How is a product created?

How is a product specified?

How is a production process selected?

How are the performance of a production process evaluated?

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1. Product Design and Development

1.1 The Cycle - The Steps

The following diagram was used in the introduction to describe the interactions between Marketing and Production.

<table>
<thead>
<tr>
<th>Design (R&amp;D)</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Market Analysis</td>
<td>Promote Product</td>
</tr>
<tr>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Customers</td>
<td>Distribution - Sales</td>
</tr>
</tbody>
</table>

By starting the cycle at the customer level, we obtain the sequence of operations by which a product is born, designed, manufactured and sold.

These different steps are described separately for clarity reasons. It does not mean they must be done by different persons or departments. Often they are. However, in the best companies, they are done by a same team, for example, composed of people from marketing, R&D, finance, manufacturing and maybe other departments. Such a team organization allows a quick feedback between the different steps of the product design and development.

We roughly describe in the next pages the main phases of the development of a new product. All these phases exist in the development of a new service too.
1.2 Main Steps

Let us have a closer look at three main steps of the product design and development:

Step 1  idea generation  (Marketing or ...)
Step 2  product selection and product design  (Product development)
Step 3  process selection and capacity planning  (Manufacturing)

In parenthesis is the organization unit usually in charge of the corresponding step.

Consumer needs; 
Innovation; 
⇒  Idea generation  ⇐  Selection; 
  Ranking;

↓

Market analysis; 
Economic anal.; 
Feasibility anal.; 
⇒  Product selection  ⇐  Choice of specific product features;

↓

Evaluation of alternative designs; 
⇒  Preliminary design  ⇐  Choice of the final specifications:
  -component list
  -assembly drawing

↓

Process Selection  ⇐  Choice of specific equipment and process flow;

↓

Capacity and Production planning

These three main steps are described in the following pages.
1.3 Idea Generation

Most often, Marketing is in charge of generating new product ideas. However, more and more companies do rely on teams made of people from different horizons of the organization (for example, R&D, Product Development, Manufacturing, Finance).

1. Generation

- **listening to the customers**
  
  Sales people have often the best perception of the customers’ needs.

- **market study**
  
  This is another way of getting information on customers’ needs.

- **allow internal contacts**
  
  Even if the needs are well known, the solutions still need to be found. One way consists in bringing (physically) together those who know the customers’ needs and those who know the solutions.

- **R&D**
  
  Ideas or solutions can also come from technological breakthroughs. However, note that much less than one percent of the new products result from technological breakthroughs.

Once ideas have been generated, they should be ranked in order to determine which products/services are worth being further developed.

2. Ranking and Selection of the “New Products”

The project value index is a very simple rule for comparing different projects. This rule is quite heuristic but allows a first rough ranking. Note the square root factor for the product life which has been introduced to anticipate the market evolution.

- **Project value index**

\[
PVI = \frac{CTS \times CCS \times AV \times P \times \sqrt{L}}{TPC}
\]

<table>
<thead>
<tr>
<th>PVI</th>
<th>Project Value Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTS</td>
<td>Chances for Technical Success [1 - 10]</td>
</tr>
<tr>
<td>CCS</td>
<td>Chances for Commercial Success [1-10]</td>
</tr>
<tr>
<td>AV</td>
<td>Annual volume (in units)</td>
</tr>
<tr>
<td>P</td>
<td>Profit per unit</td>
</tr>
<tr>
<td>L</td>
<td>Life of product (in years)</td>
</tr>
<tr>
<td>TPC</td>
<td>Total Project Cost</td>
</tr>
</tbody>
</table>

The project value index is a financial measure of the project. Other financial measures like the payback period or the internal return rate can also be used. Other aspects have to be taken into account in the project selection phase, e.g. “does this product line belong to our marketing strategy?” or “can the project investments be useful for another activity?”.
1.4 Product Selection and Design

1. Product/service selection

The selection of a product consists first in the specification of all the performance standards it should meet. For example

⇒ set of performance standards:
   - style, capacity, ease of use,
   - reliability, maintainability, service life

Technique: House of Quality (HOQ)\(^1\)

The house of quality describes a sequence of rooms that have to be built, that is a sequence of operations that have to be performed to translate the customer needs into performance standards for the product. This sequence is the following:

- Room 1. List and rate the customer needs.
- Room 2. List the design characteristics the design team think are necessary for meeting these needs.
- Room 3. Build the relationship between the design characteristics and the needs.
- Room 4. Ask the customers to evaluate the competing products.
- Room 5. Perform a technical evaluation of the competing products.
- Room 6. Evaluate the correlation between the design characteristics.
- Room 7. From the needs importance, determine the importance of the design characteristics.
- Room 8. Select the targets for the performance of the product.

What are the objectives guiding the selection of the product (performance standards)?

**Objectives for the product selection:**

---

• increase the product performance
  the set of characteristics (in comparison with the anticipated customer needs).

• reduce the development time
  the time for the product to be on the market (time to market).

• reduce the product cost
  the total cost of the product (for the customer).

• reduce the development program expenses
  the cost of developing this new product.

⇒ Find the right compromise

Here are two small examples which show that there is no absolute right answer.
Example 1. Should we incorporate an additional feature into the final product? This increases the performance but could delay the product introduction in the market.
Example 2. Should we look for a cheaper technical solution for some feature? The aim is a decrease of the product cost. The product development will unfortunately be longer and more expensive.

2. Final design: 1. components
   2. assembly drawing

The final design is the detailed list of all the components of the product along with the way they are assembled together. By means of prototypes (debugging), alternatives solutions are compared and sound specifications are derived.
Here again a compromise between the following objectives is required.

Objectives for the final design:

• compatibility (sound specifications)
  be sure the product fulfills its specifications;

• product costs
  simplify or eliminate product components;

• manufacturing costs
  use simple, standard and re-usable parts (design for manufacturing);

• ease future change
1.5 Final Design: components

Here is an example of final design. Please try to criticize this design.

1. Components

Here is the list of all the components which will compose the final product.

Nomenclature

A clear description of all the components is more than necessary. This description should also include the technical performance each component must and does meet. This will ease possible future replacements of components.

A clear and unambiguous code system is also needed to avoid mistakes in operations management.

<table>
<thead>
<tr>
<th>Part</th>
<th>Name</th>
<th>Description</th>
<th>Code</th>
<th>Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>...</td>
<td>...</td>
<td>prod/2100/001</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>...</td>
<td>...</td>
<td>prod/2100/002</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>...</td>
<td>...</td>
<td>prod/2100/003</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>Tube</td>
<td>diameter:[4 - 5]mm</td>
<td>prod/2100/004</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>Tray</td>
<td>...</td>
<td>prod/2100/005</td>
<td>1</td>
</tr>
</tbody>
</table>
1.6 Final Design: assembly

2. Assembly Drawing

or how the different components are positioned with respect to one another.

It is important to describe the products (finished or semi-finished) as precisely as the components.

<table>
<thead>
<tr>
<th>Part</th>
<th>Name</th>
<th>Description</th>
<th>Code</th>
<th>Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>...</td>
<td>...</td>
<td>prod/2100/001</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>...</td>
<td>...</td>
<td>prod/2100/002</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>...</td>
<td>...</td>
<td>prod/2100/003</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>Tube</td>
<td>diameter: [4 - 5]mm</td>
<td>prod/2100/004</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>Tray</td>
<td>...</td>
<td>prod/2100/005</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>Full tray</td>
<td>...</td>
<td>prod/2100/010</td>
<td>1</td>
</tr>
</tbody>
</table>

Could you criticize this final design with respect to the objectives which were pursued.
Throughout these notes, the name FTRAY will be used for referring to our final product.
2. Production Process

Once the final design has been specified, we must choose how the product will be manufactured, i.e. by which production process. The transformations which a product undergoes determine the production process type.

**Types:**

**Conversion process**
Typical products: plastics, metal, beer, gasoline.

**Fabrication process**
Typical products are basic components such as wires, screws, tissues, food.

**Assembly process**
Typical products are cars and appliances.

**Processes for manufacturing the FTRAY’s:**

In order to produce our final product from raw material, all three processes are needed.

- **conversion process:** for the production of paper
  Our final product is made of plastic and paper. With our technology, paper is obtained by "converting" wood.

- **fabrication process:** for the fabrication of cups
  Paper must be cut and glued to yield cups.

- **assembly process:** for the assembly of trays
  All the components must be assembled as shown in the assembly drawing.

Let us now focus on the assembly process. The question is how to structure, to organize, to implement this assembly. To answer this question, you must decide: “who will do what and how?”.

**How will you produce the f-trays?**

The flow structure of a process refers to the way the material flows in the system.

For the production of FTRAY’s, here are three possible solutions (among many others):

1. Several workers, each doing everything. In this case the components go to one person who does all the different operations. This tells who does the job but not yet how. This solution is incompletely specified. We still need to specify the sequence of operations, their contents and where they are done. If a unique worker performs all the operations, the organization can be called “individual organization”.

2. The sequence of operations is defined as follows (an example): place the cups on the tray - glue the stickers on the cups - place the lids - insert the straws. Each operation is performed by one worker along an assembly chain. Each worker performs one operation and passes the part to the next one as soon as she/he's finished. This flow structure is an assembly chain or line. We will name this organization: “line organization”. It is also referred to as "flow shop" or "product layout" because the machines and the workers are physically placed according to the different steps of the product manufacturing.

3. The sequence of operations is as above. However, the workers are organized in shops. Each shop is responsible for a family of operations. The cups are first mounted on the trays in the “stamping shop”. They are then sent to the “painting shop” for getting the stickers. And so on. This organization is called "job shop" or "process layout".
2.1 Performance

There are many possible organizations. We will review them later. For this example, we should use the flow structure with the performance which best fits our objectives. How can we measure the performance? Here is a first list which should be optimized and/or compared with our objectives.

- **Production Rate P**
  
  How many units can I produce with a given process flow structure?
  
  The production rate (also called productivity or throughput) is the number of items produced per time unit (per day, for example).

- **Product Cost**
  
  How much does it cost to produce one unit?
  
  It depends on the workforce (both its size and its qualifications) and on the equipment (basic machines and handling material). Note that the accounting system plays a non-negligible role.

- **Product Quality**
  
  What is the quality level to be expected from the production process?
  
  Two possible measures are the scrap rate and the rework rate. Quality can also be defined in a much broader sense (see the chapter on quality).

- **Product Customization**
  
  Can my customers modify the product specifications? To what extent?

- **Product Flow time (sojourn time, lead time)**
  
  How much time does each product spend (waiting and processing) in the system?
  
  This is the time between the moment a customer places an order and the moment the customer receives delivery. One example is the time you must wait for your telephone to be connected to the network (after you placed the request). Another example is the time required for your shopping.

- **Process Work-In-Progress (WIP)**
  
  On the average, how many products (started but not yet finished) are in the system?
  
  This is the work-in-progress. Its amount is determined by the flow time and the production rate:

  \[
  \text{WIP} = \text{Production rate} \times \text{Flow time}
  \]

  This expression is known as Little’s law. For example, if each customer stays about 1 hour in a department store and if one customer leaves every 15 seconds, then there will be on the average 240 customers in the department store.

  You can replace the output rate (production rate) by the input rate in the above formula when both are equal, on the average.

- **Process Flexibility**
  
  What will happen if I suddenly need to produce more products than foreseen? Or if I need to manufacture products different than foreseen? Can my process be adapted?

  Such questions are critical in the youth of a product, when its characteristics and the size of the market are not yet completely defined.

- **Process Dependability**
  
  Can I rely on my production process? What happens if a machine breaks down or if a worker is absent?

- **Process Control**
  
  How do I plan and co-ordinate the different activities of the process?

  How do I control the process? What should I check? How can I interfere?
Does it take lots of time?

- **Process Investments**
  How many machines do I need? Shall I invest in “handling” material? How much does it cost me? Can I re-use this investment?

- **Workforce Features**
  How many workers does your process require and how skilled should they be? Do they need training?

- **Human Aspects**
  Will the workers feel fine, be motivated and work efficiently?

- **Learning**
  How much freedom do the workers have in their job? Can they improve the process? Do they have the necessary background for improving the process?

- **Environmental Aspects**
  How does our process impact the environment?
2.2 Description

The final design specifies what the product components are and where they are positioned into the final product. The production process must first tell in which sequence these components are assembled (sequence of operations). This is the purpose of the "process flow chart". Afterwards, the questions "where is each operation performed and by whom?" must be answered.

Assembly Drawing and Process Flow Chart

Here is an example for the manufacturing of the FTRAY's. Note that other representations of the process flow are possible. Conventional symbols are usually used.

Note that non-productive operations like moving, storing, or retrieving are also specified.

Blueprint and Poka-Yoke

Such a detailed description can also be used (and should also be used) to describe services. For example, refer to chains of restaurants. The way your order is taken has been minutely described. Even the smile is "programmed".

Such descriptions are called service blueprints. In addition to the sequence of activities, they also specify "fail points" (what should be done if the operation fails) and time estimates. Poka-Yokes are tricks used to guarantee that some operations are well performed.
3. Individual Organization

Here we will assume that a single worker performs all the operations in sequence as described by the process flow chart. Let us try to review the general performance of such an organization (what we call the “individual” organization).

- **Workforce Features**
  
The number of workers will be determined by the production rate. In terms of qualification, multiple skills are required. The jobs are broad in scope since they require the ability to perform all the operations.

- **Learning**
  
  It is rather low since the worker does not specialize and remains rather alone.

- **Process Investment**
  
  It is quite high, since the equipment must be duplicated for each worker, even if the machines are needed for a single operation only.

- **Production Rate**
  
  It can be low for two reasons. First, the workers do not specialize. Second, you cannot afford the most effective equipment since you must buy it for each worker.

- **Product Cost**
  
  It can be very high. You may need high investments in terms of machines, many workers because their production rate is low and pay high wages since they are multi-skilled.

- **Product Quality**
  
  Average. The positive aspect is the absence of any unnecessary manipulations. The negative part results from the non-specialization of the workers.

- **Product Flow time**
  
  Small. The flow time is small since there is no wait between the start and the end of the manufacturing.

- **Product Customization**
  
  High. Each worker could be assigned with different customer orders.

- **Process Flexibility**
  
  High. In order to regulate the production volume, workers can be added or withdrawn. The scalability of this organization is high. The adaptation to modifications in product specification depends on the level of machine investments.

- **Process Control**
  
  Simple. For the planning you just split the work among the workers. There is no extra need for co-ordination or organization. The control of each worker’s production is also easy.

- **Process Dependability**
  
  Rather high. If a worker is absent, all the others keep or proceed working.

- **Human Aspects**
  
  Average. Every worker sees what she/he does and perhaps knows who is the customer. This is a positive aspect. The isolation is the (rather) negative side.
4. Line Organization

4.1 Description

Here we will assume the same sequence of operations. However, each operation will now be performed by a different worker and the workers will be placed in a line. This is called the “assembly line” or the “production line” organization.

Since different workers collaborate in the process, their interactions (the move operations, for example) must be clearly defined. These additional operations could reduce the effectiveness of the process.
4.2 Evaluation

Let us first try to review the features of the line organization.

- **Workforce Features**
  
  The jobs are specialized and narrow in scope. They require narrow skilled jobs.

- **Learning**
  
  The learning rate is high because of the task specialization. In addition, the comments from the downstream workers can also contribute to the learning.

- **Process Investment**
  
  Average. Compared to the individual organization, a single set of machines is sufficient. Furthermore, the machines used for each task can be tailor-made. The best compromise between labor money and machine money can also be chosen. The negative aspect arises if the machines are not fully used. Since they are tied to the line, they cannot easily be used by others.

- **Production Rate**
  
  High. The narrowing of the scope of the tasks allows the workers to specialize and the best equipment to be used. The production rate will thus be very high. This rate depends on the speed of the slowest workstation. The workstations which are quicker are either waiting for some input (idle) or waiting to deliver their output (blocked). In any case, a line organization has to be balanced.

- **Product Cost**
  
  Low. The specialization of the tasks makes it possible to use an adequately qualified person for each task. Tailor-made equipment is used. Fewer machines are needed. This leads to a low cost product.

- **Product Quality**
  
  High. The specialization of the worker and the low level of extra manipulations usually results in a rather high quality product.

- **Product Flow time**
  
  The flow time can be rather small. The products which enter the system are quite quickly out of it. In fact the assembly line works like a conveyor belt. There are 4 operations so that one unit remains about (4 / production rate). If the production rate is one product each 20 seconds, the flow time will be 80 seconds.

- **Product Customization**
  
  Low. An assembly line can only be used for standard products. Any customization should be foreseen from the beginning. Car assembly constitutes a typical example.

- **Process Flexibility**
  
  Low. It is not easy to add or remove a worker nor to change the routing of the products. This is a major weak point.

- **Process Control**
  
  Rather simple. The problem consists in balancing the line.

- **Process Dependability**
  
  Low. Any problem will disrupt the chain and stop the whole system.

- **Human Aspects**
  
  These specialized jobs can be demotivating. However, the team spirit could play an important role. It can also have a major impact on quality and learning.
4.3 Production Rate

In the next pages, we will focus on the evaluation of the production rate of a line process. Two cases have to be considered: either the line already exists and can be observed or it does not yet exist and the production rate should be evaluated on the basis of estimations of the operation times. Both cases are considered below.

A. Observation of a real line

In order to determine the production rate of an existing line, we should first load the line and wait till the transient behavior has disappeared.

A1. Start the simulation and wait for "steady-state".

Before starting a car race, all the cars are allowed one warm up lap. Before measuring some performance, you must also wait for the system to be "warmed up". The steady-state is also called equilibrium state. Then and only then, measures can be taken.

A2. Measure $Pr$, the number of units produced per time unit.

If 12 units are produced in 4 minutes, the production rate $Pr$ is 3 units/minute or 180 units/hour. It is a speed and different units can be used.

If 3 units come out of the system every minute, 3 units must enter the system every minute too. This is true as long as nothing is created nor lost along the process. In this case, at any station, 3 units pass every minute. In other words, 20 seconds separate, on the average, every two arrivals or every two departures. This provides us with another way to determine the production rate $Pr$.

If flow is conserved, then:

1. select any workstation;

2. compute $T$, the average time between two arrivals or two departures;

3. set the production rate $Pr = T^{-1}$

Note that this is true only if nothing is created or lost in the system.

In fact during these $T$ seconds, a workstation can be busy, starved or blocked. We use the qualifier "starved" (or "idle") to denote a workstation waiting for the items to work on, and "blocked" to denote a workstation that has finished its operations but cannot forward its product to the next stage for space reasons.

$\Rightarrow$ at each workstation :

$$T = \text{starved time} + \text{processing time} + \text{blocked time}$$

To perform such observations, the line must already exist. During the design of a new product or of a new process, it is usually too expensive to build a line just for an experiment.

In such cases, the production rate will be evaluated on the basis of estimations of the operation times. Later in this chapter, we will consider the problem of obtaining such estimations.
B. Evaluation based on "operation times".

Let us first assume there is no variation in the operation times.

B1. Deterministic "operation times"

The table below lists the successive operations, the time they take and the workstation where that operation is performed.

<table>
<thead>
<tr>
<th>Operation</th>
<th>time (sec.)</th>
<th>performed at workstation</th>
<th>time per workst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 assemble 4 A on E</td>
<td>14</td>
<td>E</td>
<td>1</td>
</tr>
<tr>
<td>2 move</td>
<td>3</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3 glue 1B on each A</td>
<td>16</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4 inspect</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5 move</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>6 fix 1C on each A</td>
<td>17</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>7 move</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>8 fix 1D in each C</td>
<td>14</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>9 inspect</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

The maximal production rate of the line is determined by the following procedure.

1. Compute the total time, each operator (or workstation) spends on each product;

2. Determine the largest total time: $T$

3. Set the maximal production rate $Pr = 1/T$

⇒ the bottleneck defines the production rate

Here, the largest total time is reached at workstation 2 where 23 seconds of work are required per item. This workstation is called the bottleneck of the system. It determines the production rate of the system. In this case, the production rate $Pr$ is 1 unit per 23 seconds. This rate can only be reached if the bottleneck is kept busy all the time. This condition is always satisfied when all the operation times are deterministic.

B2. Random Operation times

Here we will assume that some variation in the duration of the operations is possible. For example, we will assume that all the operations at workstation 2 take either 18 or 28 seconds. On the average, the duration of the operations at workstation 2 remains equal to 23 as before.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (seconds)</td>
<td>17</td>
<td>{18,28}</td>
<td>20</td>
<td>16</td>
</tr>
</tbody>
</table>

Question: What is the average production rate?

In order to answer this question we will introduce the Gantt chart.
4.4 Gantt Chart

The Gantt chart constitutes a very useful tool for planning operations.

**Principles:**

- **X axis:** time axis
- **Y axis:** workstations or operators
- **(X,Y):** what does workstation (or operator) Y do at time X?

The principles are quite simple. The chart describes what everybody does at each time. Here is an empty Gantt chart for our system with 4 workstations.

Let us for example sketch what happens when the line is empty and the production of a first item is started at time 0. We assume the deterministic operation times of the previous page (17, 23, 20, 16).

**Schedule the manufacturing of P1 (deterministic op. times)**

As an exercise, you are asked to sketch what happens if a second item is produced immediately after the first one. Use another color for this second item. Please do not forget that you can be prevented from working if you do not have the material (starved) or if you cannot deliver the previous one (blocked).
B1. Deterministic "operation times"

Schedule the manufacturing of P1-P5

Here is what you should obtain when the manufacturing of 5 products have been scheduled. We see that after the product P2, a regular pattern appears in the Gantt chart. The fact that it is regular indicates that a steady-state has been reached. After product 2, the transient behavior (the warm-up) is over.

Let us analyze this steady-state. We observe the following. Workstation 2 is the bottleneck since it is the slowest. It keeps busy all the time. It processes one unit every 23 seconds.

Workstation 1 works during 17 seconds and then waits (it is blocked) for 6 seconds until it can deliver its part to workstation 2. This pattern is repeated.

Workstation 3 works during 20 seconds and then waits (it is starved) for 3 seconds until workstation 2 delivers the next part. Workstation 4 works similarly.

B2. Random "operation times"

Schedule the manufacturing of P1-P7

Here we assume that the speed of workstation 2 alternates between 18 and 28 seconds. Here is the Gantt chart we obtain when 7 products have been scheduled.

We observe that a steady state is reached after product number 2. At that point, we observe a cycle that covers the production of 2 units.

⇒ The bottleneck is not always busy

The major observation on this Gantt chart is that the bottleneck of the system, workstation 2, stops working from time to time. Why does this happen? Consider first the case where the operator 2 performs his work in 28 seconds. When he finishes, he can pass his product to operator 3 and immediately gets a product from operator 1. In this case he does not wait. However, when he performs his work in 18 seconds, he must wait 2 seconds for the operator 3 to terminate.

⇒ The average production rate decreases
Indeed, the average operation time is \((1/2 \times 28 + 1/2 \times (18+2)) = 24\) seconds. The variability in the processing time has introduced some loss of productivity. As an exercise, try to understand what happens at the other workstations and check that the average time between two arrivals is indeed 24 seconds.

\[ \Rightarrow \text{Variations of operation times can induce productivity losses} \]

How can we avoid such losses? By keeping the bottleneck busy. How can we keep the bottleneck busy? By keeping him from being starved or blocked. How can we keep him from being starved or blocked? By providing him sufficient input material for him to work and sufficient output space for him to dispose its products.

**Solution: Buffers can be used to protect the bottleneck**

Look what happens when we introduce a buffer between workstation 2 and workstation 3. This buffer allows workstation 2 to dispose its product even if workstation 3 is not free. In this way, workstation 2 is kept busy all the time and the production becomes 1 unit per 23 seconds.

As a first exercise, try to determine whether a buffer in front of the bottleneck, that is between workstations 1 and 2, is useful. Though buffers help to keep the bottleneck busy and therefore increase the productivity, several performance measures worsen with their introduction.

**N.B. drawbacks of using buffers:**

- increased flow time and WIP
- increased space requirements
- increased handling
- separation of the workstations

Our example assumed that workstation 2 requires either 18 or 28 seconds for its work. As another example, let us consider a uniform distribution for workstation 2:

**Question : what is the production rate if Workstation 2 operation time is uniform [18 sec - 28 sec] ?**

If the processing time is in [20-28], then he can give his product to operator 3 immediately and proceed with the next product. This happens with a probability 8/10. If he works in less than 20 seconds, he must then wait for operator 3: on the average, 1 second. This happens with a probability 2/10. The operator spends therefore \(8/10 \times 24 + 2/10 \times 20 = 23.2\) seconds per product on the average. One could also say that he waits 1 second after each product with a probability 0.2 or that he waits 0.2 seconds after each product. This leads to a total time of 23.2 seconds too.
4.5 Productivity

Here we address the problem of computing the production over a long period of time. Most of the comments are not specific to line organizations.

**Question:** What is the production $P$ in a shift?

The direct answer is as follows. 1 shift = 8 hours. The production rate is 1 unit every 23 seconds. The production during a shift is then:

$$P = 8(\text{hours}) \times 60(\text{min/hours}) \times 60(\text{sec/min}) / 23(\text{sec/unit}) = 1252 \text{ units}$$

This is however optimistic since in reality some time will be lost.

**4.5.1 Productivity is lost when:**

Production time can be lost because of the workers, because of the machines or because of the products, or because of all of them.

- the workers are late / absent / sick
- the workers take their normal breaks
- the workers are required somewhere else
  Examples here are: training, administration, meetings.
- the equipment is in setup mode
- the equipment is broken / in maintenance
  The setup is the time needed before a machine or a process can really start working. Examples are: waiting for a machine to warm up or to be set up; preparing the working area or loading the system (transient).
  By opposition to repair, the maintenance is a scheduled operation. It consists in checking, cleaning, replacing machine parts.
- the product is not acceptable (scrap)

**4.5.2 Example**

<table>
<thead>
<tr>
<th>Workstation 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production rate</strong></td>
<td>1 unit / 23 sec</td>
</tr>
<tr>
<td><strong>normal pause</strong></td>
<td>2 * 15 min + 1* 40 min</td>
</tr>
<tr>
<td><strong>machine breakdown</strong></td>
<td>MTBF : 11 hours</td>
</tr>
<tr>
<td></td>
<td>MTTR : 1 hour</td>
</tr>
<tr>
<td><strong>Scrap</strong></td>
<td>2 %</td>
</tr>
</tbody>
</table>

**MTBF**  Mean time between failure

**MTTR**  Mean time to repair

The MTBF is defined as the average time between two failures. In our example, the machine works on the average 11 hours before a failure occurs. This failure takes, on the average, 1 hour to be repaired. Then it works for about 11 hours again. And so on.

Each workstation could be characterized by such a set of values. Here we will assume that these values are valid for workstation 2 and that there are no breakdowns, no pauses and no scrap at the other workstations.
**Question : What is the production \( P \) in a shift ?**

<table>
<thead>
<tr>
<th>Workstation 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production rate</strong></td>
<td>1 unit / 23 sec</td>
</tr>
<tr>
<td><strong>normal pause</strong></td>
<td>2 * 15 min + 1* 40 min</td>
</tr>
<tr>
<td><strong>machine breakdown</strong></td>
<td>MTBF : 11 hours</td>
</tr>
<tr>
<td></td>
<td>MTTR : 1 hour</td>
</tr>
<tr>
<td><strong>Scrap</strong></td>
<td>2 %</td>
</tr>
</tbody>
</table>

The production in a shift can be determined as follows.

\[
P_1 = (8 \times 60 - 70) \times (11/12) \times (60/23) \times 0.98
\]

\[
= 960.8 \text{ units/ shift}
\]

The factor 11/12 comes from the fact that the machine is only available 11 hours out of 12 (MTBF/(MTBF+MTTR)).

Here below we propose another way for computing the productivity. It is based on a sketch of what happens during three shifts. Do not forget that the failures occur at random in reality and not deterministically as the diagram seems to indicate.

Based on this diagram (where 3 shifts are considered), we obtain \( P_2 \).

\[
P_2 = (24 \times 60 - 210 - 120) \times (1/3) \times (60/23) \times 0.98
\]

\[
= 945.9 \text{ units/ shift}
\]

\( P_1 \neq P_2 \). Either there is a mistake somewhere or different assumptions are used.

**Question: Where does the difference come from ?**
Let us consider the computation of $P_1$.

$$P_1 = (8\times 60 - 70) \times (11/12) \times (60/23) \times 0.98$$

$(8\times 60 - 70)$ is the time the workers do work in a shift. This is the effective operation time, $eot$. The factor $11/12$ therefore means that for every 12 hours of $eot$, 1 hour is dedicated to machine repair and the 11 remaining hours are dedicated to effective production.

<table>
<thead>
<tr>
<th>$(8\times 60 - 70)$</th>
<th>effective operation time ($eot$) in 1 shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\times (11/12)$</td>
<td>the machine is down for 1 hour of $eot$ every 11 hours of $eot$</td>
</tr>
</tbody>
</table>

We implicitly assumed that the machine may break down only when it is operated. When the workers have a break, then the machine is not operated and cannot break down.

$P_1$ is correct if the failures are function of the $eot$, and if no pause is taken during the repair time.

Maybe the workers are not very cooperative or they simply perform the repair themselves and therefore cannot take their pauses at another time.

Let us now consider the computation of $P_2$ and let us rewrite it as follows.

$$P_2 = (24\times 60 - 210 - 120) \times (1/3) \times (60/23) \times 0.98$$

$$= (8\times 60 - 70 - 40) \times (60/23) \times 0.98$$

$$= (8\times 60 \times (11/12) - 70) \times (60/23) \times 0.98$$

We clearly now see (as the diagram also indicates) that 1 hour for machine repair is extracted every 11 hours of absolute time. The MTBF is now an absolute time. Furthermore, there is no overlap between machine repairs and pauses.

<table>
<thead>
<tr>
<th>$8\times 60$</th>
<th>absolute time (at) in 1 shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\times (11/12)$</td>
<td>the machine is down for 1 hour every 11 hours of absolute time</td>
</tr>
<tr>
<td>- 70</td>
<td>from the up time of the machine in a shift, the workers take 70 minutes pause.</td>
</tr>
</tbody>
</table>

The difference between $P_1$ and $P_2$ comes thus from the interpretation of MTBF. $P_1$ assumes that the failures are operations dependent while $P_2$ assumes they are time dependent.

$P_2$ is correct if the failures are function of the absolute time, and if no pause is taken during the repair time.

$\Rightarrow$ Use a Gantt chart for computing the productivity
4.5.3 Other Problems

Here are some additional problems related to the evaluation of the production rate.

Problem. A preventive maintenance program was installed to prevent breakdowns. This program requires 40 minutes maintenance every 7h20. There are no breakdowns any more. What is the production P in a shift?

\[
P_3 = (8 \times 60 - 70) \times \frac{440}{480} \times \frac{60}{23} \times 0.98
\]
\[
= 960.8 \text{ units/shift}
\]

P3 is calculated as P1 is. The same comments thus apply.

Correct if a maintenance operation is performed every 7h20 of effective operation time and if no pause is taken during the maintenance.

Compared with P1, we did not save anything: the machine stops working every 7h20 of eot and requires 40 minutes for maintenance. The workers may perform or participate in the maintenance. If they don't, then the maintenance could be scheduled during their main pause.

\[
P_4 = (8 \times 60 - 70) \times \frac{60}{23} \times 0.98
\]
\[
= 1048.2 \text{ units/shift}
\]

Here, of course, the maintenance is performed by a different team.

Correct if the maintenance is performed during the main pause (every noon).

Additional Questions

Up to now, we considered only the pauses, the failures and the scrap related to workstation 2.

1. What about the pauses of the other operators?
   It does not change anything if they take their pause at the same time or if there are enough buffers to keep the operators of workstation 2 busy (not blocked nor starved).

2. What if other machines break down?
   Most of the time, each machine failure will stop the whole chain. Only a large number of buffers could keep the workstation 2 busy. If there are no buffers, the productivity calculation is based upon the time during which all the machines are operational and the production during this time.

3. What if you need a maintenance program for all the machines?
   Maintenance takes also time. The main advantage is that maintenance is scheduled. This means the maintenance could be performed on all the machines simultaneously and possibly during the normal worker pauses.
4.5.4 Productivity: Improvements

How to improve the productivity of the system?

The first way to improve productivity is to avoid non-productivity.

- **reduce the working time which is lost**
  - solve worker absence problems
  - solve machine breakdown problems
  - reduce / avoid machine setups
  - reduce scrap rates

- **reduce the task lengths**

Here we reconsider each task. For example, a task can be speeded up through a better design of its environment.

- **improve the allocation of tasks to workers by balancing the line**

Here we reconsider the allocation (task-worker). The manufacturing process can be optimized in order to equilibrate the line. Here is an example where the tasks are redistributed among the operators 2, 3 and 4. The goal is here to avoid starved or blocked time by balancing the line.

<table>
<thead>
<tr>
<th>Operation</th>
<th>time /task</th>
<th>op.</th>
<th>time /oper</th>
<th>op.</th>
<th>time /oper</th>
</tr>
</thead>
<tbody>
<tr>
<td>assemble</td>
<td>4 A on E</td>
<td>14</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>move</td>
<td>3</td>
<td>1</td>
<td>17</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>glue</td>
<td>1B on A</td>
<td>16</td>
<td>2</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>inspect</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>move</td>
<td>3</td>
<td>2</td>
<td>23</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>fix</td>
<td>1C on A</td>
<td>17</td>
<td>3</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>move</td>
<td>3</td>
<td>3</td>
<td>20</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>fix</td>
<td>1D in C</td>
<td>14</td>
<td>4</td>
<td>4</td>
<td>19</td>
</tr>
<tr>
<td>inspect</td>
<td>2</td>
<td>4</td>
<td>16</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

The problem of balancing the line is considered in more detail in the next pages.

- **improve the process organization**

Here we reconsider the assembly line. Perhaps another process organization is more adequate?

- **improve the product design**

Here we reconsider the product design.
4.6 Line Balancing

The problem of balancing a line organization is that of distributing the tasks uniformly among the workers (or among the machines) in order to avoid starved or blocked time. An example was already given on the previous page. Here we propose a systematic technique for balancing a line.

**Given:**
- 1 type of final product
- \( n \) tasks of duration \( t_i \), \( 1 \leq i \leq n \),
- production rate \( P \) or cycle time \( T \)

We have only one type of product to manufacture (our trays for example). The manufacturing requires \( n \) operations. We want to assign these tasks to workstations (operators). The goal is to reach some production rate \( P \) by using as few workers as possible or as little equipment as possible.

**Define:**
- the number of workstations
- the tasks performed at each workstation

Precedence constraints may impose that some tasks be performed before others. For example, for the manufacturing of our tray, it is hard to believe that the straw can be introduced in the lid before the lid is placed onto the cup. Other constraints may also apply. Some operations may for example not take place at the same workstation.

**Such that:**
- production objective is reached
- precedence constraints are met

Here is an example that illustrates the balancing problem.

**Example:**

The goal consists in balancing a line for the production of a finished good FG. The line should produce 28 units per day, or (since a day is made of 420 minutes) one unit every 15 minutes. The manufacturing of each FG requires 12 tasks to be performed.

**Objective:** \( P = 28 \) units / day or \( T = 15 \) minutes/unit

<table>
<thead>
<tr>
<th>task</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>duration ( t_i )</td>
<td>12</td>
<td>6</td>
<td>6</td>
<td>12</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>after</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3, 5</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td>4, 9</td>
<td>8, 10</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Here is the graph of precedence constraints. An arrow from task \( i \) to task \( j \) means that the operation \( i \) MUST be performed before task \( j \).
Heuristic (Helgeson / Birnie)

The term “heuristic” refers to a method that does not guarantee the optimality of the result. It just provides a “good” result. It is made of the following first three steps.

1. Determine the minimum number of workstations

   \[ P = 28 \text{ units / day} \]
   \[ \Rightarrow \text{Cycle time: } T = \frac{1}{P} = 15 \text{ minutes / unit} \]
   \[ \Rightarrow \# \text{Workstations} = \left\lfloor \frac{\sum t_i}{T} \right\rfloor = \left\lfloor \frac{70}{15} \right\rfloor = 5 \text{ workstations} \]

   Since one unit must be produced every 15 minutes, no product can remain more than 15 minutes in any workstation. Since one FG requires altogether 70 minutes of work, there must be at least 70/15 workstations.

2. Order the tasks according to their positional weights

   The positional weight \( PWi \) of a task \( i \) is the minimum work which remains to be done when task \( i \) is started.

   A task with a high weight is a task which should be started as soon as possible since lots or work remains to be done when we start it.

3. Assign the tasks to the workstations in this order, while meeting all the constraints;

   By proceeding in this order, we aim to assign the tasks which should be done early to one of the first workstations.

4. Record the number of workstations really needed.

   Now the solution must be analyzed. First, the number of workstations we need could be larger than foreseen.

5. Try other solutions:

   - try to reduce the number of workstations by increasing the cycle time (for example, \( T=16, 17 \))
   - try to better use the number of workstations by decreasing the cycle time (for example, \( T=14, 13 \))

   In this case, neighbouring solutions must be analyzed.

6. Verify that another line shape cannot give better results.

   Other line shapes (like the U-shape) could lead to better solutions.
Solution

Here we will apply this technique to the example above.

1. **Number of workstations: 5**
   Altogether they could produce 75 minutes of work, that is enough for one FG.

2. **Order the tasks according to PW<sub>i</sub>**
   Here are the values we obtain for each task. Let us consider task 8 as an example. Its positional weight is the sum of the durations of 8, 11 and 12, that is 18.

<table>
<thead>
<tr>
<th>task</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td>4 , 9</td>
<td>8 , 10</td>
<td>11</td>
</tr>
<tr>
<td>t&lt;sub&gt;i&lt;/sub&gt;</td>
<td>12</td>
<td>6</td>
<td>6</td>
<td>12</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>PW&lt;sub&gt;i&lt;/sub&gt;</td>
<td>70</td>
<td>58</td>
<td>31</td>
<td>29</td>
<td>27</td>
<td>25</td>
<td>20</td>
<td>18</td>
<td>18</td>
<td>17</td>
<td>13</td>
<td>7</td>
</tr>
</tbody>
</table>

You note that the tasks were already numbered in this order.

3. **Create as many pots as workstations.**
   - Set each pot capacity to the cycle time T.
   - Fill the pot with the tasks in the above order while satisfying capacity and precedence constraints

   All the pots have initially the capacity 15. We put the task 1 in pot 1. Its remaining capacity (idle time) drops now to 15-12=3. Take task 2. You cannot put task 2 in pot 1 because of the capacity constraint. You put task 2 in pot 2 since you do not have enough capacity left in pot 1. You put task 3 in pot 2 and task 4 in pot 3. Task 5 could fit pot 1 but the precedence constraint tells you must start task 5 after task 2. Pot 2 is the first pot where you could put task 5. It has enough capacity. You put it in pot 2. And so on. You observe that there is no more space for task 12. You must create an additional 6th pot (workstation) for it. In other words, an additional worker is needed if we want to keep a cycle time of 15. In reality, we could possibly consider splitting a task in 2 as well.

4) **Station 1 2 3 4 5 6**
   - **Tasks**
     - **busy time**
     - **idle time**
     - **Station**
     - **Cycle time**
       - 13
       - 14
       - 15
       - 16
     - **# workstations**
       - 6
       - 6
       - 5
     - **Idle time**
       - 8
       - 20
       - 10
     - **Daily production**
       - 32.3
       - 30
       - 28
       - 26.25

Here are the solutions obtained using other cycle times.

5) **Other solutions**
### 4.7 Summary

Summarized here are the main features of the line production organization. These features have been discussed in detail earlier in this document.

<table>
<thead>
<tr>
<th>Performance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Production rate</td>
<td>high</td>
</tr>
<tr>
<td>Product Flow time</td>
<td>low</td>
</tr>
<tr>
<td>Process Investments</td>
<td>high</td>
</tr>
<tr>
<td>Product Cost</td>
<td>low</td>
</tr>
<tr>
<td>Process Flexibility</td>
<td>low</td>
</tr>
<tr>
<td>Product Customization</td>
<td>low</td>
</tr>
<tr>
<td>Process Dependability</td>
<td>low</td>
</tr>
<tr>
<td>Workforce</td>
<td>low-skilled</td>
</tr>
<tr>
<td>Human Aspects</td>
<td>?</td>
</tr>
<tr>
<td>Quality</td>
<td>high</td>
</tr>
</tbody>
</table>

**Pay attention to:**
- the balance of the line
- the full utilization of the line
- the dependability of the line
- the human aspects (team, coop.)

**Use the assembly line for:**
- high (standard) volumes
- small flow times

**What if you want more flexibility?**

Assume for example you want to produce every day:
- A: 100 trays with blue stickers?
- B: 100 trays with red stickers?
- C: 100 trays with red stickers but without lids on the cups?
- D: 100 trays with blue stickers on the straw instead of on the cup?
- E: 100 trays with blue stickers on the straw and on the cup?

**⇒ problems with the line organization**

If the products are just different, we can sequentialize them on the assembly line. However, the products could require different amounts of work at each workstation. In such cases, it quickly becomes impossible to keep the line balanced.

Another solution consists in building different production lines. However, this requires more investment and the different lines could be under-utilized. Another production organization (process flow structure) could then become necessary.
5. Job-Shop organization

After the individual organization and the line organization, the job-shop is the third main kind of production process organization. The production plant is organized as a set of (work)shops. Each shop is responsible for one function or for one family of operations (labeling, stamping, painting, shipping, ...). The different shops work independently of each other.

**Job-Shop = Set of independent specialized (work)shops**

For the FTRAY's, the plant organization could be as follows. Among the many different shops of the plant, three are relevant to the manufacturing of the FTRAY's. These are the Labeling, the Cup-Assembly and the Tray-Assembly shops.

**FTRAY:**
The FTRAY's would be manufactured by the following route:

```
Warehouse    Warehouse    Warehouse    Warehouse
⇒         ⇒         ⇒         ⇒
         − Labeling  ⇒ Cup Assembly  ⇒ Tray Assembly
```

The arrows denote the transfer between the shops. Depending on the synchronization, the products could flow from one shop to another or could be stored in a warehouse at each intermediate step.

Many production systems are organized in shops: a repair shop in charge of servicing cars; a hospital; a department store. As an exercise, try to identify in each of these examples what the different shops are.

**Main consequences of the Job-shop organization:**
The job-shop structure leads to two main features that distinguish the job-shop from other organizations.

1. **A new sequence of operations is easily defined.**
   For example, in order to produce trays with blue stickers on the tray and on the cup, the labeling shop will be visited twice. If we decide to produce and sell assembled cups independently, you do not need to visit the tray assembly shop.

2. **The resources are available for all the products**
   If we have only one labeling machine, it can be put separately and used for labeling both the cups and the trays.
   In a hospital, there is usually at most one scanner for cost reasons. This machine is thus shared by all those who need it. We could talk about the scanning shop.
   On the other hand, thermometers are cheaper. Even if they are seldom used, one thermometer can be bought for each production line. In fact we will find a thermometer in each room.
   Material for echography is expensive too. However, if the gynecological department makes sufficient use of it, there will be one such machine dedicated to this department only.
   This example perfectly illustrates the compromise between the cost of some equipment, its percentage of utilization and its degree of dedication to some product line.
5.1 Job-Shop Performance

- **Workforce Features**
  The workers of a same workshop always perform the same kind of operations and therefore specialize in their job (less than in the line, though).

- **Learning**
  Average. On the one hand, the workers do specialize in their function (painters, packers, ...) and are therefore able to learn. On the other hand, the separation of the shops prevents the communication which can improve the product quality.

- **Process Investment**
  In terms of machines, the investment is minimum. A machine in a shop is indeed available for all the products and no new machine will be bought before its capacity has been exceeded. In terms of handling, equipment is usually needed for transferring the products between the shops.

- **Production Rate**
  High. The specialization of the workers play in favor of a high productivity. Two negative aspects could reduce this productivity: the use of general purpose machines (compared to dedicated machines of the line) and the additional handling required by the job-shop layout.

- **Product Cost**
  Rather small. Few investments and specialized workers lead to low costs.

- **Product Quality**
  Average-low. The positive aspect comes from the task specialization. However, the absence of feedback from the next users prevents the quality of the products from being continuously improved. Furthermore, the additional handling required by the job-shop organization leads to an increased defect rate.

- **Product Flow time**
  Very long. Indeed, the flow time is a cyclic succession of: "wait for turn in front of shop"; "wait for processing of complete lot"; "wait for transfer to the next shop". Sometimes, transits to a local warehouse introduce additional delays. Besides, the flow time is also variable.
  This long flow time also leads to a large amount of WIP.

- **Product Customization**
  High. A new product is simply created by defining a new route in the plant.

- **Process Flexibility**
  High, both in terms of volume and scope. Indeed, since all the investments in equipment are done on a shop basis, they all can be reused for products different than those foreseen or for a product mix different than foreseen.

- **Process Control**
  Very difficult. Indeed, the manufacturing of a product relies on many different shops which are rather independent. Keeping track of the routes and of the states of the various orders is a difficult problem. Let us consider the following example. An order for 100 FTRAY's could be in the following state: 300 cups have already been labeled; 100 of them have been assembled and 10 FTRAY's are already available. Defining what has still to be done is not easy.

- **Process Dependability**
Rather high. If a worker is absent, anybody else in his shop can replace him. Furthermore, the other shops are not affected by this absence. Similarly, a down machine has a relatively low impact too.

- **Human Aspects**

Average. The workers perform different jobs (of the same type). However, they do not see the final products nor the customer who is behind the order. This could lead to a rather low involvement.

**Main Use:**

- **Small lots of very different products**

The job-shop is primary used in sectors that require low cost and high flexibility.

**Main concern:**

The focus will be on the weak points of the job-shop organization. These are:

1. **Difficult Control**
   
   ⇒ **MRP systems**

   Keeping track of the routes and of the states of the various orders is a difficult problem. MRP systems have been designed for such purposes. The principle consists in decomposing an order into the different tasks that need to be carried out at the different shops and in providing due dates for these different tasks. MRP systems will be described in detail in the section on short-term planning.

2. **Long Flow Time**
   
   ⇒ **MRP systems**
   
   ⇒ **Scheduling techniques**

   The long flow times and the independence of the different shops make it difficult to meet the due dates of the orders. In other words, it is rather difficult to keep promises on the delivery time of an order.

   Based on the delivery time of an order, MRP systems aim at providing due dates for the different tasks that are required. These tasks will then be performed in the different shops. However, each shop is loaded with many different tasks and trying to meet the due dates of these different tasks is a constant problem. Scheduling techniques tackle this problem by deciding in which sequence the various tasks will be performed. A brief overview of scheduling techniques is given in the following pages.

3. **Increased Handling**
   
   ⇒ **Layout techniques**

   The organization requires the transfer between the shops (or between the shops and the warehouse) to be organized. A good layout could reduce the distances that need to be traveled. This would improve both the cost and the quality performance.

   Another indirect impact of the layout is the size of the transfer lot. When the distances are short, a production lot can be transferred in several smaller lots. This allows the tasks to be “pipelined” and the total flow time to be reduced. Layout techniques are briefly introduced in the following pages.

   ⇒ **JIT systems**

   Finally, the JIT technique has been designed to address all these job-shop drawbacks. It aims at transforming the job-shop in order to reduce its shortcomings while keeping its advantages. It will also be described in the section on short-term planning.
5.2 Job-shop Scheduling

In this section we briefly introduce the main aspects related to the scheduling of jobs.

What is scheduling the job-shop?

1. Allocate orders and personnel to workstations.
2. Determine the sequence of orders at each workstation.

These are the decision variables.

Objective of the job-shop Management

- Meeting due dates
- Minimizing flow time and WIP
- Minimizing idle time

These are some of the different possible objectives.

Characteristics of the job-shop

1. Job arrival pattern
2. Number and variety of machines, of workers
3. Priority rules for allocating jobs to machines
4. Schedule evaluation criteria

Here is a list of the most commonly used priority rules.

Priority rules

<table>
<thead>
<tr>
<th>FCFS</th>
<th>first-come first-served (FIFO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT</td>
<td>shortest processing time first</td>
</tr>
<tr>
<td>DDate</td>
<td>job with the earliest job due date first</td>
</tr>
<tr>
<td>STR</td>
<td>jobs with the smallest slack time first</td>
</tr>
<tr>
<td>CR</td>
<td>critical ratio: shortest ratio ((due date - current date) / remaining processing time), first</td>
</tr>
</tbody>
</table>

Let us now consider an example to illustrate the first three priority rules.

Example

Each job must be scheduled on the basis of its features: arrival time, processing time, and due date. The chosen schedule will define the departure time of the job and therewith, its flow time and its lateness.

<table>
<thead>
<tr>
<th>Job Number</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival date $a_i$</td>
<td>-9</td>
</tr>
<tr>
<td>Departure date $d_i$</td>
<td></td>
</tr>
<tr>
<td>Processing time $P_i$</td>
<td>9</td>
</tr>
<tr>
<td>Flow time $f_i$</td>
<td>$f_i = d_i - a_i$</td>
</tr>
<tr>
<td>Due date $D_i$</td>
<td>20</td>
</tr>
<tr>
<td>Lateness $l_i$</td>
<td>$l_i = \max(0,d_i-D_i)$</td>
</tr>
</tbody>
</table>
(-9 for the arrival date means 9 days ago). Let us now consider an example. We are at time 0
and we have 4 jobs which can be processed according to different priority rules. Let us try
each of them and record their performance. Let us start with FCFS.

<table>
<thead>
<tr>
<th>FCFS</th>
<th>$P_i$</th>
<th>$A_i$</th>
<th>$D_i$</th>
<th>$d_i$</th>
<th>$f_i$</th>
<th>$l_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>-9</td>
<td>20</td>
<td>9</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>-6</td>
<td>10</td>
<td>17</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>-3</td>
<td>15</td>
<td>19</td>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>-1</td>
<td>18</td>
<td>25</td>
<td>26</td>
<td>7</td>
</tr>
</tbody>
</table>

Let us now consider “shortest processing time” first.

<table>
<thead>
<tr>
<th>SPT</th>
<th>$P_i$</th>
<th>$A_i$</th>
<th>$D_i$</th>
<th>$d_i$</th>
<th>$f_i$</th>
<th>$l_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>-3</td>
<td>15</td>
<td>2</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>-1</td>
<td>18</td>
<td>8</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>-6</td>
<td>10</td>
<td>16</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>-9</td>
<td>20</td>
<td>25</td>
<td>34</td>
<td>5</td>
</tr>
</tbody>
</table>

Let us finally consider “Due date” first.

<table>
<thead>
<tr>
<th>Ddate</th>
<th>$P_i$</th>
<th>$A_i$</th>
<th>$D_i$</th>
<th>$d_i$</th>
<th>$f_i$</th>
<th>$l_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8</td>
<td>-6</td>
<td>10</td>
<td>8</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>-3</td>
<td>15</td>
<td>10</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>-1</td>
<td>18</td>
<td>16</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>9</td>
<td>-9</td>
<td>20</td>
<td>25</td>
<td>34</td>
<td>5</td>
</tr>
</tbody>
</table>

The following properties can be stated for the single machine case.

**On a single machine:**

1. **FCFS minimizes the maximum flow time.**
2. **Ddate minimizes the maximum tardiness.**
3. **SPT minimizes the average flow time.**

Assume two jobs, i and j with arrival date $a(i) \leq a(j)$. With FCFS, the departure dates satisfy
d(i) $\leq$ d(j). In this case, with FCFS, job i remains d(i)-a(i) and job j, d(j)-a(j). Let us now try to
interchange two jobs and show that the maximum flow time can only increase. If you now flip i
and j, then i will leave at time d(j). And it is easy to show that the new flow time of job i is equal
to f(i)=d(j)-a(i). We then have f(i) $\geq$ d(i)-a(i) and f(i) $\geq$ d(j)-a(j). In other words, the new flow
time of job i is larger than that of job i and j in FCFS. A similar proof holds for Ddate.
For SPT, it is easy to show that the total flow times is \( (n-1)p[1] + (n-2)p[2] + ... \),
where $p[i]$ is the processing time of the job scheduled in position i. In order to minimize the
average flow time, the shortest job (in processing time) should thus be scheduled first and so
on.
5.3 Job-shop Layout

Objectives:
Here is a list of possible objectives.

- Minimize the investment required in new equipment
- Minimize the time required for production
- Utilize existing space most efficiently
- Provide for convenience, safety and comfort
- Maintain a flexible arrangement
- Minimize the material handling cost
- Facilitate the manufacturing process

Let us take the following example of a one floor apartment.

<table>
<thead>
<tr>
<th></th>
<th>Kitchen</th>
<th>Sleeping room</th>
<th>Dining room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bathroom</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Living</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Let us consider two approaches.

1. **Build an activity relationship chart and solve**

   The following chart aims to define which proximity is useful and which one is undesirable.

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>K</th>
<th>B</th>
<th>S</th>
<th>D</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall</td>
<td></td>
<td>I</td>
<td>U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td></td>
<td></td>
<td>X</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bath</td>
<td></td>
<td></td>
<td></td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleeping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U</td>
<td></td>
</tr>
<tr>
<td>Dining</td>
<td></td>
<td></td>
<td></td>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Living</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

   Afterwards, the work consists of finding the layout which best meets these constraints.
   On the next page is another approach which aims to minimize the average distance that needs to be traveled.

2. **Build “From-To” Charts**
The first chart describes the number of trips between the different shops. These numbers depend on the routes of the products (the type of products) and on the amount produced (the volume of products). These numbers are derived from the sales report.

**Trips per day (independent of layout)**

<table>
<thead>
<tr>
<th>t(k,r)</th>
<th>H</th>
<th>K</th>
<th>B</th>
<th>S</th>
<th>D</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall</td>
<td>3</td>
<td>1</td>
<td>0.1</td>
<td>0.5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Bath</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Sleeping</td>
<td>0.01</td>
<td>0.1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Dining</td>
<td>3</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Living</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

In this example, we assume we make many more trips between the dining room and the kitchen than between the dining room and the bathroom.

**Distances (dependent of layout)**

The next step consists of measuring each of the trips. These distances depend on the real layout of the plant.

<table>
<thead>
<tr>
<th>d(i,j)</th>
<th>00</th>
<th>01</th>
<th>10</th>
<th>11</th>
<th>21</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
<td>2.5</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>01</td>
<td>1.0</td>
<td>1.5</td>
<td>1.0</td>
<td>2.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>1.5</td>
<td>1.0</td>
<td>1.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2.0</td>
<td>2.5</td>
<td>1.0</td>
<td>1.5</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

This problem could be formulated as an integer quadratic optimization problem.

Minimize the average distance:

$$\sum_{i,j,k,r} d_{i,j} \times t_{k,r} \times x_{ki} \times x_{rj}$$

where $x(k,i) = 1$ if shop $k$ is assigned to position $i$.

**Computerized Layout Techniques: Craft - Corelap**

Different software programs are available to help solve this problem.
6. Processes in general

6.1 General structures

The flow structure of a process refers to the way the material flows in the system.

Structures:  Continuous (conversion)

The flow of products at the process output is continuous.
Examples: steel, plastics, chemical, beer, petroleum, energy.

Line (fabrication and assembly)

All the products (discrete) follow the same sequence of operations.
Examples: automobiles, appliances, toys.

Batches (fabrication and assembly)

All the products follow the same sequence of operations for some time. Then, another sequence is set up.
Examples: microprocessors, clothes, BigMac.

Job shop (fabrication and assembly)

Each product or group of products follows a different route in the plant.
Examples: repair facility, department store.

By plotting the flow structure with respect to the volume, we obtain the following product-process matrix.

<table>
<thead>
<tr>
<th>Low</th>
<th>Volume</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job-shop</td>
<td>Dept. Store</td>
<td></td>
</tr>
<tr>
<td>Batch proc.</td>
<td>Clothes</td>
<td></td>
</tr>
<tr>
<td>Line</td>
<td>Car Assembly</td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>Brewery</td>
<td></td>
</tr>
</tbody>
</table>

When the volume increases, the equipment utilization increases and a complete production line can be dedicated to this product. However, this move also corresponds to a decrease in flexibility.

A similar reasoning holds for the other characteristics of a production process. As an exercise, state this reasoning for the following characteristics.

Characteristics: labor, cost, stock/order, contact

When trying to position companies in the above chart, we observe that most companies operate along the diagonal.

Service:

customization ⇒ job-shop, individual
standardization ⇒ line

Here, the service industry does not differ from the manufacturing industry.
6.2 Constraints

The choice of the best process flow structure is subject to many constraints brought either by the product specification or by the environment.

**Constraints : Product → Process**

Here are some of them.

<table>
<thead>
<tr>
<th>Design</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>It is difficult to keep flexibility in a brewery!</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Automation, Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td>High volume</td>
<td>High automation with low-skilled labor.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variety</th>
<th>Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>A broad product palette</td>
<td>Keeping a flexible production process.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Life Cycle</th>
<th>Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>The production of a young product will not be automated before all its final specifications are known.</td>
<td></td>
</tr>
</tbody>
</table>

The flow structure of the production process often evolves with the life of the product: from a job-shop structure at the beginning of the life to a line when maturity has been reached.
6.3 Performance comparison
We recommend that students compare the three types of organization we have seen: the individual organization, the line, and the job-shop. Here is an empty table to be filled. Do not fill any cell without understanding why.

<table>
<thead>
<tr>
<th>Workforce Features</th>
<th>individual</th>
<th>line</th>
<th>job-shop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Learning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Investments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Flow time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Customization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Flexibility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Dependability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Aspects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Customer Contact</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We recommend that you also use the following example. Let us assume that the sequence of operations at your dentist is always the same: reception (5 min), first examination and injection (6 min), wait for the injection to be effective (10 min), dentist operations (14 min) and finally, some more administration (8 min). If the dentist works alone, you have the individual organization. If he is helped by a secretary for the reception and the final administration, we have a U-shaped line. Finally, if the dentist and the secretary work with several customers in parallel (using a waiting room for the customers who wait for their injection to be effective), we obtain the job-shop structure. Review this example and try to check whether the typical features of these organizations appear.
6.4 Production optimization software

Here we quickly introduce a classical approach to optimize the production rate of a production process. The first step is the determination of the bottleneck of the system: which equipment or operation or operator constraints my productivity.

• **Bottleneck / non bottleneck resource**

Once detected, the first way to improve the system productivity consist in keeping this bottleneck resource from remaining idle. Two other ways are then: to reduce the load of the bottleneck resource or to increase its capacity.

• **Increase output at a bottleneck**

Keep the bottleneck busy.

- buffer the bottleneck
- reduce setup time
- clear up area

Reduce its load.

- use alternate equipment or routing
- overtime - subcontract

Increase its capacity.

- increase bottleneck resource

• **OPT's strategy**

OPT is a commercial software (among others) designed for the evaluation and the optimization of production processes. Here are the main steps for the productivity optimization.

1. detect the bottleneck operations;
2. buffer and dimension the bottleneck operations;
3. dimension the non bottleneck operations;
4. split the lots at non bottleneck stations.

The productivity cannot always be analytically calculated as shown in the earlier examples. Variable processing times, finite buffers and the existence of several chains make the problem much more complicated. Two possible approaches are then simulation and numerical tools such as Markov Chains.

• **Performance Evaluation Software**

However, you should rely on these methods only as a last resort. In many cases, good approximations or bounds can be obtained by an analytical evaluation. Furthermore, the analytical approach has the advantage of telling you where the problems are.

→ Simulation tool
→ Numerical evaluation
6.5 Getting time estimates

When we try to balance a line or when we look for the bottleneck of a job-shop, we need estimations of the time required by the different operations. This is the question addressed here.

**Question: How to get the processing times?**

Before evaluating the productivity of a production process, the times of the elementary operations need to be obtained.

- **table of elementary operations**
  For very basic operations, tables exist. Machine characteristics also mention the time for the various machine operations.

- **measurement**
  Be careful when measuring people. They usually do not behave normally and a pace factor has to be introduced.
    - pace / speed
    - confidence interval:
      the average of n measures is \( N(m, s/\sqrt{n}) \)
    - frequency distribution
  Measuring a set of identical or similar operations allows you to get a distribution for the length of that operation.
  To evaluate the performance of a complete system, we could then use the average of the measured values and assume a deterministic operation time. We could also measure the variance of the measures or keep the complete histogram of observed values.

If the operator acquires experience with production, we cannot assume a fixed operation time. That's the reason why learning curves are often introduced. They aim at capturing the improvement in processing speed. Here is an example of such a learning curve.

- **learning curves** \( Y_i = a i^{-b} \)
  This curves gives the time \( Y(i) \) requires for producing the \( i \)th unit; \( a \) is the time for producing the first unit and \( b \) determines the learning speed. The following development shows that the production time of the \((2i)\)th unit is equal to the production time of the \(i\)th unit but for a factor \(2^{-b}\).

  \[
  Y_{2i} = a i^{-b} 2^{-b} = Y_i 2^{-b}
  \]

  If \(2^{-b}\) equals 0.8, then the time required for producing the 100th unit is 80 percent of the time required for producing the unit numbered 50. Each time the production doubles, the production time is multiplied by \(2^{-b} = 0.80\), that is the production time is reduced by 20 percent.

  Here are some values of \(b\) and of the factor \(2^{-b}\).

  \[
  \begin{array}{ccc}
    b & 2^{-b} & \text{no learning} \\
    0 & 1.00 & \text{no learning} \\
    0.152 & 0.90 & \\
    0.322 & 0.80 & \\
  \end{array}
  \]

  The following table has been computed for \(b = 0.322\).

<table>
<thead>
<tr>
<th>Unit</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>...</th>
<th>128</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>100</td>
<td>80</td>
<td>64</td>
<td>51</td>
<td>...</td>
<td>21</td>
</tr>
</tbody>
</table>
7. Equipment Selection: Checklist

The choice of production equipment comes after the choice of the process flow structure. Here is a kind of checklist of the factors to consider when comparing different equipment.

<table>
<thead>
<tr>
<th>Decision variables</th>
<th>Factors to consider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial investment</td>
<td>Price, Manufacturer, Space requirements, Avail. of 2nd hand models, Needed support equipment</td>
</tr>
<tr>
<td>Output rate</td>
<td>Actual / desired capacity</td>
</tr>
<tr>
<td>Output quality</td>
<td>Consistency with specs., Scrap rate</td>
</tr>
<tr>
<td>Operating requirements</td>
<td>Ease of use, Safety, Human factor impacts</td>
</tr>
<tr>
<td>Labor requirements</td>
<td>Skills and training</td>
</tr>
<tr>
<td>Flexibility</td>
<td>General / special purpose, Special tooling</td>
</tr>
<tr>
<td>Setup requirements</td>
<td>Complexity, Changeover speed</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Complexity, Frequency, Availability of parts</td>
</tr>
<tr>
<td>Obsolescence</td>
<td>State of the art, Modification for other use</td>
</tr>
<tr>
<td>In-process inventory</td>
<td>Timing and buffers</td>
</tr>
<tr>
<td>System-wide impacts</td>
<td>Fit with strategy</td>
</tr>
</tbody>
</table>
8. Investment Analysis

The break-even analysis is a basic method for choosing among different alternatives.

⇒ Choosing among alternative processes / equipments

Assume you have two alternatives for manufacturing your products: a job-shop process or an assembly line process. In the following table, the fixed costs represent the initial investments and the unit costs give the production costs of one unit with each production alternative.

<table>
<thead>
<tr>
<th></th>
<th>Job-shop</th>
<th>Assembly line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Cost (FC)</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Unit Cost (UC)</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The break-even analysis aims at computing the most adequate solution for different production volumes.

⇒ Break-even chart

The job-shop curve satisfies here the equation: cost(x) = 100 + 0.5 x.
The A.L. curve satisfies here the equation: cost(x) = 150 + 0.3 x.
Equating both curves gives x=250. For volumes smaller than 250, the job-shop solution is adequate; for higher volumes, the assembly line solution is better.

\[ \text{FC}_{JS} + \text{UC}_{JS} \#\text{Units} = \text{FC}_{AL} + \text{UC}_{AL} \#\text{Units} \]

⇒ \( \#\text{Units} = (\text{FC}_{JS} - \text{FC}_{AL}) / (\text{UC}_{AL} - \text{UC}_{JS}) \)
Investment Analysis

This does not tell us whether any of the solutions is profitable. Therefore the revenue versus volume curve is needed. It satisfies the equation: \( \text{revenue}(x) = x \times \text{unit price} \)

- Profitability?

<table>
<thead>
<tr>
<th></th>
<th>Job-shop</th>
<th>Assembly line</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>Unit Cost (UC)</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Unit Price (UP) = 0.8

Equating a cost curve with a revenue curve gives the break-even point, that is the volume at which there is no profit and no loss. For the job-shop alternative, the break-even point is 333; for the assembly line alternative, the break-even point is 300.

\[
\text{UP} \times \#\text{Units} = \text{FC}_{\text{AL}} + \text{UC}_{\text{AL}} \times \#\text{Units}
\]

\[
\Rightarrow \quad \#\text{Units} = \frac{\text{FC}_{\text{AL}}}{(\text{UP} - \text{UC}_{\text{AL}})}
\]

At this point the conclusion is: "If we can sell more than 300 units, then use the assembly line process for their production".

This conclusion is of course correct only if the investments and the revenues occur at the same time. Otherwise some actualization must be performed. An example of such an actualization is shown next.
Investment Analysis

• Profitability?

Let us assume that the sales forecasts are given in the following table. Altogether, 350 units should be sold; a quantity which seems sufficient for the project to be profitable.

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>50</td>
</tr>
</tbody>
</table>

However, since the investments and the revenue are performed/collection at different times, we cannot directly compare them. We must first transform these quantities into money at a same instant, "today's dollars" for example.

• Net Present Value

The net present value is the value some money to be collected in the future is worth today (at the present time). Assume for example an interest rate of ten percent.

Interest rate : $r = 0.10$

With this interest rate, 100Euro spared today at the bank will become 110Euro in one year, 121Euro in 2 years, etc. The factor is $(1+r)^n$, for $n$ years.

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Money</td>
<td>100</td>
<td>110</td>
<td>121</td>
<td>133</td>
</tr>
</tbody>
</table>

After 0 year | 100 | 100
After 1 year | 100 * $(1 + 0.1)$ | 110
After 2 years | 100 * $(1 + 0.1)^2$ | 121
...
After $n$ years | 100 * $(1 + r)^n$

Reciprocally, 100Euro collected in the future are only worth 90.9Euro one year earlier; 82.6Euro, 2 years earlier, etc. The factor remains the same. Since $n$ is negative, the 100 Euros will in this case be divided by the factor.

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Money</td>
<td>75.1</td>
<td>82.6</td>
<td>90.9</td>
<td>100</td>
</tr>
</tbody>
</table>

Let us consider the assembly line solution. Each unit is sold with a profit of 0.5. The actualization of these profits (see below) represents a net present value of 137.4. This value does not justify the initial investment of 150. The project is therefore not profitable. Note that this calculation should also be done for the job-shop alternative.

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>Profit</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>NPV</td>
<td>22.7</td>
<td>41.3</td>
<td>56.3</td>
<td>17.1</td>
</tr>
<tr>
<td>Total</td>
<td>350</td>
<td>175</td>
<td>137.4</td>
<td></td>
</tr>
</tbody>
</table>

A more complete calculation would incorporate the influence of the tax system.

An alternative to the NPV computation is the internal return rate (IRR).