order has compared to the orders already present. So: no, that makes no sense.

**15 Project-Based Production**

**Key concepts**

After studying the theory you should be able to understand and describe the following key concepts:

* *Network Diagram*
* *Precedence Diagram*
* *Activity-on-Node (AON) Network*
* *Activity-on-Arrow (AOA) Network*
* *Earliest Starting Time*
* *Earliest Finishing Time*
* *Latest Starting Time*
* *Latest Finishing Time*
* *Early Start Schedule*
* *Late Start Schedule*
* *Critical Path*
* *Slack (time)*
* *Workload Diagram*
* *PERT*
* *Optimistic Time*
* *Pessimistic Time*
* *Most Likely Time*
* *Expected Time*
* *Variance (standard deviation)*
* *z-value Standard Normal Distribution*

**Theory**

**Question 15.1.1**

Mention the 7 characteristics of project-based production

**Question 15.1.2**

What are the relevant decisions from a Production Unit Control perspective?

**Question 15.1.3**

Why are dummy activities used?

**Question 15.1.14**

What is the goal of Resource leveling?

**Question 15.1.5**

Mention 5 priority rules used in (constrained resource) scheduling.

**Question 15.1.6**

Mention the three important measures for measuring the effectiveness of the schedule.

**Question 15.1.7**

Mention 5 resource allocation heuristics drawn directly on PERT/CPM.

**Basic Exercises**

**Exercise 15.2.1**

Check out the network in Figure 15.1. The present time is "0".

|  |
| --- |
| A diagram of a network  AI-generated content may be incorrect. |

**Figure 15.1** A certain network.

A Determine the earliest start time for activity A.

B Determine the earliest finish time for activity A.

C Determine the earliest start time for activity B.

D Determine the earliest finish time for activity B.

E Determine the earliest start time for activity C.

F Determine the earliest finish time for activity C.

G Determine the earliest start time for activity D.

H Determine the earliest finish time for activity D.

I Determine the latest start time for activity D.

J Determine the latest finish time for activity D.

K Determine the latest finish time for activity C.

L Determine the latest start time for activity C.

M Determine the latest finish time for activity B.

N Determine the latest start time for activity B.

O Determine the latest finish time for activity A.

P Determine the latest start time for activity A.

**Exercise 15.2.2**

For a task, the following estimates have been obtained regarding the required task time:

- optimistic estimate: 6 hrs

- pessimistic estimate: 10 hrs.

- most likely estimate: 7 hrs.

a Determine the expected task time according to the PERT approach.

b Determine the expected variance of that task time.

**Exercise 15.2.3**

Consider the project network in Figure 15.2.

|  |
| --- |
| A diagram of a complex structure  AI-generated content may be incorrect. |

**Figure 15.2** A certain project network with the Earliest Start and Finishing dates.

Create a workload diagram for this network assuming an early start schedule, If all tasks require 1 operator, except for task C: that task requires 2 operators.

**Exercise 15.2.4**

a Create a workload diagram for the network of exercise 15.2.3 with a time bucket of one week, based on the earliest start and using Table 15.1.

b Indicate in this diagram the workload of the activities “on the critical path”.

c Assuming that the maximum available capacity is 6 men per week, is there going to be a problem when the “earliest start-network” is being used? Explain.

If so, can you solve this problem without extending the earliest project finish time? Explain.

|  |  |
| --- | --- |
| Task | Nr. Operators |
| A | 2 |
| B | 1 |
| C | 3 |
| D | 2 |
| E | 3 |
| F | 3 |
| G | 2 |
| H | 1 |
| I | 2 |

**Table 15.1** The tasks and required number of operators for a certain project.

**Exercise 15.2.5**

A large maintenance project is planned using the principles of CPM and PERT. The data on the activities are given in Table 15.2.

a Using the principles of PERT, determine the expected times for each activity.

b Construct the appropriate network for this project.

c Determine for each activity the earliest start/finish and latest start/finish.

d Determine the critical path for this project.

e What would be a PERT-based estimate of the standard deviation of the activities on the critical path?

f What would be the total expected variance of the time this project will be finished?

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Activity | Predecessor | t-optimistic | t-most likely | t-pessimistic |
| 1 | - | 2 | 3 | 4 |
| 2 | 1 | 1 | 2 | 3 |
| 3 | 1 | 4 | 5 | 12 |
| 4 | 1 | 3 | 4 | 11 |
| 5 | 2 | 1 | 3 | 5 |
| 6 | 3 | 1 | 2 | 3 |
| 7 | 4 | 1 | 8 | 9 |
| 8 | 5, 6 | 2 | 4 | 6 |
| 9 | 8 | 2 | 4 | 12 |
| 10 | 7 | 3 | 4 | 5 |
| 11 | 9. 10 | 3 | 5 | 13 |

**Table 15.2** Activities in a project (time in working days).

**Complex Exercises**

**Exercise 15.3.1**

Check the network created in exercise 15.5.

Table 15.3 shows the expected costs of the activities. Most of these activities can also be performed in a more expensive mode resulting in a reduction in the expected activity processing time. For instance: the expected processing time for activity 2 can be reduced by 1 day; the normal cost for this activity would be € 4000, but in the reduced mode the cost would become € 5000.

|  |  |  |  |
| --- | --- | --- | --- |
| Activity | Reduction  expected time | Normal cost  (€) | Cost when reduced (€) |
| 1 | - | 6 000 | - |
| 2 | 1 | 4 000 | 5 000 |
| 3 | 1 | 10 000 | 12 000 |
| 4 | 1 | 8 000 | 9 000 |
| 5 | 1 | 6 000 | 7 000 |
| 6 | 1 | 4 000 | 6 000 |
| 7 | 2 | 16 000 | 20 000 |
| 8 | 1 | 8 000 | 11 000 |
| 9 | 2 | 6 000 | 8 000 |
| 10 | 1 | 8 000 | 10 000 |
| 11 | - | 14 000 | - |

**Table 15.3** The activities, normal costs, the possible expected reduction in processing time, and the corresponding costs of a certain network.

If the project is to be shortened by two days, which activity should be done in the reduced mode if the costs should be kept as low as possible?

**Exercise 15.3.2**

A construction project (project X) is planned using the principles of CPM and PERT. The data on the activities are given in Table 15.4.

a Determine the earliest moment this project X could be finished by constructing the appropriate AON network based on the expected times for each activity as determined by the principles of PERT.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Activity | Predecessor | t-optimistic | t-most likely | t-pessimistic |
| 1 | - | 2.00 | 3.50 | 8.00 |
| 2 | 1 | 3.50 | 5.50 | 10.50 |
| 3 | 1 | 2.00 | 4.00 | 12.00 |
| 4 | 2, 3 | 1.50 | 2.50 | 6.50 |
| 5 | 3, 7 | 5.50 | 7.25 | 7.50 |
| 6 | 4 | 0.50 | 1.00 | 7.50 |
| 7 | - | 4.25 | 4.75 | 6.75 |

**Table 15.4** The activities, their predecessors, and the optimistic, most likely, and pessimistic processing times of the network of exercise 15.3.2.

b Create for project X a workload diagram based on the latest possible starting time of each activity without delaying the project, assuming that each activity is carried out by one operator at a time.

How many operators would be required according to this diagram?

c How many operators would be minimally required without delaying the project?

**Exercise 15.3.3**

Table 15.5 represents a project that should be scheduled using CPM:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| task | predecessor | t(optimistic) | t(most likely) | t(pessimistic) |
| A | - | 1 | 3 | 5 |
| B | - | 1 | 2 | 3 |
| C | A | 1 | 2 | 3 |
| D | A | 2 | 3 | 4 |
| E | B | 3 | 4 | 11 |
| F | C, D | 3 | 4 | 5 |
| G | D, E | 1 | 4 | 6 |
| H | F, G | 2 | 4 | 5 |

**Table 15.5** The activities, their predecessors, and the optimistic, most likely, and pessimistic processing times of the network of exercise 15.3.3.

a What is the critical path, assuming the expected task times (cf. PERT)?

b What is the expected project completion time?

c What is the probability of completing this project within 16 days? (You may assume the project lead time resembles a Normal distribution).

**Exercise 15.3.4**

Consider a project with an action plan as given in Table 15.6.

Several modes are possible for each activity. For example, activity A can be carried out in 5 days with 2 employees, in 4 days with 3 employees, or in 3 days with 4 employees. This gives considerable flexibility to achieve a good distribution of work over time.

a Provide the AON representation of the PERT/CPM network and determine the critical path and the total project duration in case each activity is carried out in its first mode.

b Give a graph of the capacity picture for the corresponding early-start work plan.

|  |  |  |
| --- | --- | --- |
| Act. | Pred. | Alternative Modes |
| A | - | 5 days with 2 empl., 4 days with 3 empl., 3 days with 4 empl. |
| B | - | 5 days with 1 empl., 3 days with 2 empl., 2 days with 3 empl. |
| C | - | 3 days with 2 empl., 2 days with 3 empl., 1 day with 6 empl. |
| D | A | 4 days with 1 empl., 2 days with 2 empl. |
| E | A | 8 days with 2 empl., 5 days with 3 empl., 4 days with 4 empl. |
| F | B, D | 6 days with 4 empl., 5 days with 5 empl., 4 days with 6 empl. |
| G | C | 5 days with 2 empl., 4 days with 3 empl. |
| H | B, C, G | 4 days with 1 empl., 2 days with 2 empl. |
| I | G | 4 days with 5 empl., 3 days with 6 empl. |
| J | D, E, F | 2 days with 1 empl., 1 day with 2 empl. |

**Table 15.6** The different activities, their predecessors and possible alternative capacity modes, and corresponding processing time options for the project of exercise 15.3.4.

The project is to be carried out in the shortest possible time, taking into account the available number of employees. Of course, one may use the freedom to carry out activities in other modes than the first mentioned in the table above. The best possible length of time that can be obtained is indicated by *Tmin*(*W* ), where *W* is the number of available employees (*W ∈* *ℕ* ).

a Based on the number of employees to be deployed per activity, determine a lower limit for *Tmin*(*W* ), *W ∈ ℕ*? What value is found for *W* = 8?

b Assume that one has *W* = 8 employees. Determine an approved work plan in which the project duration is as small as possible. Describe your solution and the method followed. Also, indicate how good your solution is (as far as possible).

**Exercise 15.3.5**

For a particular project, the project action plan is given in Table 15.7.

|  |  |  |  |
| --- | --- | --- | --- |
| Activity | Immediate  Predecessor | Duration  (in weeks | Required  Cap. (in empl.) |
| A | - | 4 | 4 |
| B | A | 2 | 5 |
| C | A | 6 | 3 |
| D | B | 3 | 7 |
| E | C | 10 | 6 |
| F | - | 2 | 5 |
| G | D | 5 | 6 |
| H | F | 7 | 2 |
| I | D, E, G | 1 | 8 |
| J | H | 10 | 2 |

**Table 15.7** The different activities, their predecessors, durations, and required capacity for the project of exercise 15.3.5.

a Determine the critical path and provide the "early start Gantt chart", i.e. the Gantt chart where all activities start at the earliest possible time. Also, display the slack for each activity in this Gantt chart.

b Provide the time-phased capacity plan (= load chart) for both the "early start work plan" and the "late start work plan" (= the work plan where all activities start as late as possible without extending the critical path).

For this project, so-called permanent and temporary workers can be hired. A permanent employee is a person who is hired for the entire duration of the project. This costs € 25000,= per permanent employee. Temporary workers are people who are hired per week. These cost € 2500,= per man per week. These workers are used to have some flexibility in manning activities. The goal is to minimize total labor costs.

c How high are the wage costs if everything is carried out with temporary workers?

d For the early start work plan, determine the optimal choice for the number of permanent employees. How high are the associated wage costs? We call these costs the minimum total labor costs for the early start work plan.

e As in question d, but then for the late start work plan.

f For the early start work plan, the minimum total labor costs appear to be lower than for the late start work plan (without extending the duration of the project). Determine a work plan for which the minimum total labor costs are even lower. Can you guarantee that there is no work plan with even lower total wage costs for the last work plan?

**Exercise 15.3.6**

Consider the project information as shown in Table 15.8. For each activity, the duration is shown in weeks and the required capacity is simply in number of employees.

|  |  |  |  |
| --- | --- | --- | --- |
| Activity | Predecessor | Duration (wks) | Number of employees |
| A | - | 2 | 3 |
| B | A | 5 | 3 |
| C | A | 2 | 2 |
| D | B | 1 | 2 |
| E | B | 2 | 1 |
| F | C | 6 | 3 |
| G | C | 4 | 4 |
| H | D, E, F, G | 1 | 5 |

**Table 15.8** The different activities, their predecessors, durations, and required capacity for the project of exercise 15.3.6.

a What are the critical activities in this project? How long will the project take?

b Provide the corresponding "early start Gantt chart", i.e. the Gantt chart where all activities start at the earliest possible time. Also, display the slack for each activity in this Gantt chart.

c For the early start work plan, determine the number of employees needed per day and show this in a graph.

d The company has five employees. For every week in which more people are needed, temporary workers must be hired. These cost a fixed amount per temporary worker per week. Try to level the number of employees needed per week in such a way that the costs of hiring temporary workers are minimal. The project duration may *not* be extended. Provide the new capacity plan. How many man-weeks should be hired? Is your new plan optimal, and, if so, why?

Consultation with the client shows that it is sufficient if the project is completed in 14 weeks. This creates room for a better distribution of work and the reduction of the number of man-weeks that have to be fulfilled by temporary workers.

e Assume a project duration of 14 weeks and determine the new slack for each of the activities.

f Carry out question d again, whereby the project duration may now be extended to 14 weeks.

**Exercise 15.3.7**

For a given project Q, the project action plan looks like the one given in Table 15.9.

|  |  |  |  |
| --- | --- | --- | --- |
| Activity | Predecessor(s) | Duration (in weeks) | Required capacity  (number of people) |
| A | - | 4 | 2 |
| B | A | 1 | 3 |
| C | A | 6 | 2 |
| D | B | 3 | 2 |
| E | C | 10 | 3 |
| F | - | 2 | 2 |
| G | D | 5 | 3 |
| H | F | 7 | 2 |
| I | D, E, G | 1 | 1 |
| J | H | 6 | 1 |

**Table 15.9** Project action plan for project Q (the people are needed for the entire duration of an activity).

a Which activity should be the most likely to take time without jeopardizing the duration of the project?

The duration of activities A, D, E, and F appears to be rather uncertain. Estimates for the duration of these activities are given in Table 15.10.

b What lead time must be given for the project so that it is met with 95% certainty?

Analysis shows that activity H can also be performed by 1 person, but this takes twice as long (use the times in Table 15.9). It also appears that only 6 people can be used during the entire project.

c Does this limitation about the available number of people have consequences for the delivery time? (Substantiate your answer).

|  |  |  |  |
| --- | --- | --- | --- |
| Activity | Optimistic | Most likely | Optimistic |
| A | 1 | 4 | 7 |
| D | 2 | 2.5 | 6 |
| E | 8 | 10 | 12 |
| F | 1 | 1.5 | 5 |

**Table 15.10** Different estimates for the duration of the four uncertain activities A, D, E, and F.

**Exercise 15.3.8**

A national accounting firm has identified the set of activities, mentioned in Table 15.11, that must occur to carry out an audit for one of their major clients. For each of the activities, only full crashing is allowed (and not partial crashing).

a Give the AON representation of the PERT/CPM network for the project. The project is finished when all activities are finished. Determine the critical path and the total project duration (in days) when all activities are carried out in normal mode.

b Determine the cost-duration diagram using the greedy method (=CPM heuristic).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Activity | Predecessor activities | Normal duration [days] | Normal cost [€] | Crash duration [days] | Crash cost [€] |
| A | - | 3 | 550 | 2 | 900 |
| B | - | 3 | 500 | 1 | 2000 |
| C | - | 2 | 200 | 1 | 400 |
| D | A | 2 | 650 | 1 | 1200 |
| E | B, C | 4 | 500 | 3 | 850 |
| F | C | 6 | 1500 | 3 | 2200 |
| G | D, E | 4 | 700 | 2 | 1000 |
| H | F | 2 | 500 | 2 | 500 |

**Table 15.11** Activity information for audit project of exercise 15.3.8.

After closer inspection of the plan, the activities E, F, and G have rather uncertain duration times. Estimates for the duration of these activities can be found in Table 15.12.

|  |  |  |  |
| --- | --- | --- | --- |
| Activity | Optimistic | Most likely | Pessimistic |
| E | 1 | 3 | 11 |
| F | 2 | 5 | 14 |
| G | 1 | 2 | 15 |

**Table 15.12** Different estimates for the duration of three uncertain activities.

c What project duration time are you 95% confident of achieving for the audit project, assuming that all activities are carried out in normal mode?

**Exercise 15.3.9**

In Table 15.13, the relevant data about the activities, the precedence constraints, and the time and costs (in normal and crash mode) are given for project PIC. Partial crashing of an activity is allowed.

a Calculate the minimal project duration without crashing and give the corresponding critical path.

b With how many euros do the costs increase by crashing with minimal costs if the requested project duration is 21 days? Show all intermediate steps.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Activity | Immediate predecessor | Nominal duration [days] | Crash duration [days] | Nominal costs [€] | Crash costs [€] |
| A | - | 6 | 4 | 70 | 180 |
| B | A | 8 | 7 | 40 | 70 |
| C | B | 4 | 2 | 40 | 120 |
| D | - | 5 | 5 | 160 | 160 |
| E | D | 4 | 2 | 60 | 100 |
| F | D | 2 | 1 | 60 | 90 |
| G | E, F | 7 | 4 | 80 | 200 |
| H | C, G | 7 | 6 | 50 | 120 |

**Table 15.13** Data for project PIC of exercise 15.3.9.

**Exercise 15.3.10**

For a certain project X, the project activity processing times (three estimates) and precedence relationships are given in Table 15.14.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Activity | Immediate predecessor activities | Optimistic duration [days] | Most likely duration [days] | Pessimistic duration [days] |
| A | - | 2 | 5 | 14 |
| B | - | 2 | 4 | 6 |
| C | A | 1 | 2 | 3 |
| D | A | 2 | 5.5 | 14 |
| E | A, B | 3 | 6 | 15 |
| F | C, D, E | 5 | 6.5 | 14 |
| G | E | 1 | 3 | 7 |

**Table 15.14** Project activity information for project X of exercise 15.3.10.

a Give the AON (Activity On Node) representation of the PERT/CPM network for project X. The project is finished when all activities are finished. Determine the critical path and the total project duration (in days) based on the expected activity durations. Show the calculations of both the forward and the backward pass.

b Determine, using the PERT approximation, the probability that the project will be completed within 24 days.

**ANSWERS**

**Theory**

**Exercise 15.1.1**

More or less (comparable) unique products

Large variety in orders small, medium, and large

High uncertainty in the medium term about orders and capacity

High rate of change in customer requirements

Order planning is based on rough estimates (milestones)

Complex relationships between activities

Constrained resources

**Exercise 15.1.2**

Allocating constrained resources

Multi-project scheduling (prioritizing project)

**Exercise 15.1.3**

To represent a certain precedence relation

**Exercise 15.1.4**

Minimizing the period-by-period variations in resource load

**Exercise 15.1.5**

As soon as possible

Most resources first

Mot successors

Shortest task first

Minimum slack first

**Exercise 15.1.6**

Schedule slippage

Resource utilization

In-process inventory

**Exercise 15.1.7**

Minimum late finish time

Greatest resource demand

Most possible jobs

**Answers**

**Basic exercises**

**Exercise 15.2.1**

See Table 15.15.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | ES | EF | LS | LF |
| A | 0 | 3 | 0 | 3 |
| B | 3 | 8 | 3 | 8 |
| C | 3 | 5 | 6 | 8 |
| D | 8 | 12 | 8 | 12 |

**Table 15.15** The earliest start and finishing dates and the latest start and finish dates.

**Exercise 15.2.2**

a texp=7.33 hrs

b var(t)=0.44 hrs2

**Exercise 15.2.3**

See Figure 15.3.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  | B |  |  |  |  |  |  |
|  |  |  |  |  | C |  |  |  |  |  |
|  | A |  |  |  |  |  |  | D |  |  |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

**Figure 15.3** The workload diagram, assuming an early start schedule.

**Exercise 15.2.4**

* + - * 1. and b. See Figure 15.4.

A screenshot of a computer

Description automatically generated

**Figure 15.4** The workload diagram, assuming an early start schedule, and the critical path.

c1. Yes

c2. Yes, see Figure 15.5.

A screenshot of a computer

Description automatically generated

**Figure 15.5** The workload diagram, assuming an early start schedule and a maximum available capacity of 6 men per week, and the critical path.

**Exercise 15.2.5**

a See Table 15.16.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Activity | Optimistic | Most likely | Pessimistic | Expected |
| 1 | 2 | 3 | 4 | 3.00 |
| 2 | 1 | 2 | 3 | 2.00 |
| 3 | 4 | 5 | 12 | 6.00 |
| 4 | 3 | 4 | 11 | 5.00 |
| 5 | 1 | 3 | 5 | 3.00 |
| 6 | 1 | 2 | 3 | 2.00 |
| 7 | 1 | 8 | 9 | 7.00 |
| 8 | 2 | 4 | 6 | 4.00 |
| 9 | 2 | 4 | 12 | 5.00 |
| 10 | 3 | 4 | 5 | 4.00 |
| 11 | 3 | 5 | 13 | 6.00 |

**Table 15.16** The expected processing times, using the optimistic, most likely, and pessimistic processing times.

b/c/d See Figure 15.6

e 1: 0.33; 3: 1.33; 6: 0.33; 8: 0.67; 9: 1.67; 11: 1.67

f 8.00

A screenshot of a computer

Description automatically generated

**Figure 15.6** The network, earliest start/finish dates, latest start/finish dates, and the critical path.

**Answers**

**Complex exercises**

**Exercise 15.3.1**

Activity 9 (2 days) and Activity 4 (1 day)

**Exercise 15.3.2**

a 16.00

b See Figure 15.8.

A screenshot of a computer

Description automatically generated

**Figure 15.7.** The workload diagram using the latest possible starting time.

c 2

**Exercise 15.3.3**

a B-E-G-H

b 14.67

c 0.785

**Exercise 15.3.4**

a Critical path: A-D-F-J. Project duration: 17 days.

b See Figure 15.8.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  |  | I |  |  |  |  |  |  |  |  |  |
|  |  | C |  |  |  | G |  |  |  | H |  |  |  |  |  |  |  |  |  |
|  |  |  | B |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | A |  |  |  | D |  |  |  |  | F |  |  |  | J |  |  |  |
|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |  |

**Figure 15.8** Capacity graph using the early start work plan.

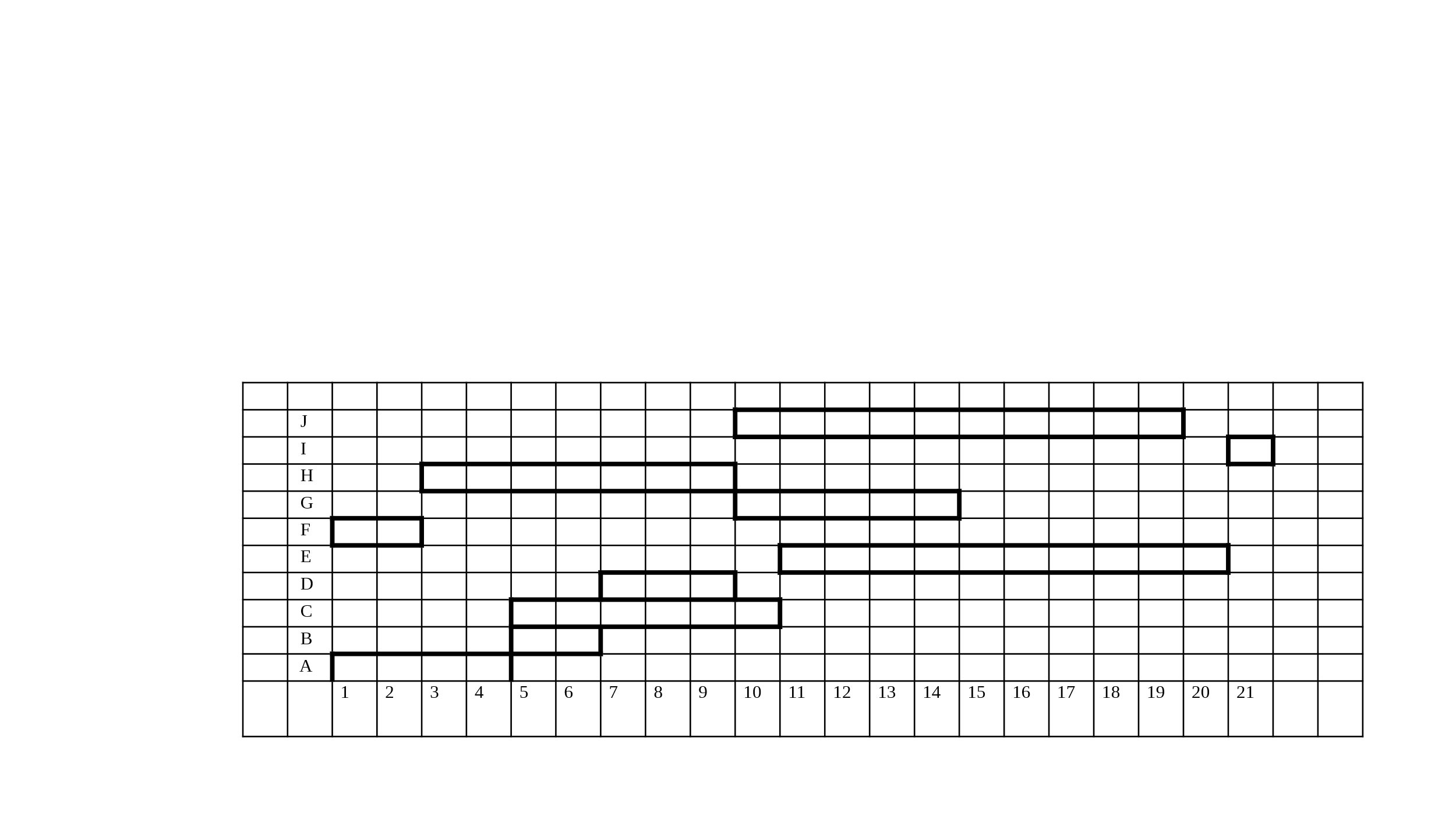
c *Tmin*(8) *≥* 13 days.

*W*

d It is possible to find a work plan with a project duration of 14 days. (There are good reasons to think that a work plan with a duration of 13 days will not be found.)

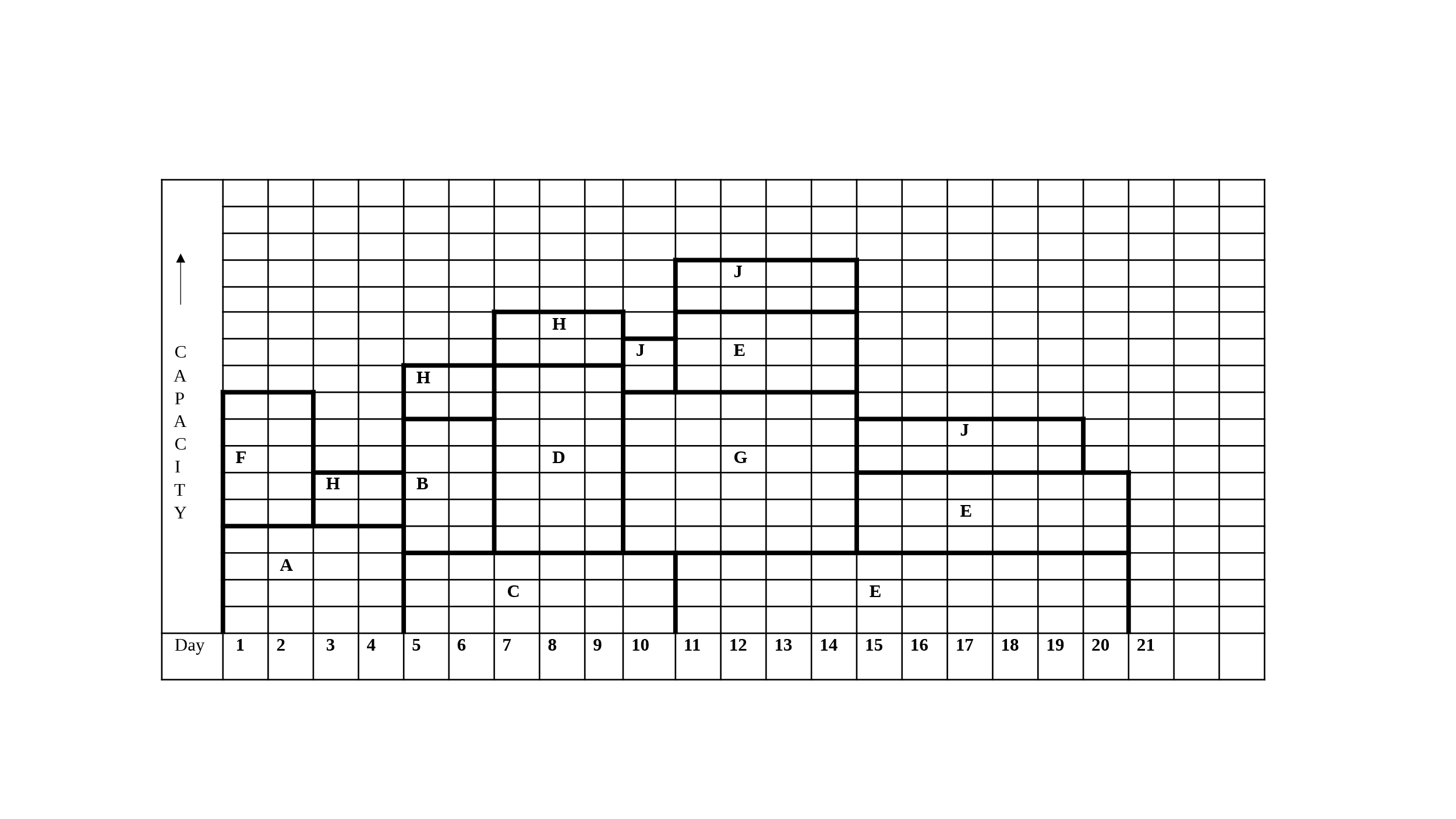
**Exercise 15.3.5**

a See Figure 15.9. Critical path: A-C-E-I. The slack for activities A to J is equal to 0, 6, 0, 6, 0, 2, 6, 2, 0 and 2 respectively.



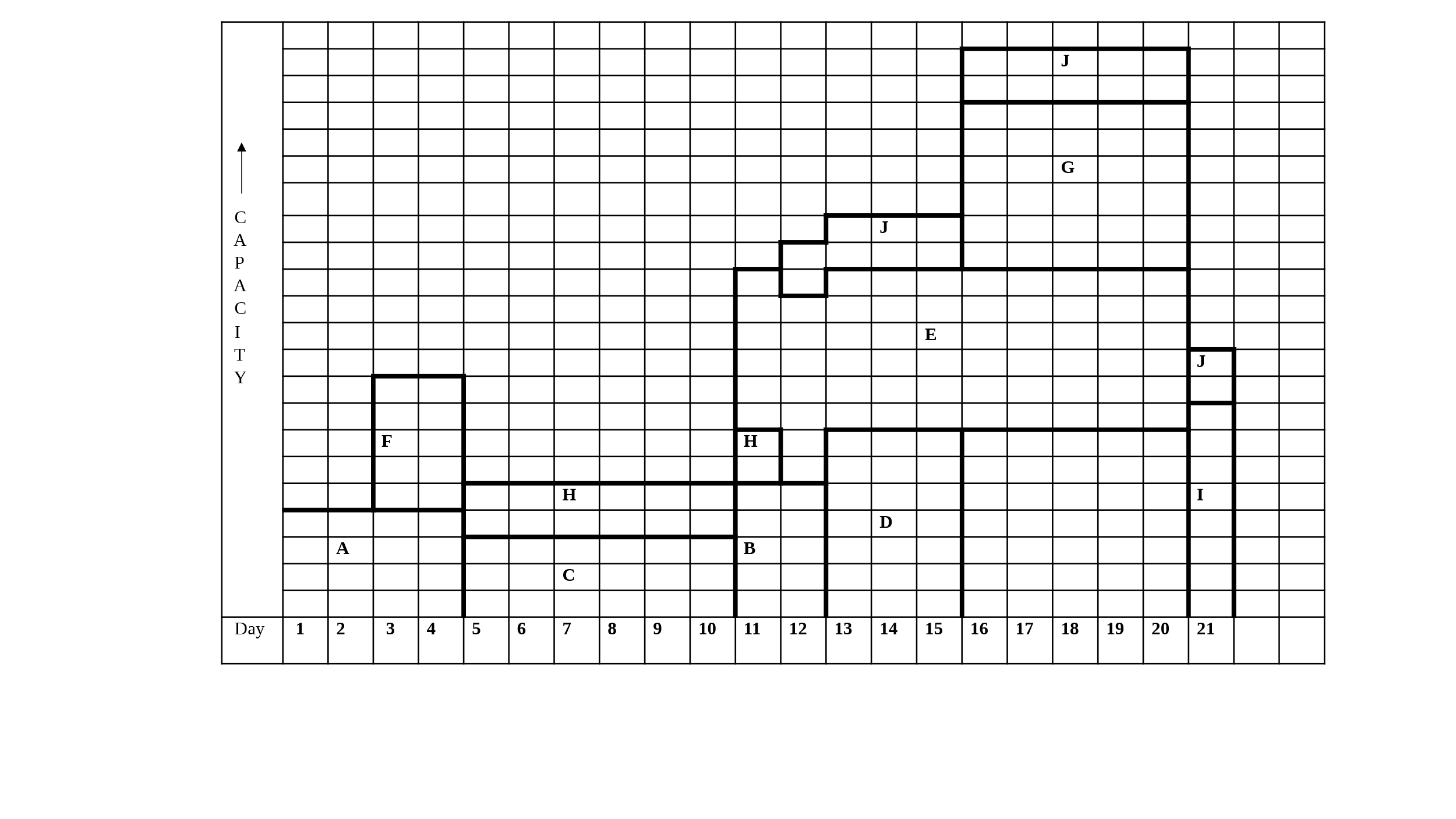
**Figure 15.9** The early start Gannt chart.

b Early start work plan: see Figure 15.10.



**Figure 15.10** Load chart for the early start work plan.

Late start work plan: see Figure 15.11.



**Figure 15.11** Load chart for the late start work plan.

c € 517 500,=.

d 9 or 10 permanent employees; € 307 500,=.

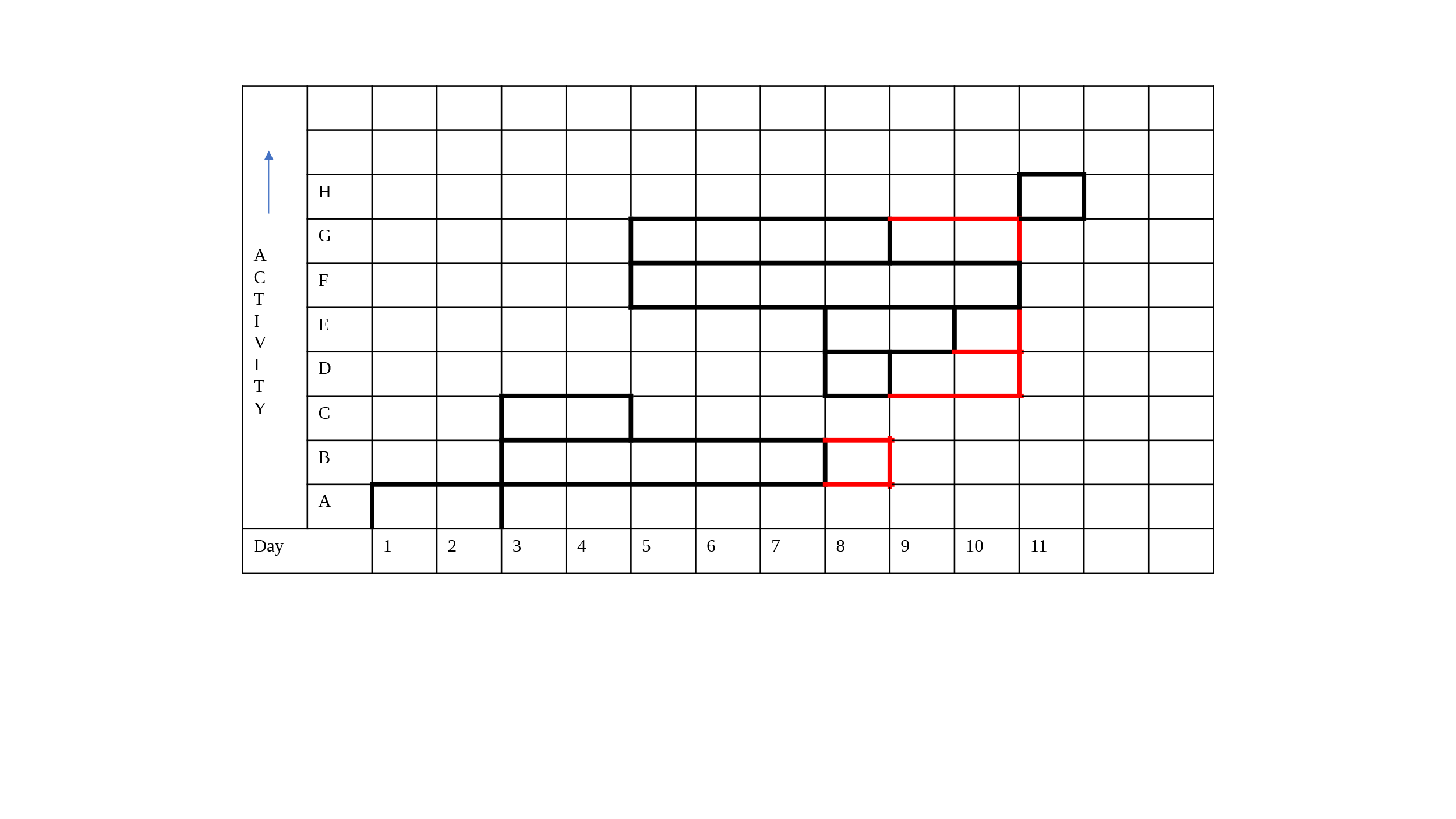
e 10, 11, 12 or 13 permanent employees; € 352 500,=.

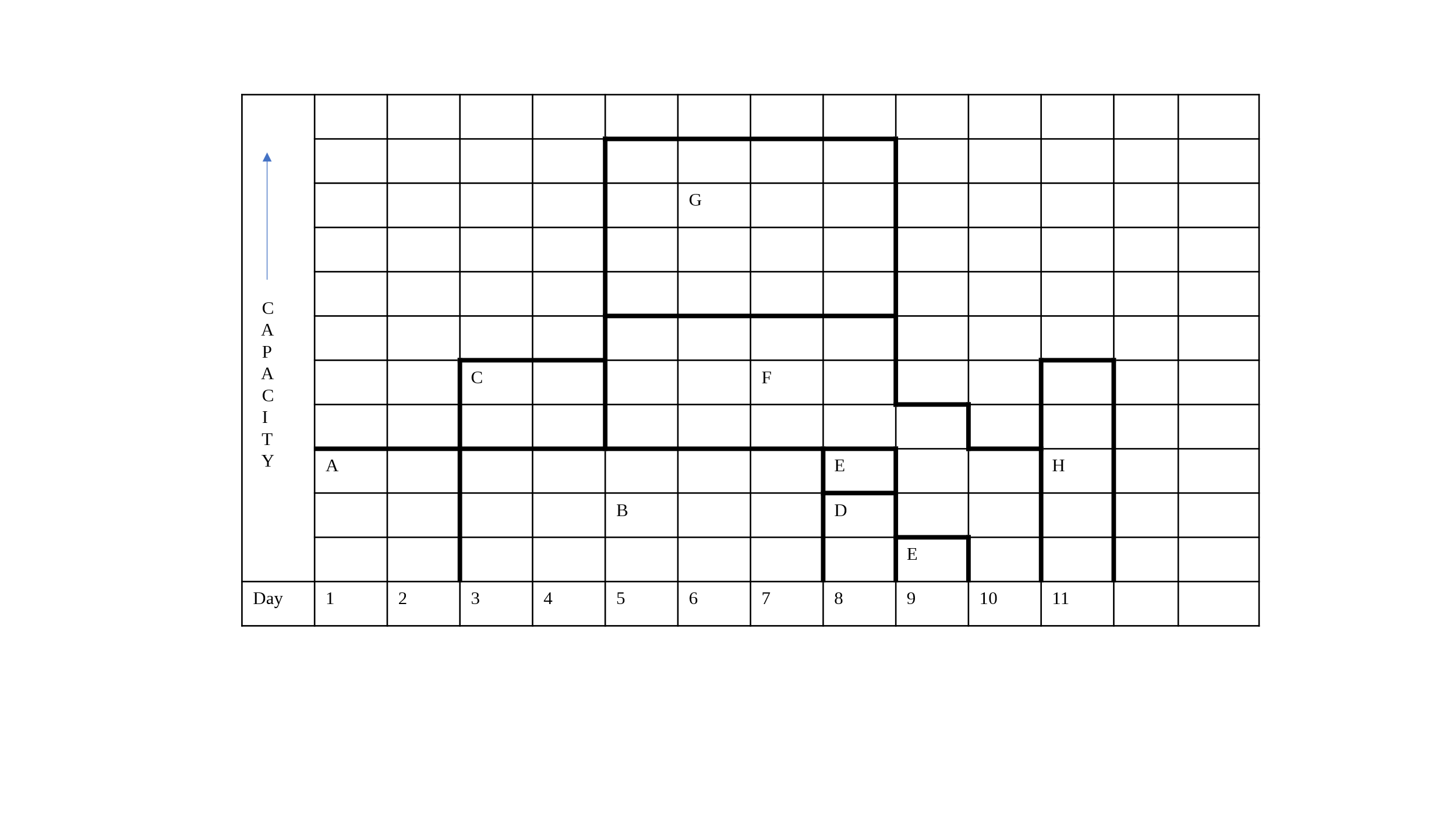
f Better work plan: Take the early start work plan, but have activity J start two weeks later. With this work plan, the costs are at least 9 or 10 permanent employees. The costs are then € 300 000,=. One can reason that this plan is optimal.

**Exercise 15.3.6**

a A, C, F en H; 11 weeks.

b See Figure 15.12. Slacks for the activities: 0, 1, 0, 2, 1, 0, 2, 0.

**Figure 15.12** Early start Gannt chart.

**Figure 15.13** Number of employees needed per day using the early start work plan.

c See Figure 15.13.

d 17 man-weeks.

e 2, 3, 2, 4, 3, 2, 4, 2.

f 7 man-weeks.

**Exercise 15.3.7**

a Activities B, D, and G have a slack of 7. These activities should be allowed to run the most without jeopardizing the duration of the project.

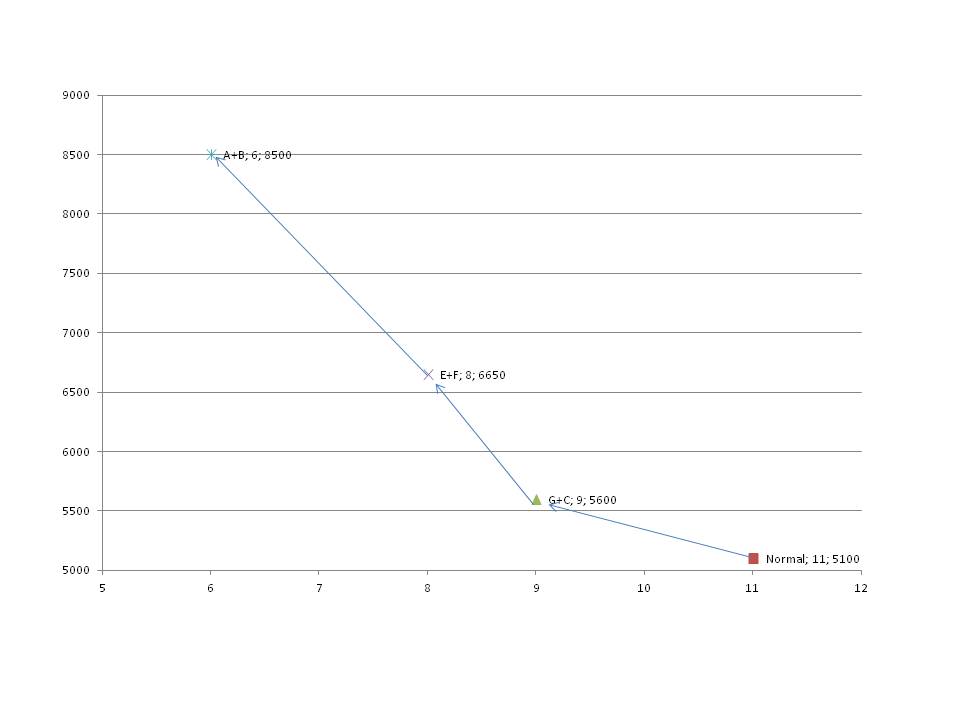
b The 95% certain delivery time is then equal to: 22.977

c So there are no consequences for the delivery time.

**Exercise 15.3.8**

a The critical path is Start-B-E-G-End with a project duration of 11 days and a cost of € 5100,=.

b See Figure 15.14.



**Figure 15.14** The cost-duration diagram.

c *D ≈ 15.7*

**Exercise 15.3.9**

a The project duration is 25 and the critical path is A-B-C-H.

b The additional costs are € 200,=.

**Exercise 15.3.10**

a See Figure 15.15.

A diagram of a flowchart

Description automatically generated

**Figure 15.15** AON network for project X.

Critical path A-E-F and with a duration of 20.5 days

b