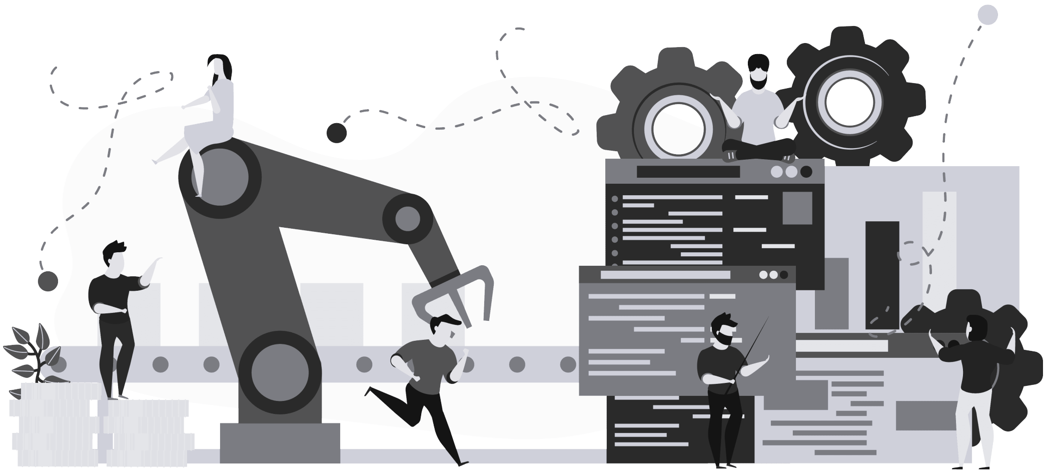
Politecnico di Torino

AUTOMATION AND PLANNING OF PRODUCTION SYSTEMS

Lecture notes



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Chapter 1

Introduction

In this chapter we will see...

Manifacturing is a word which is derived from Latin and it means *made by hand*. This is suited to a reality where most commercial goods where totally made by hand. After many years, factory appeared and the way the products were made changed a lot! In particular the attention was on the use of *machines* instead of *handcrafted mehtods*. In the modern era machines, people and processes to handle them are grouped in complex *production systems* that not rarely are **automated** and **computerized**.

1.1 Production systems

A **production system** is a compound of people, machine, procedures whose aim is to *perform the manifacturing operations* of a firm. Any production system can be divided in two basic components:

Facilities they consist of the factory (physical structure), machines, material handling and inspection equipments and all computer systems to control the manifacturing operations. The **plant layout** is included in this part and is related to the way equipment and workers are *arranged* into the factory. Machines and general equipment are divide into **manifacturing systems** that are groups of machines to carry out some operations fort the production. Roughly speaking, they are all the components that "touch" the products.

Manifacturing support systems These are all the procedure used by the company to manage production and to solve all the problems related to it. In this branch are included product design, the planning of the manifacturing and some control and business operations.

The Figure 1.1 shows schematically what we have just briefly explained here. Along this notes the scheme will be gradually enriched by other topics.

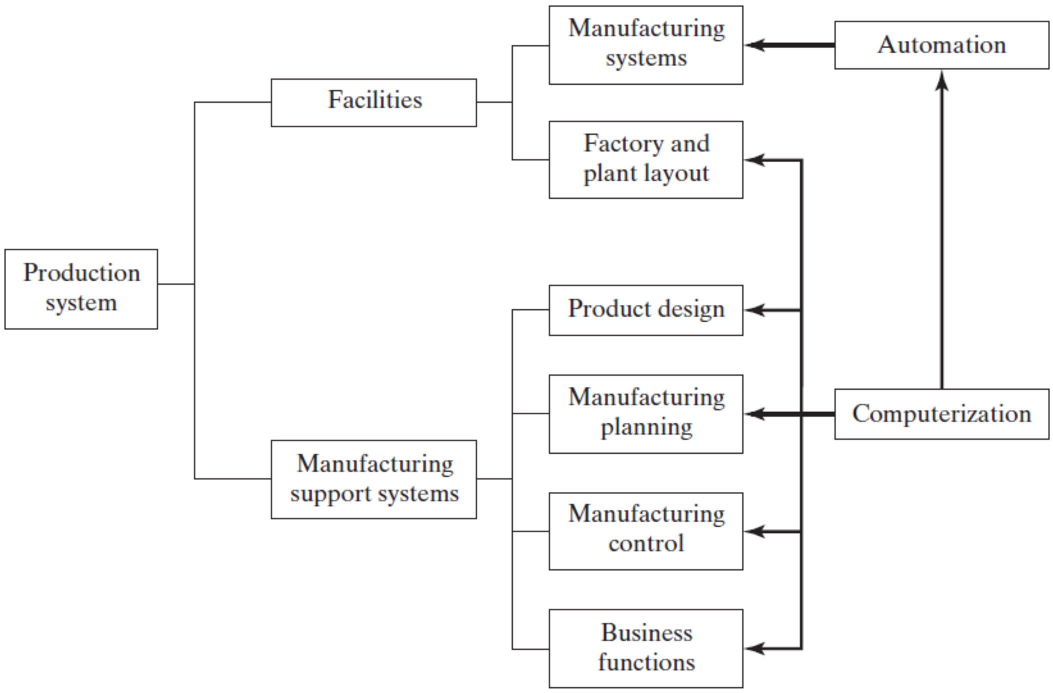


Figure 1.1: Production system structure and types of automation

1.2 Automation in production systems

Automation refers to the possibility to substitute human through machines in order to execute different works. Mainly two types of automation on machines can be considered: (i) *semiautomated machine* which execute only a part of the task independently; (ii) *fully automated machine* is capable to work for long period without the human attention.
Some components of the production system are prone to be automated while other tasks require to operated manually. Also in these case we can divide such components in two categories:

1. **Automation** of the manifacturing systems
2. **Computerization** of the manifacturing support systems

1.2.1 Automated manifacturing systems

Three basic types of automation can be distinguished that practically operates as fully automated systems.

Fixed automation

The sequence of processing operation is *fixed* in the equipment configuration. If there is a sequence of operations to be performed they are usually simple, or they are combination of simple tasks. Such type of systems are used when there is the necessity to produce large quantities of pieces. They are suitable especially when there is small variations in the products.

Programmable automation

At the opposite, we find the **programmable automation**. Here there is the possibility to change the sequence of operations. The sequence of operations is dictated by a **program** which is a sequence of instructions written so that they can be interpreted by the system. They are used for low quantities and for batch production. Note that to produce a new batch of a different item: (i) we have to rewrite the program; (ii) we have to change the setup for equipments. This requires a *changeover time*. Instances of programmable automation are Numerical controlled (NC) machines and Programmable logical controllers (PLCs).

Flexible automation

Such a type of automation is an extension of the previous with the difference that the changeover time is virtually avoided. What makes *flexibility* possible is the fact that the differences between processed parts are not significant, so the changeover necessity is "little". Manifacturing systems which performs machinery processes are in this category.

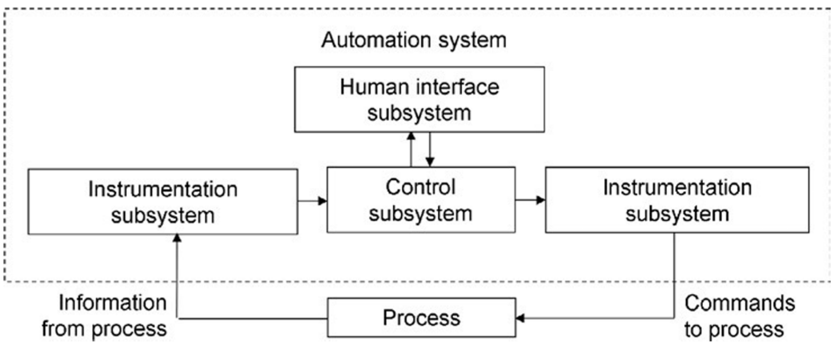
1.2.2 Computerized manifacturing support systems

Automating the part of the production system devoted to manifacturing support is in order to reduce the manual and clerical required effort. In this context the term **Computer Integrated Manifacturing (CIM)** refers to the pervasive use of computers to *design products*, *plan the production*, *control the operations* and so on. Other terms are used to indicate components of the CIM, in particular the *Computer Aided Design (CAD)* supports the the design of the product, while *Computer-Aided manifacturing (CAM)* is used for functions related to the planning.

A core operation in automation is **control**, which can be practically carried out using an **open-loop procedure** (or *feedforward*) or in a **closed-loop** fashion, which exploting the negative feedback principle makes the overall system capable to correct the actions to be performed. Such a type of control strategy is used in the great majority of the application, this is why we focus on automation system which are based on them.

1.2.3 Closed-loop automation system

A **closed-loop automation system** can be divided into three subsystems: (i) Instrumentation subsystem, (ii) Control subsystem, (iii) Human-interface subsystem.



i) Instrumentation subsystem

Is the part devoted to the acquirement of information related to the behaviour of the process (by measuring its variables), such measurements are then sent to a conditioning circuit and

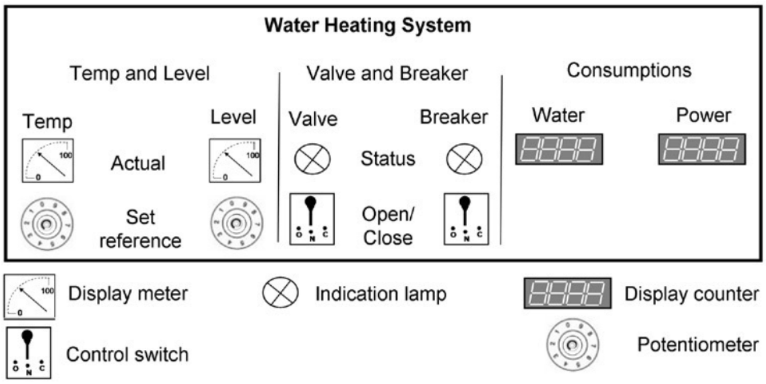


Figure 1.2: Human-Machine Interface

then to the control subsystem.
The instrumentation devices (practically **sensors**) have different structures according to the input and output signals to be measured. They can be both analog or digital. Moreover they can be classified as **transducer** if their output is sent over short distances, **transmitter** if the output signal is sent over long distances.

ii) Control subsystem

It is the heart of any closed-loop automated system and it is in charge for carrying out several (basic) functions regarding:

- Instrumentation subsystem, in particular measured variables are compared to reference values in order to steer the control action through a certain direction by using again the instrumentation;
- Human Interface subsystem, in particular the associated information are an input of the control part which through the instrumentation sends information to the process.

Other advanced tasks of control systems are: i) *safety monitorning* in which some sensors are used in order to track potentially dangerous operations; ii) *maintenance and repair diagnostic* in which the system assists in identifying the source of potential failures; iii) *error detection and recovery* the error detection step uses the available sensor to pick data, classify the error and adopt the needed operation so that the system could achieve again the normal status.

iii) Human-Interface subsystem

The **Human interface** is very important since allows the human to interact with the process in order to change its behaviour. Anyway, if a manual change is not needed the operator can observe it and eventually steer the direction of the process being carried out. The interaction between humans and the process is done essentially by using **valves/breakings** in order to force the process going through a certain direction.

How computers are involved in control

Computers can be used in automating production systems in different modalities. In the following we propose a brief review.

Continuous control Here the objective is *keep the value of an output value at a certain desired level* (clearly this concept can be extended, in the sense that in industrial field many different variables can be **regulated**). Such a type of controllers can be implemented through **embedded systems** (mostly operational amplifiers, resistors and capacitors). An example could be the control of the output of a chemical reaction. To be more specific we can distinguish the following tipologies of continuous control:

- **Regulatory control** where the objective is to maintain the process performacnce within a given tolerance, a compensating action is taken whether there is an output which is different than the desired one (that is the same to state that thee is a non-zero reference tracking error).
- **Feedback-Feedforward control** In presence of disturbances a feedforward controller can be introduced in order to sense and compensate its effect;
- **Adaptive control** It is particularly useful in order to control time-variant systems or to control systems in a time-variant environment. After having identified what are the varied variables, and what should be changed into the control, a modification is implemented.

Discrete control In this case the variables of the system are changed at discrete time, moreover also the action to be performed are discrete typically ON/OFF decisions. This type of control is implemented by using **PLCs**. This can be event driven (the system state is changed) or time-driven (a certain amount of time is spent).

Remark. Continuous control strategies can be also implemented by using digital controllers. In this case the controller is put in an A/D/A chain in order to properly convert relevant signals. By using the digital control approach one is able to perform more complex control actions, think about input constraints, nonlinearities and so on.

To conclude this paragraph we provide a glossary with some important concept together with their definition.

Numerical control	Concerns the use of a computers or a microcontroller in order to control a *machine tool* by using a program with a sequence of operations (see G-Code)
Programmable Logic Controllers (PLCs)	They were introduced in the 70s to substitute electromechanical relays, they can be programmed in order to perform timing, sequencing and counting operations
Supervisory control	It is applied to an higher level than the process, and the objective is to optimize some well-defined function
Distributed control systems	It is made up of a communication network between computers and PLCs in order to distribute as much as possible the process workload. In this context there is a central control room in which Supervisory control happens and local operator stations are present in ordet to introduce redundancy.

1.3 Levels of automation

We have seen that a production system is the composition of different subsystems than can be themselves automated, this is the same to say that in a factory we can talk about automation at different levels.

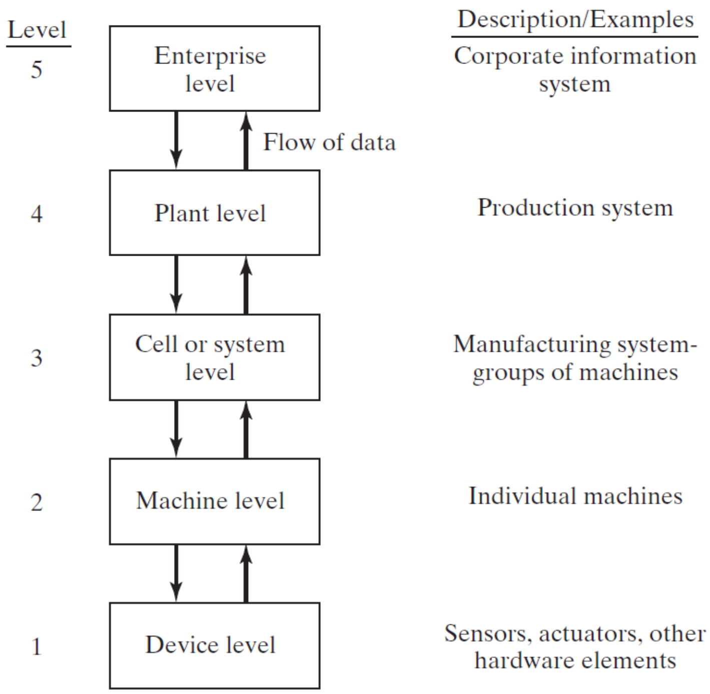


Figure 1.3: Different levels of automation

1. *Device level* Is the lowest level and it is made up of the different components of a single machine. For example at device level we have the feedback loop controlling a single manipulator arm;
2. *Machine level* Putting together all the parts of a device, control happens at machine level. Typical actions at this stage are performing some basic functions described by a program.
3. *Cell level or system level* A cell is nothing but a group of machines connected each other by a computer to which is associated a certain function for the manifacturing system. Typical control functions are the coordination between different machines in order to perform a certain task.
4. *Plant level* This is the factory or production system level and it receives instructions from the enterprise level and translate them into process planning, purchasing and quality control. At this level control is implemented by using a **SCADA (Supervisory control and Data Acquisition)** which: (i) displays the current state of the process; (ii) displays alarms and error logs; displays the trends analyzing them.
5. *Enterprise level* the control actions at this stage are in order to manage the company.

What is interesting to analyzein this form of hierarchy is that *the higher the level, the longest the response time with respect to the control actions*. Moreover the decisions are less but more complicated ones, the same holds for the quantity of informations that flows from one level to another.

1.4 Operation and Process Databases

In an automated production system, some databases are used in order to store relevant information about the single operations or the process.

The Figure 1.4 shows the interactions between the different parts of the automated production system and the databases themselves. We can distinguish:

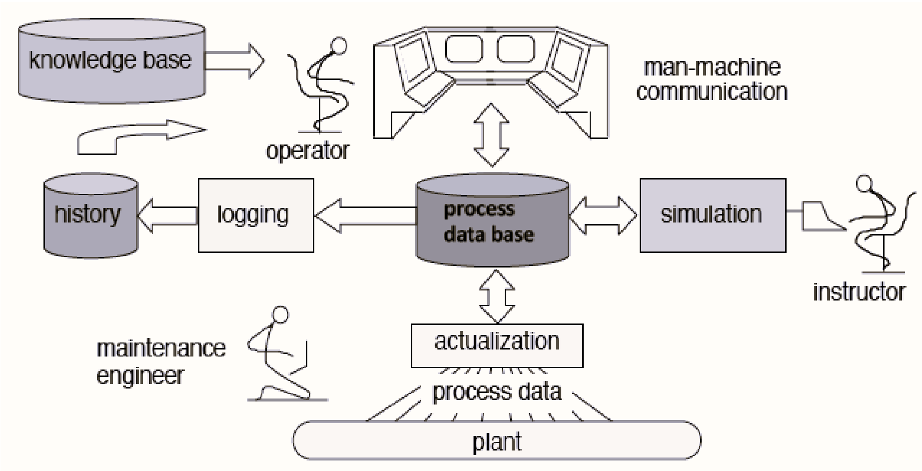


Figure 1.4: Databases in automated manifacturing system

- Process Database this keeps the latest known states of the plant (the granularity of the tracked operations are of the order of the day, hour or minute);
- Historical Database registers snapshot (namely `VIEW`) from the historical database capturing what happened to the plant in a given period (eg. a bimester, a semester...)
- Knowledge Database Is the most particular database which comprises a mixture of process and history data in order to track solved issues, trouble-shooting procedures, documentation and so on.

In order to conclude this chapter we present an example of automated industrial production system, highlighting the different levels of automation and used devices and protocols (*ABB Industrial IT*).

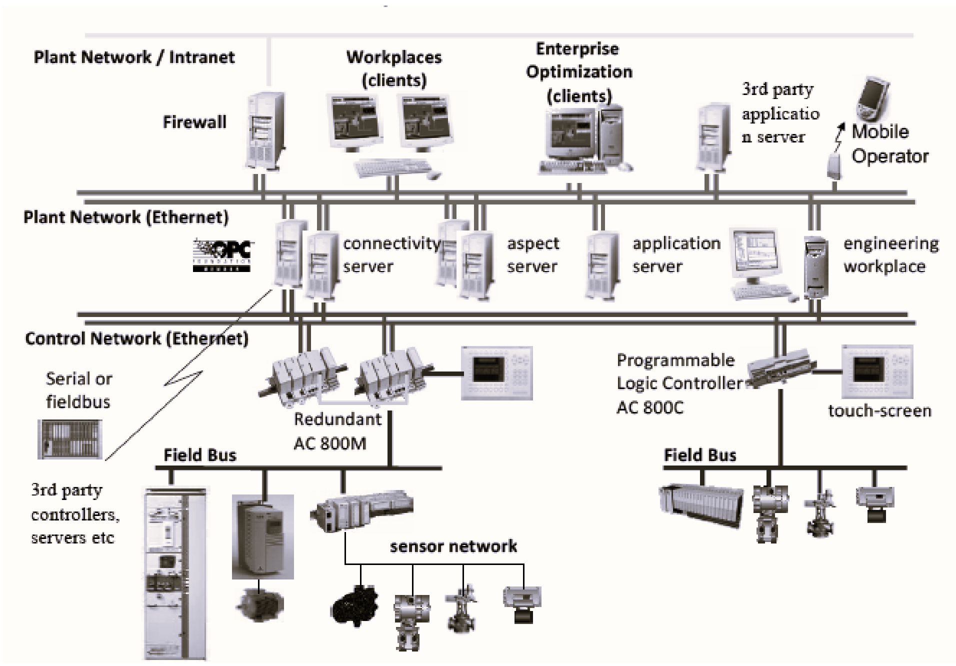


Figure 1.5: ABB Industrial IT

Chapter 2

Manufacturing, production layouts and related metrics

In this chapter we will see...

Manufacturing can be seen as the process which turns starting material into completed/finished products. In this chapter a *classification for industries and products*, a taxonomy of classical operations in manufacturing, a *classification of typical facilities layouts* is made.

From a **technological point of view** the manufacturing process is the application of machinery, tools, power and labor in order to convert some *starting material*[1] into *completed part* also known as *products*. There is another **economic definition** which focuses on the fact that by performing the processing transforming starting material into values, the manufacturing **adds value** to them. Common examples can be made: into transforming sand into glass, manufacturing adds value; into transform iron in steel, value is added and so on.

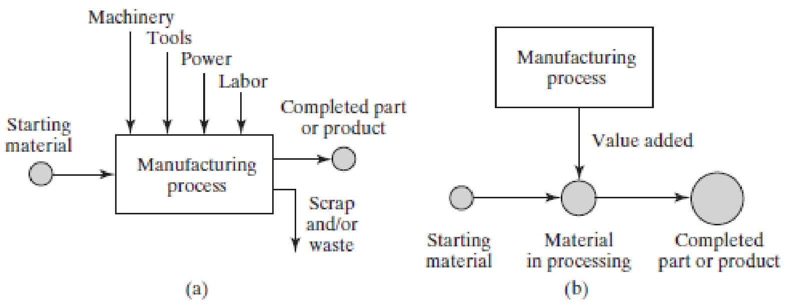


Figure 2.1: Manufacturing: economic and technological views

[1] In some cases, these are raw materials

2.1 Manifacture industries and products

The types of operations involved in the manufacturing process depend on the products a certain factory produces. All of the insustries can be in general classified as:

1. *Primary Industries* they exploit natural resources and materials. Examples of such activities are the agricolture and the mining;
2. *Secondary Industries* convert primary industries materials into products;
3. *Tertiary Industries* is the service sector of the economics.

A further distinction about industries can be made according to the type of products they do. In particular, we can distinguish between **process industries** like chemicals and energy and those industries which produces **discrete parts and products**. The production operationn can be divided into *continuous production* and *batch production*. In the former case the equipment is used exclusively for the fiven product and the output of the process is uninterrupted. In the latter case, starting materials are processed in finite amount or quantities. Such finite amount is called **batch**. Differently from the first case, batch production is discontinuous because there can be interruptions between batches. This distintion is valid for both continuous and discrete manufacturing industries. The figure Figure 2.2 depicts schematically the distinction we have just introduced here.

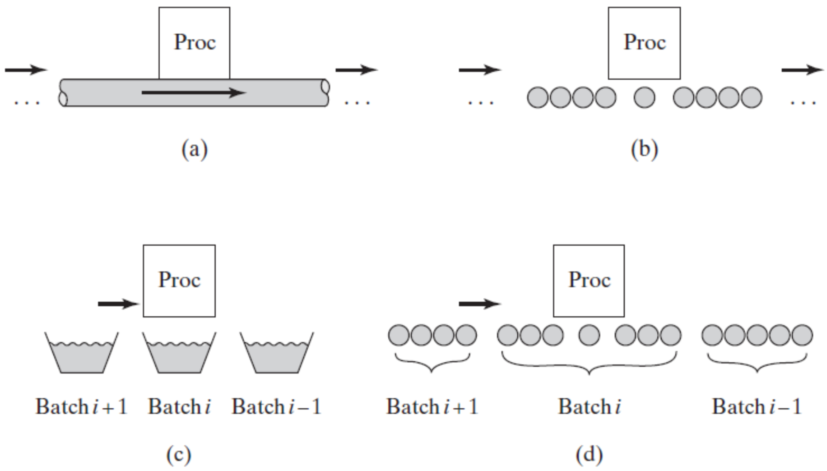


Figure 2.2: (Process/Discrete) vs (Continuous/Batch) production

2.2 Manufacturing operations

What is inside the box depicted as *Manufacturing process* in Figure 2.1? There are some basic activities that must be executed in order to transform raw materials into products. In particular they are: (1) Processing and Assembly operations, (2) Material handling operations, (3) Inspection and tests, (4) operations involving coordination and control.

2.2.1 Processing and Assembling

These are two subclasses of manufacturing process. ***Processing operations*** deal with transforming raw material from one initial state to another which is *closer to the final state*. How it happens for other operations, value is added and in particular the shape, geometry and other

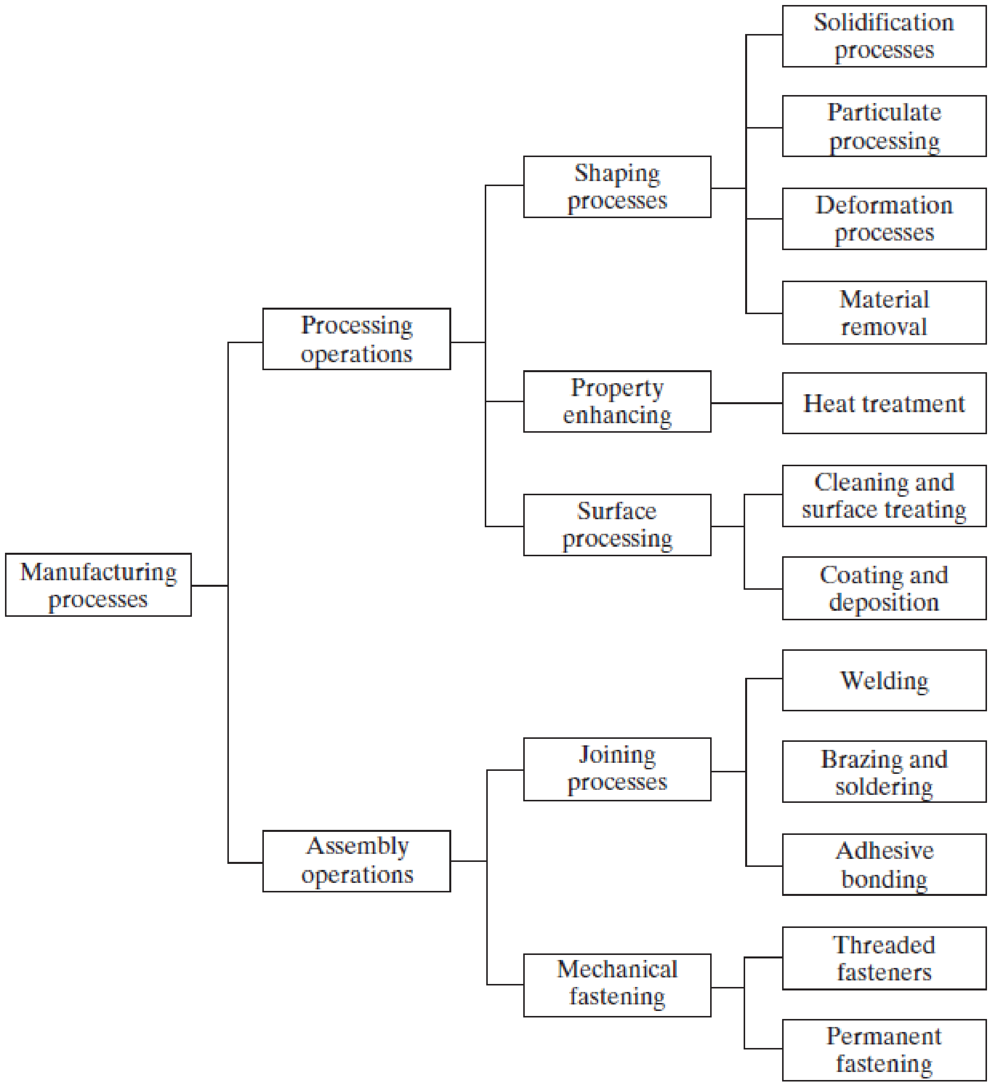


Figure 2.3: Manufacturing processes breakdown

properties are changed. On the other hand, ***Assembling operations*** are in order to put together more elementary parts with the aim of creating **new entities** which sometimes is called *assembly* or *subassembly*. We can add that the different parts are connected together either permanently (eg. soldering) or in a way that at a certain point can be disassembled. This technique for assembling is referred as *semipermanent*.
The figure Figure 2.3 shows a complete classification of processing and assembling operations.

2.2.2 Material handling

Material handling concerns with those operations which are finalized to moving parts and materials between processing or assembling operations. A famous advocate, in a study observed that materials in a typical industry spent the great majority of their time to be moved and properly stored (tipically the 95% of the time a typical part (for batch production) passes its time moving or on shelves).

2.2.3 Inspection and test

Both **inspection** and **testing** are *quality control activities* they are in order to decide whether the products respect standard and specification. More specifically, when one talks about *inspection* examines if the single parts of a certain object are within the tolerances dictated by the engineering drawing of the part itself. The *test* is more referred as testing the **functionalities** of the final product rather than the single pieces constituting them.

2.2.4 Coordination and control

These are all those operation involving plant-level activities. The difference is that here we are talking about support functions, while the first three basic basic activities "touch" in some way either the starting material or the final products.

2.3 Production facilities and Manufacturing layouts

The way a certain factory decides to organize their facilities depend on the type, variety and quantities of pieces, the factory itself can produce. It could seem trivial, but such factors influence a lot the way the facilities can be organized in order to optimize the production. The number of products a given plant produces annually is called **production quantity**. They can be classified into three ranges (namely *small, medium and high* production) whose breakpoint are reported in the figure and are in some sense overlapped. Another important parameter is the **product variety** which, in a quantitative way, can be seen as the number of different products the plant can produce. As you can see in the Figure 2.4 there is a sort of inverse correlation between the two aspects. The higher the variety the lower the annual quantity of produced items.
While the production quantity is a well-quantifiable parameter it is not trivial to give exact numbers on the variety. A mean to introduce a sort of quantifiable distinction is the following criterium: how many differences there are between one product and another? In this context we are referring to **hard variety** (there are substancial differences between products) and **soft variety** (small differences like the ones are made on producing cars).

The Production quantity parameter, moreover, is used in order to individuate **three basic categories** of production plants.

2.3.1 Low Production (1-100 units)

The type of production plant associated with low production is said **job-shop**. The type of products are tipically very complex (for example aircraft, heavy machinery), workers are highly specialized in doing some tasks. In order to tackle the dimensions of such products, they are always in the same position, while moving toward them workers and equipment. This type of layout is known as **fixed layout**. In the practice such products are assembly of large modules made at single location.
The individual parts are built in factories whose plant has got a **process layout** where, basically, equipment is arranged according to its type or function, moreover workers and the equipment they use are arranged in *departments* specialized with a single function. The main advantage of the process layout is the *flexibility* since operations do not have to follow a fixed sequence. At the opposite, more intense *moving/handling* operations are needed to move intermediate artifacts from one department to another.

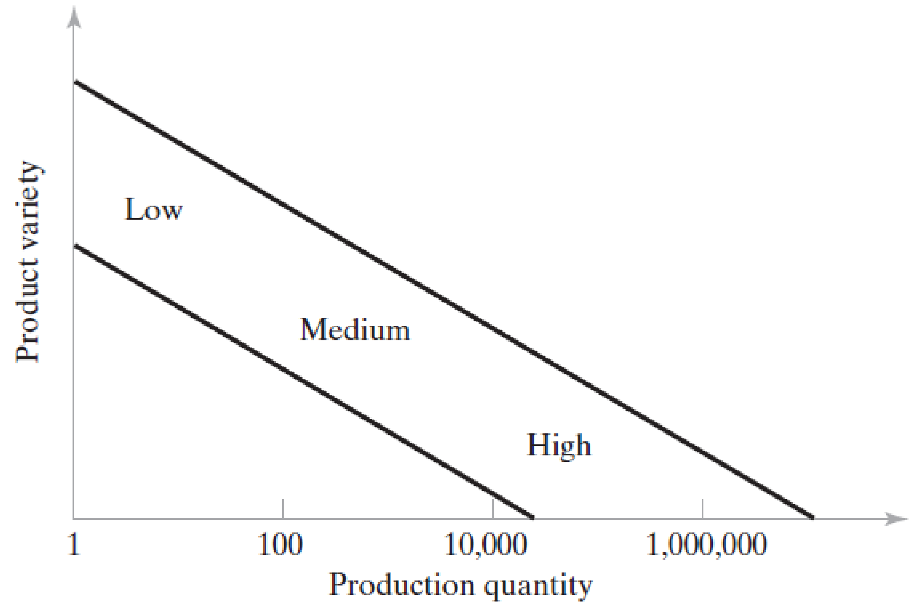


Figure 2.4: Quantity vs Variety plot

2.3.2 Medium production (100-10000 units)

For medium production quantity we can have basically two types of production plants according to the variety for the products. In particular for hard variety we have a **batch production** parts are produced in batches that are later furthermore elaborated (a changeover time is required in order to pass from one step to another). A suitable layout for such a type of plant is the just seen process layout. At the opposite, when you have soft variety for products the equipment (computers and machine) can be organized in cells. Here similar parts/products can be made on the same machinery without a significant time loss for changeover. This is called a **cellular layout**.

2.3.3 High production(10000-1000000 units)

We also refer it as **mass production**, moreover two categories can be distinguished: *quantity production* and *Flow-line production*. **Quantity production** is referred as the production of single parts on single pieces the equipment is specialized in the production of one part type, the classical layout is the process layout. In **Flow-line production** we have multiple workstations arranged in a sequence here materials or assemblies are moved through the sequence in a way that *step-by-step* the final product is obtained. Since the sequence of machines is organized according to the product, this is known as **product layout**.

The figure above summarizes most of the discussion we had on facilities and their layout.

2.4 Product/Production relationship

In the first part of this chapter we have seen that the factories organize their facilities in the most efficient manner according the products they produce. It is particularly useful to observe that there are certain product parameters which are relevant for manufacturing. In particular: (1) production quantity, (2) production variety, (3) product complexity, (4) part complexity.

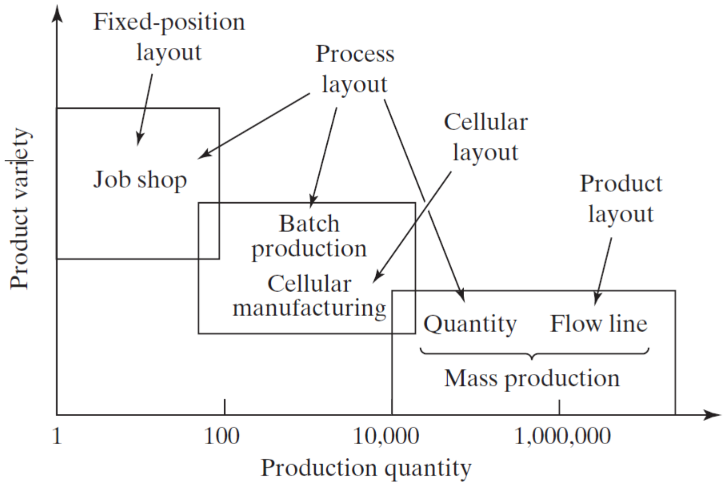


Figure 2.5: Production plants and related layouts

2.4.1 Production quantity and product variety

Production quantity and variety are important parameters which have been discussed previously. We indicate them respectively with Q and P. We can indicate with Q_j the quantity for parts or product of a certain style j while Q_f is the total amount of products/parts ofer all the styles:

$$Q_f = \sum_{j=1}^{P} Q_j \tag{2.1}$$

where P is the number of styles of products/parts. The parameter P is related to the product variety and in order to better embed the concepts of hard/soft variety we can divide it into two sublevels: P_1 is the number of different product lines, P_2 is the number of styles for that product line. In this way the total number of models is given by:

$$P = \sum_{j=1}^{P_1} P_{2j} \tag{2.2}$$

2.4.2 Product and part complexity

Stating something about the complexity of the production is a non-trivial task since they involve both quantitative and qualitative aspects. However, for assembled products the complexity can be seen as the number of components, while for a manifactured part, complexity can be explained by the number of operations that product requires. The tables in Figure 2.7 and Figure 2.8 shows examples of number of processing stages and number of components, respectively, for parts and products.

In the following we will call n_p and n_o the number of parts of which is composed a certain product and the number of operations a certain part requires. From both n_p and n_o can be obtained a classification for industries which is given in Figure 2.9.

There are several relationships can be obtained from Q, P, n_o, n_p, here we are ignoring the diffeerence between P_1 and P_2. The Table 2.1 reports them. Average values of the four parameters Q, P, n_o, n_p could be used to simplify the factory model.

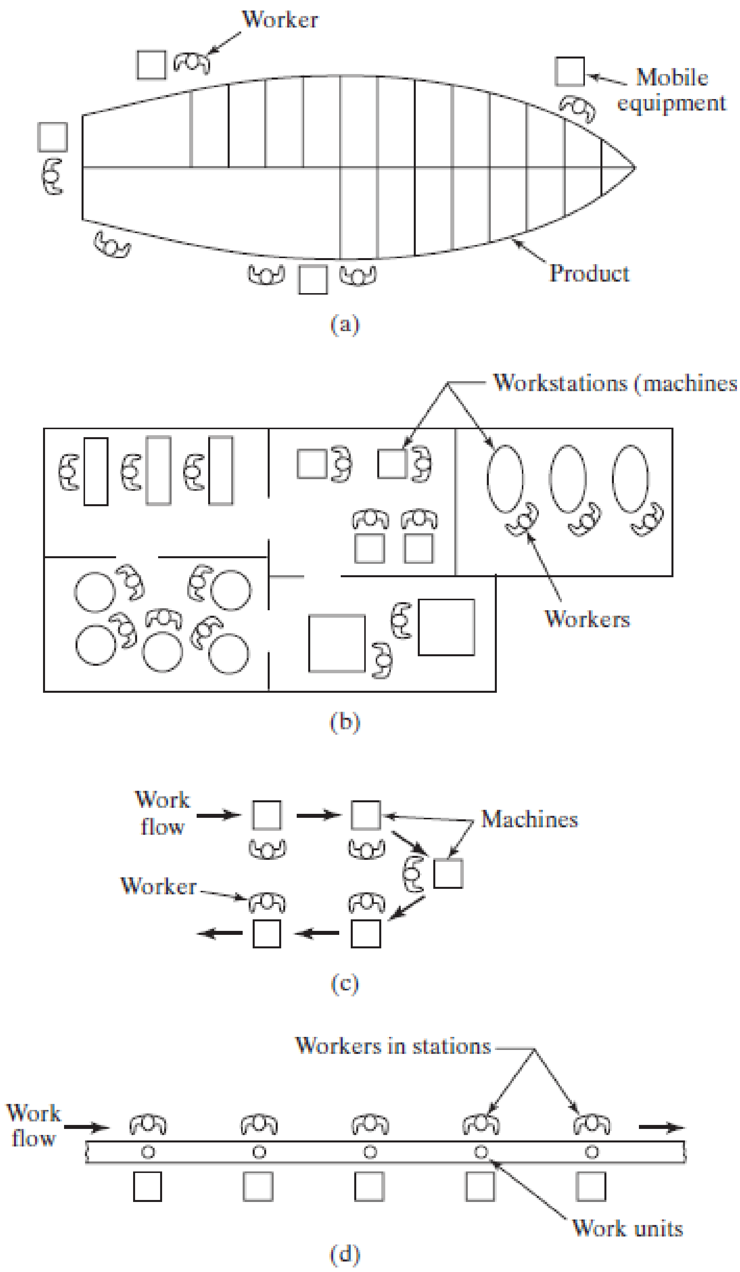


Figure 2.6: (a) fixed layout, (b) process layout, (c) cellular layout, (d) product layout

Part	Approx. Number of Processing Operations	Typical Processing Operations Used
Plastic molded part	1	Injection molding
Washer (stainless steel)	1	Stamping
Washer (plated steel)	2	Stamping, electroplating
Forged part	3	Heating, forging, trimming
Pump shaft	10	Machining (from bar stock)
Coated carbide cutting tool	15	Pressing, sintering, coating, grinding
Pump housing, machined	20	Casting, machining
V-6 engine block	50	Casting, machining
Integrated circuit chip	Hundreds	Photolithography, various thermal and chemical processes

Figure 2.7: Part complexity

Product (Approx. Date or Circa)	Approx. Number of Components
Mechanical pencil (modern)	10
Ball bearing (modern)	20
Rifle (1800)	50
Sewing machine (1875)	150
Bicycle chain	300
Bicycle (modern)	750
Early automobile (1910)	2,000
Automobile (modern)	10,000
Commercial airplane (1930)	100,000
Commercial airplane (modern)	4,000,000

Figure 2.8: Product complexity

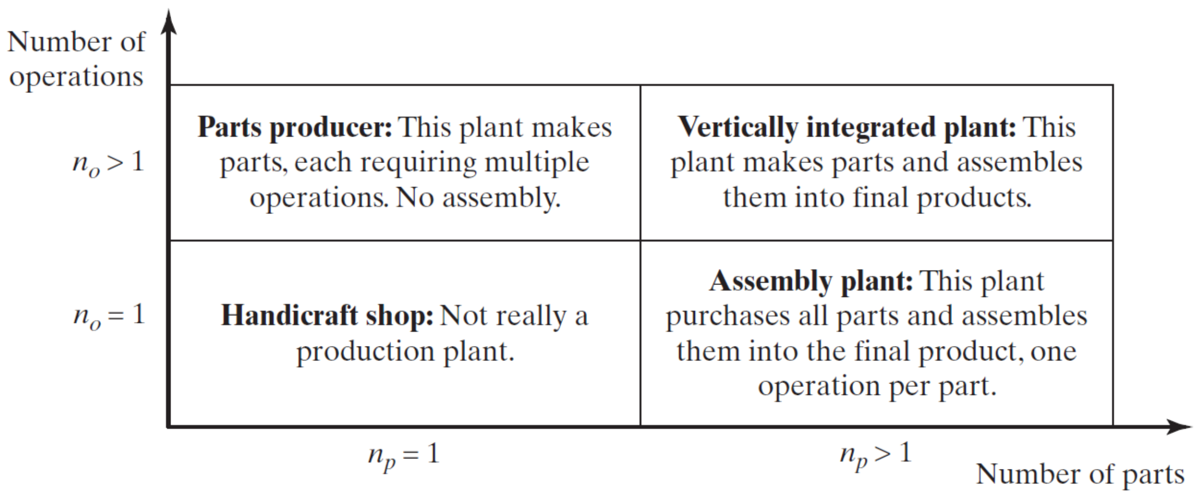


Figure 2.9: Production plants distinction according n_p and n_o

Parameter	Description
Q_f, Q_j	Total product/parts produced annually and total product/parts of a certain style
n_p, n_o	Number of parts for a product (assembly), number of operations for obtaining a certain part
$n_{pf} = \sum_{j=1}^{P} Q_j n_{pj}$	Total number of parts manifactured by the plant
$n_{of} = \sum_{j=1}^{P} Q_j \sum_{k=1}^{n_{pj}} n_{ojk}$	Total number of operatisn required for all the parts for all the products. Here n_{ojk} is the number of operations for a certain part k of a certain style j

Table 2.1: Product parameters

$$Q_f = PQ \qquad Q = \frac{\sum_{j=1}^{P} Q_j}{P} \tag{2.3}$$

$$n_{pf} = PQn_p \qquad n_p = \frac{\sum_{j=1}^{P} Q_j n_{pj}}{PQ} \tag{2.4}$$

$$n_{of} = PQn_p n_o \qquad n_o = \frac{\sum_{j=1}^{P} Q_j \sum_{k=1}^{n_{pj}} n_{ojk}}{PQn_{pf}} \tag{2.5}$$

2.5 Limitations of manufacturing plants

An important aspect to consider is that a manifacturing plant cannot do everything! Often we find the name of *focused factories* to indicate *"on a limited, coincise, manageable set of products, technologies, volumes and markets"*. The objective is then **limiting the scope** of the factory. The most immediate way is avoiding making a fully integrated factory, being a parts producer or an assembly plant is better. In general, all these concepts can be summarized with the term **manufacturing capability** which is the

technical and physical limitatioins of a manifacturing firm and of each plants

2.6 Manifacturing metrics and economics

How we have seen in the introduction quantitative metrics allow to estimate performances of the plant, individuate issues, estimating costs for products and parts. Metrics can be divided in two groups: (i) production performance metrics, (ii) manifacturing costs.

2.6.1 Production performance metrics

Cycle time: T_c (min)

For a single operation (one step) the cycle time T_c is the time that a product/part (work unit) spends being processed or assembled. This is nothing but the time elapsing between the beginning of the processing of a product and the beginning of the next piece. Tipically the cycle time is:

$$T_c = T_o + T_h + T_t \tag{2.6}$$

where T_c is given in min/pc, T_o is the actual processing or assembling operation, T_h is the handling time while T_t is the tooling time which is the time spent in changing from one tool to another.

Production rate: R_p [pc/hr]

For a single operation the *production rate* is the number of work units completed in a hour. Such a metric R_p changes according to the type of production we are considering. Mainly the steps are: (i)obtaining an expression for the production time (min/pc), (ii) inverting it for obtaining R_p (pcs/hr). The different situations arising here are:

- *Job shop.* Considering the case when $Q = 1$, the **production time** is the sum of the setup time and the cycle time, that is:

$$T_p = T_{su} + T_c \tag{2.7}$$

  where the **setup time** T_{su} is the time for preparing the machine in producing that part. In this case the production rate (in pc/hr) is given by

$$R_p = \frac{60}{T_p}$$

- *Batch processing.* Here we have to make a further distinction for pieces of the batch that are processed one at a time and the ones which are processed all together. In the former case we have that the time for processing a batch is $T_b = T_{su} + QT_c$ in the latter case we have $T_b = T_{su} + T_c$. The average production time per unit is given by

$$T_p = \frac{T_b}{Q} \tag{2.8}$$

  where Q is the batch-size, the production rate is computed as before.
- *Mass production.* We have distinguished *quantity mass production* and *flow-line mass production.* We have different formulas for the two cases. In the first case since Q becomes very large the production rate R_p tends to be the **cycle rate** R_c since the setup becomes negligible with the increasing quantity

$$R_c = \frac{60}{T_c} \tag{2.9}$$

  For flow-line production the discussion is a bit more complicated since multiple workstations are involved. At first we can say that the same holds concerning R_p which becomes R_c. But, what about T_c, the cycle time for processing a single part/product is dominated by the **operation time of the slowest machine** to which is added the time T_r to transfer the pieces between work units. Summarizing:

$$T_c = \max T_o + T_r \tag{2.10}$$

  remind that $T_c \rightarrow (min/pc)$. At this point the cycle rate can be obtained as usual.

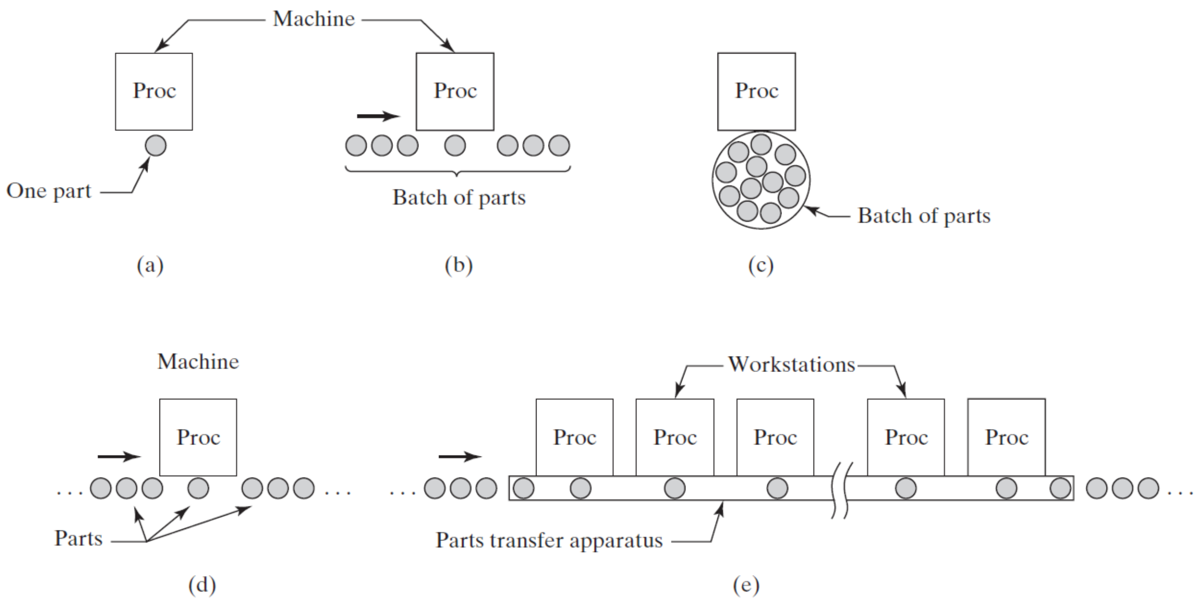


Figure 2.10: Different production plants for considering production rates

Equipment reliability: availability

Till now, we have considered the different ways by which computing the production rates in the ideal case, that is ignoring the lost time due to the *equipment reliability.* The metric we can use for reliability is the **availability** which is defined as the portion of the time the equipment works correctly. In turn, the availability A is defined according other two metrics (MTBF, Mean Time Between Failure and MTTF, Mean Time to failure). The exact formula is:

$$A = \frac{MTBF - MTTR}{MTBF} \tag{2.11}$$

the average production rate is obtained by multiplying the R_p by the availability. This is the same to say that in the non-ideal condition the production rate is reduced according to the availability of a certain machine.

Plant Capacity (PC)

The production capacity is defined as the **maximum rate of output** that a plant can produce under a set of operating conditions such as: number of shifts per day (1-3), number of days in the week... The operating conditions are not trivial to determine. Suppose you have n machines producing the same part and having the same production rate R_p, the production rate in this case is given by

$$PC = nH_{pc}R_p \tag{2.12}$$

where H_{pc} is the amount of hour in the period and PC is measured in (pc/period). The period can be for example a week, a month, a year... A slightly more complex situation arises when the n machines have different production rates, but all can work for Hp hours/period, the PC is in this case

$$PC = H_{pc}\sum_{i=1}^{n} R_{pi} \tag{2.13}$$

where R_{pi} is the production rate for the i-th machine. In case of batch production there are cases in which the same machine produces different part style j. It is useful in this case to introduce in this case the fractions f_{ij} which is the **fraction of the total operating time in which a certain machine i process the part style j**. Since they are fractions of a totale must be that

$$0 \leq \sum_j f_{ij} \leq 1 \text{ where } 0 \leq f_{ij} \leq 1 \tag{2.14}$$

The production output in presence of multiple part for multiple machine must include the effect of the operation sequence for part/product j. The average hourly production output for the plant (made up of n machines) is given by:

$$R_{pph} = \sum_{i=1}^{n} \sum_j f_{ij} R_{pij} / n_{oj} \tag{2.15}$$

where R_{pij} is the production rate of the i-th machine producing parts of the j-th style, while n_{oj} is the number of operations (number of visited machines) in processing the part of style j. The production time for the i-th machine producing the j-th style is given by:

$$T_{pij} = \frac{T_{suij} + Q_j T_{cij}}{Q_j} \tag{2.16}$$

where Q_j is the batch quantity of the part j. In order to obtain the production rate in a week, R_{pph} must be multiplied for H_{pw} which is the number of hours in a week in which the plant is operative

$$R_{ppw} = H_{pw} R_{pph} \tag{2.17}$$

It can be demonstrated that under suitable conditions $PC = R_{ppw}$. With the aim of **adjusting the plant capacity** several changes can be made which are short term or lomg term. Examples of short term actions are: (i) reducing or increasing the number of shifts; (ii) reduce/increase the number of hours per shift; (iii) Decrease or Increase the number n of machines. On the other hand, long term measures are: (i) Introducing new machines that was not present in the plant; (ii) increasing the production rate by changing technology or methods were employed before;

Utilization (U)

The *Utilization* (U) is the proportion of time that a production machine is used under the definition of the plant capacity. This is nothing but summing the fractions f_{ij} were defined before.

$$U_i = \sum_j f_{ij} \tag{2.18}$$

whee U_i indicates the utilization for the i-th machine, while f_{ij} is formerly defined. An overall metric can be obtained by averaging the U_i

$$U = \frac{\sum_j U_i}{n} \tag{2.19}$$

Workload (WL)

The *Workload* is defined as the total hours required to produce a given number of units during a given period if interes.

$$WL = \sum_i Q_{ij} T_{pij} \tag{2.20}$$

	Machine 1		Machine 2	
Part	R_p	Duration	R_p	Duration
A	25 pc/hr	12 hr	30 pc/hr	10 hr
B	10 pc/hr	20 hr		
C			7.5 pc/hr	24 hr
D			20 pc/hr	6 hr

Figure 2.11: Example of duration, R_p for $n = 2$ machines and 4 different styles $A - D$. The WL is, in general the sum of the duration over all the machines $WL = 12 + 20 + 10 + 24 + 6 = 72$, when used as plant capacity is the number of H_{pw} multiplied by the number of machines, that is $WL = 2 \cdot H_{pw} = 2 \cdot 40 = 80$

.

The workload can be used as a measure for the plant capacity for tackling the problem of mixture parts in production, that is the same to say that the production rate strongly depend on the fraction of pieces produced in the given period.

Manifacturing lead time (MLT)

The *Manifacturing Lead Time (MLT)* is the ttotale time required to process a part or a product through the plant, including any time due to delays, part being moved between operations and so on. Practically speaking it can be computed (by using average measures) as:

$$MLT = n_o(T_{su} + QT_c + T_{no}) \tag{2.21}$$

where MLT(min) is the average manifacturing lead time for <u>all parts</u> in the plant, T_{no} is the *non-operation time*[2]

Work-In-Process (WIP)

The WIP (Work in process)[3] (measured in pieces) is the total number of pieces which are present in a given firm. That is the product which are being processed or that are between processing operations. It can be defined as

$$WIP = R_{pph}(MLT) \tag{2.22}$$

The pieces computed by analyzing WIP cannot be transformed into revenue until all processing has been completed. The most desirable thing is that as soon is possible, all WIP could be converted in revenue.

2.6.2 Manifacturing costs

The decisions can be made about the automation of production systems can be made according to the **relative costs of alternatives**. In this chapter we are seeing how such costs, referred

[2] One can wonder the reason why such non-operation times are present. There is the time for transporting one batch from one operation to another, the time lost for an issue in the equipment, the time spent in assembling queues of products and so on.

[3] aka *Work-in-progress*

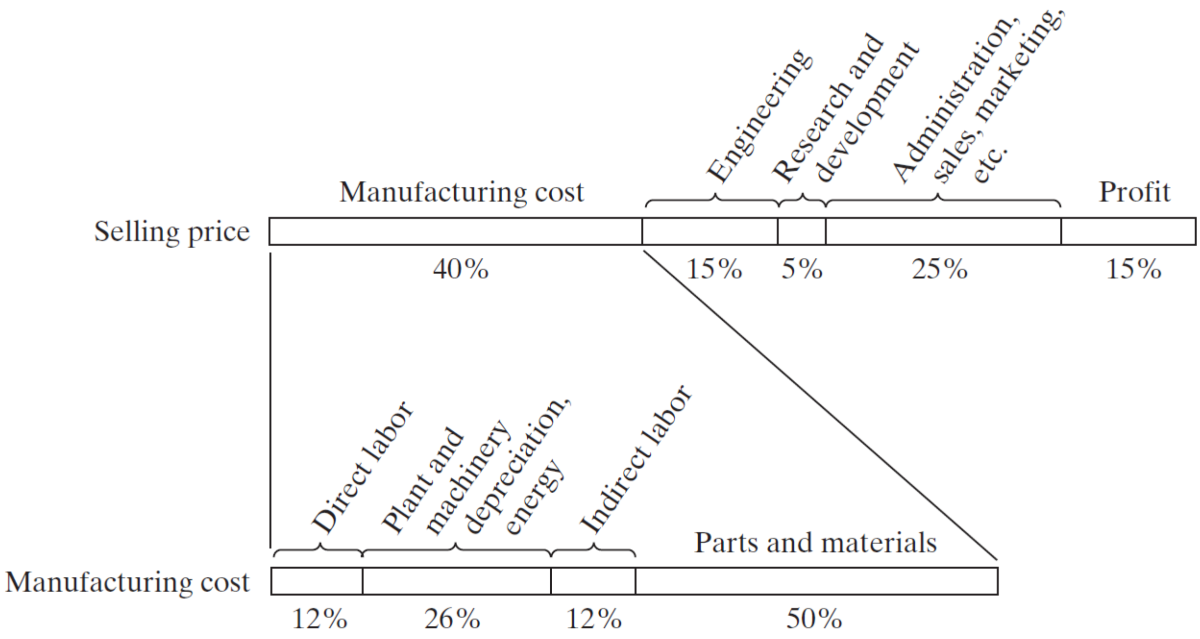


Figure 2.12: Breakdown of manifacturing costs

as *manifacturing costs* are determined.
There are two main categories of manifacturing costs:

1. *Fixed costs (FC)* which remains constant for any output level of the production plant;
2. *Variable costs (VC)* are the ones varying according to the output of the plant.

The total cost can be obtained as

$$TC = FC + VC(Q) \tag{2.23}$$

where Q is the output level. In order to evaluate some production methods, a useful thing is building a diagram of the production quantity vs the (total) costs. In fact, you can see in fact that Equation (2.23) is a line in the variable Q.
An alternative classification of manifacturing costs is the one individuating:

- *Direct labor* which are the salary for the workers;
- *Materials* comprise the cost for raw material/starting material;
- *Overhead* are all the other expenses associated with th firm which can be Factory overhead if those costs are related to the production, otherwise if they are related to the managing part, they are called Corporate overhead.

The Figure 2.12 shows a typical breakdown for selling price and manifacturing costs. Some overhead factors (tipically in percentage) can be computed in order to be able to estimate parameters like the selling price. Such factors are:

$$FOHR = \frac{FOHC}{DLC} \qquad \text{Factory overhead rate} \tag{2.24}$$

$$COHR = \frac{COHC}{DLC} \qquad \text{Corporate overhead cost} \tag{2.25}$$

where DLC is the direct labor cost.

Cost of Equipment Usage

An hourly cost of *worker-machine* system is given by:

$$C_o = C_L(1 + FOHR_L) + C_m(1 + FOHR_m) \tag{2.26}$$

where C_o is the hourly rate ($/hr), C_L is the labor rate and C_m is the machine rate while $FOHR_L$ and $FOHR_m$ are respectively the labor and machine factory overhead rate.

Cost of a Manifactured Part

The cost for a manifactured part is defined as the sum of production cost, material cost and tooling cost. For a unit operation the cost is given by

$$C_{oi}T_{pi} + C_{ti} \tag{2.27}$$

The cost for the final product/part is given by the sum of the material costs and unit costs:

$$C_{pc} = C_m + \sum(C_{oi}T_{pi} + C_{ti}) \tag{2.28}$$

Where C_{pc} is the cost per piece and C_m is the cost per piece for starting/raw material.

Chapter 3

Programmable Logic Controllers (PLCs)

The diffusion of more and more powerful and cheap computer has given the possibility to introduce in the field of industrial automation *Programmable Logic Controllers (PLCs). Such devices, with respect to traditional technologies, bring with them a lot of advantages. After a brief introduction about the different tipologies of traditional hardware for industrial automation, we will focus our attention on PLCs of which we present features and programming modalities.*

In this chapter we will see...

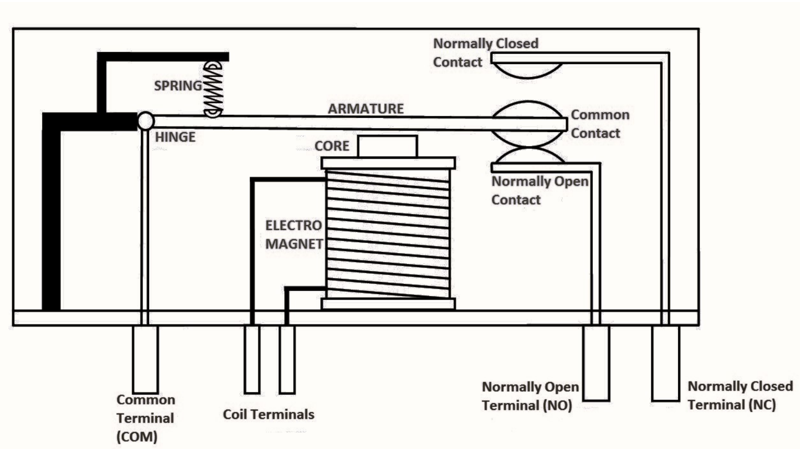


Figure 3.1: Relay scheme

3.1 Industrial Automation Hardware

In the field of *Industrial automation* the controllere can be found at different places: (i) directly in the senso or in the actuator (analog PIDs), as a separate device or as an algorithm in a computer (here there is the possibility to manage a great number of loops). There are many possibilities to realize a controller:

Wired relay systems At first in absence of computers and programmable devices, controllers was realized through ***relays***[1] and dedicated control loops; the number of such devices for automating the production was not negligible: you can imagine that the changeover time was not short at all, too. The schematic given by the engineers to the electricians which embeds the logic to implement was called *ladder schematic* which used to display sensors, motors, valves, relays you were able to find into the system. Such systems were based on mechanical systems whose moveable parts represented a problem to face. Moreover, if only one relay stopped working, the entire system had to be checked.

Analog circuits A step forward was made introducing *operational amplifier* in order to implement PID controllers; there are several circuits exploiting the *virtual ground principle* in order to simulate the proportional, integrative and derivative blocks.

Embedded circuits More modern technologies which are *microprocessor-based.* They are designed for a specific task and are parts of more complex systems including other hardware and mechanical parts. They have a lot of advantages, among the other: low power consumption and reduced sizes. They can be based on microcrocontroollers, DSP, microprocessors or FPGAs.

Industrial PC It is nothing but a PC integrated with specific expansions, machine interfaces, expanded communication ports and so on. They are characterized by different construction properties which make them more suitable to the context they are used in (for example: alternative cooling methoeds, heavier metal for the external frame...)

PLCs (Programmable Logic Controllers) whose main features are well-explained in the next paragraphs.

3.2 The advent of PLCs

The realization of low cost computer made possible the most recent evolution in automatin industrial plants: the advent of PLCs. This phenomena begain in 70s. More specifically, in 1968 *General Motors* issued a first PLC prototype request in order to progressively substitute hard-wired relays.

Definition 3.2.1. A **PLC** is a real-time microprocessor-based system that implement functions as *logic, sequencing, timing* and *arithmetic operations* in order to perform some control tasks.

PLCs, probably, will remain predominant on the factory floor. This is due to some particular features:

- They can be used to control complex mutlivariable systems;
- They are reprogrammable, for this reason they can be reapplied to different systems;
- The fact a computational abitily can be used, they can address even more complicated control tasks.
- They have analog and digital I/Os with standard levels. Depending on the tipology they can have a large number of peripherals.
- They are relatively cheap, while the value is the in the application software.

The first PLCs were programmmed using the same schematic used for describing the realization of wired relay-based systems (ladder diagrams). This eliminated the need to teach

[1]A **relay** is a simple electromechanical device that use a magnetic field to control a switch. In this device there is a coil that, when energized creates a magnetic field that pushing a piece of metal close/open the switch.

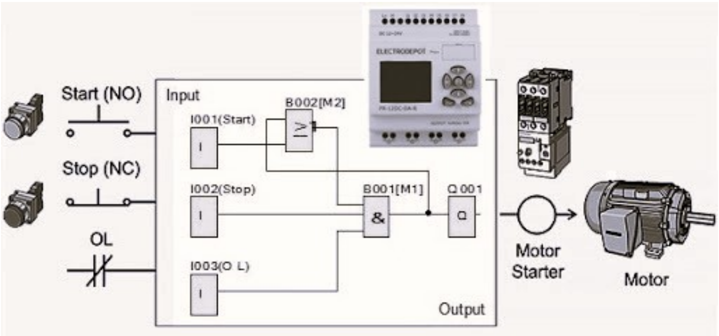


Figure 3.2: An example schematic for a PLC

the technicians to program them. Nowadays, ladder diagrams are the most common way to program a PLC.
It is remarkable, that there is a standard, the IEC 61131-3, which enumerates five programming languages for PLCs which are splittable into two categories: (i) **graphical languages** which comprises Function Block Diagram (FBD), Ladder Diagram (LD) and Sequential Flow Chart (SFC); (ii) **textual languages** which comprises Instruction List and Structured text.

3.2.1 PLC connections

How the PLCs is used? When a process is controlled by using a PLC it uses input from sensors to make decisions and provides outputs which drives actuators. The control loop, as usual, is continuous cycle for: (i) reading the inputs, (ii) solving the ladder logic, (iii) changing the outputs accordingly.

3.3 Ladder diagrams

How we mentioned before, **ladder logic** is the main programming method for PLCs that mimic the relay logic and it has been explained why the decision to use it was a strategic one[2]. An example of ladder schematic is given in the Figure 3.3.

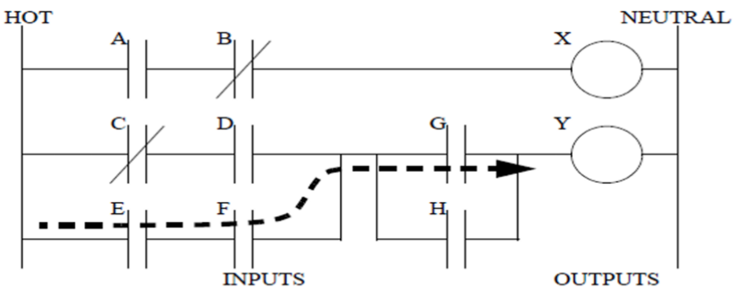


Figure 3.3: Example of ladder schematic

Just to give a bit of terminology, the power flows from left to right among two rails which are called **hot** and **neutral** rails. A basic element of a ladder schematic is the **rung** which in which there are combinations of *inputs* (vertical lines, barred vertical lines) and *outputs*

[2]Note that nowadays relays are also used in modern control systems but not for implementing the logic which is almost totally demanded to PLCs

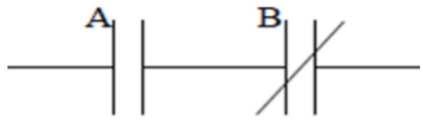


Figure 3.4: *Normally open* and *normally closed* inputs

(circles). An input can come from a sensor, while the *output* is some device which is external from the controller (light, motors) which is switched on or switched off.

3.3.1 Ladder logic Inputs

There are tipically two types of inputs for the ladder schematic: *normally open* and *normally closed* inputs. In the former case, an active x will close the contact and allow power to flow; in the latter case, power flows into the input whether the input x is not closed.

3.3.2 Ladder logic Outputs

In general, in ladder logic, there multiple types of output, but not always they are supported from all PLCs. The most common one is represented by a circle, this type of output when energized will turn on (normal output). There are also more complicate types of output which allows us to latch an output value until we do not decide to unlatch it.

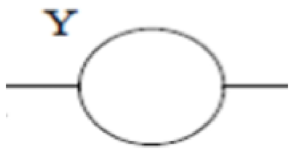


Figure 3.5: *Normal output* ladder symbol

3.3.3 Example: Design of an alarm for an house

Remark. There is a strong correspondence between boolean logic and ladder schematics. In particular, one from the problem can obtain a suitable boolean function, which being simplified[3] can be realized through a ladder schematic. Namely, in the following there are the schematics for the AND and OR ports. The NOT is realized through a *normally closed* input.

Now, we want to obtain the ladder schematic which solves the following problem:

> Consider the design of a burglar alarm for a house. When activated an alarm and lights will be activated to encourage the unwanted guest to leave. This alarm will be activated if an unauthorized intruder is detected by window sensor and a motion detector. The window sensor os effectively a piece of thin metal which encircles the window. If the window is broken, the foil breaks breaking the conductor (normally closed switch). The motion sensor is designed so that when a person is detected the output will go on. An activate/deactivate switch is also needed.

The basic operation of the alarm system is summarized in the following. In particular, the *inputs and outputs* of the system are chosen to be:

[3] Using some method. For example: Boolean algebra theorems or Karnaugh maps.

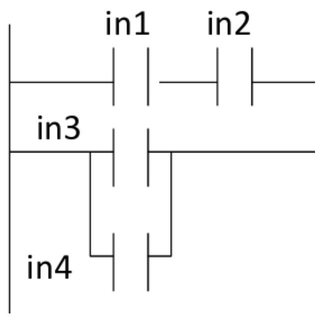
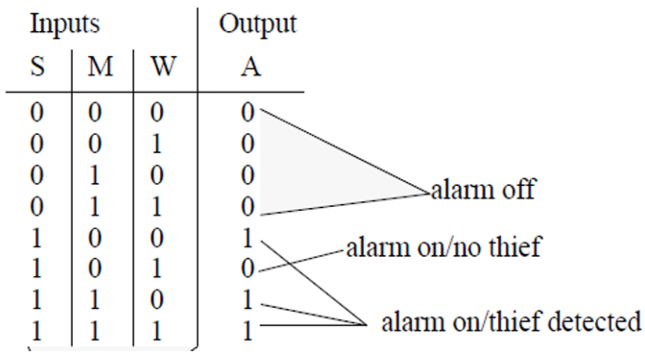


Figure 3.6: AND and OR schematics. The series of two normally open switch can be used to model an AND, the parallel connection between two normally open inputs realize an OR.



Inputs			Output
S	M	W	A
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	1

Figure 3.7: Truth table for the *Burglar Alarm* example

A=Alarm and lights switch (1=on)
W=Window/Door sensor (1=OK)
M=Motion Sensor (0=OK)
S=Alarm Active switch (1=on)

The basic operation of the alarm can be described by the following rules:

- If alarm is on, check sensors.
- Is window/door is broken (turns off), sound alarm and turn on lights.

The next step is building a **truth table** summarizing the behaviour of the alarm system. Using some simplification technique (Boolean algebra or Karnaugh maps) the simplified boolean expression related to truth table is:

$$A = S \cdot (\bar{W} + M) \tag{3.1}$$

which in ladder logic can be realized by using the series between S and the parallel $(\bar{W} + M)$.

3.3.4 Latches, Counters, Timers

Till now we have seen the basic building block to obtain any combinatorial function we want. More complex systems cannot be controlled with the combinatorial part alone. Typical, more sophisticated operations one would to solve are: (i) block a certain output and properly unlock it; (ii) waiting that a certain time elapses; (iii) count some events.

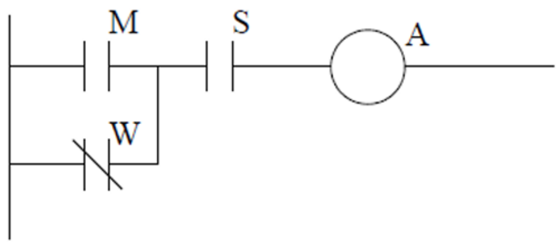


Figure 3.8: Ladder schematic for the *Burglar Alarm* example

Latches

A **latch** is like a *sticky switch*: when you push it down it will turn on, but after it stick in place, it must be pulled in order to turn it off. In ladder logic for a single latch there are two symbols one for latch the output (a circle with a L), another for unlatching it (a circle with a U).

Remark. If an output **has been latched on** it will keep its valu, even if the power has been turned off.

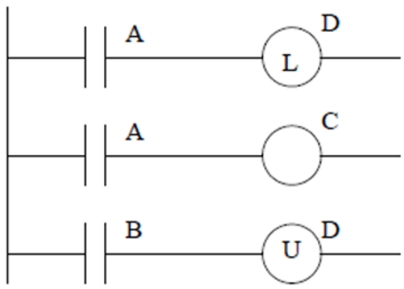


Figure 3.9: Schematic for latch/unlatch the output

In order to better understand how such devices work, we propose a *timing diagram* with inputs A, B and outputs C, D. It is interesting to observe that while C is on only when A is on, the output D is instead locked (latched) until the input B is not active, this event automatically turns off the output D.

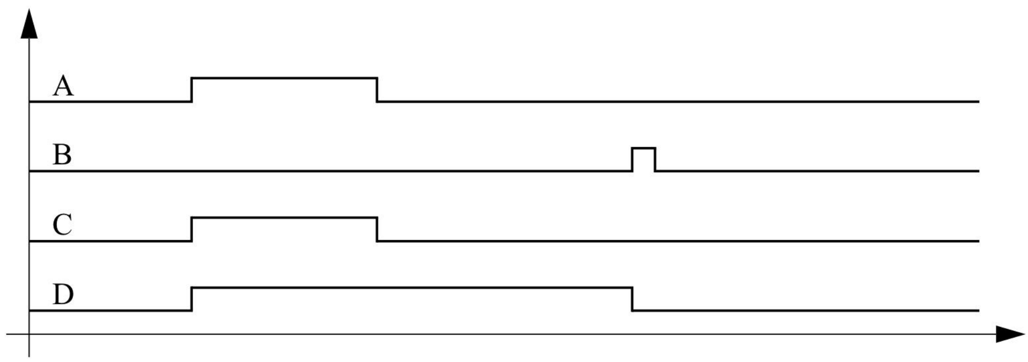


Figure 3.10: Timing diagram

Such devices have different behaviour with respect to latches, with the only difference that for them a different notation is used.

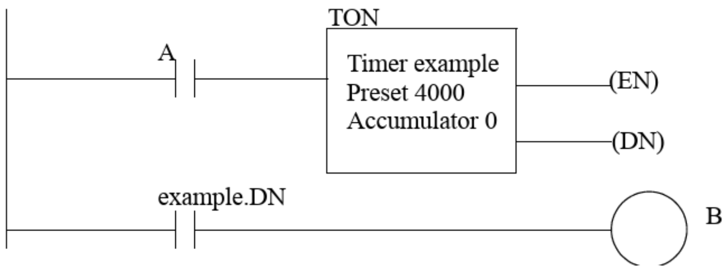


Figure 3.11: Ladder schematic for a timer

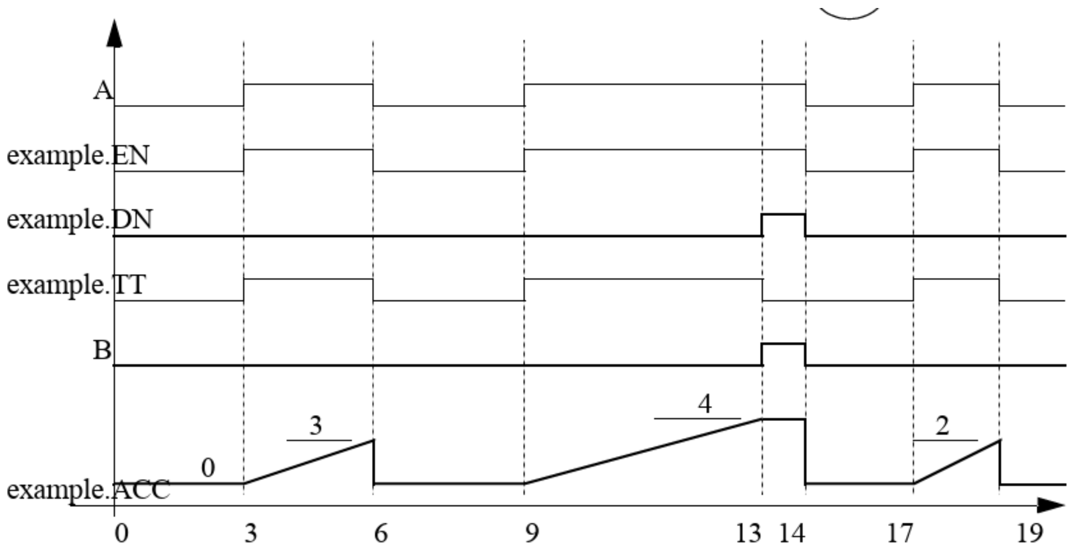


Figure 3.12: Timing diagram for the timers

Timers

There are tipically two types of timers:

1. *On-delay timers* whose output is <u>activated</u> after a certain time interval elapses;
2. *Off-delay timers* whose output is <u>deactivated</u> after a certain time interval elapses.

Here we consider only **non-retaining timers**, when they are turned off, the time delay starts from zero. In the following we give the typical representation for a sample timer.

The one showed in Figure 3.11 activates and starts incrementing the *Accumulator* when A is activated. The (EN) output is active whenever A is active while the output (DN) is active when incrementing *Accumulator* the value in *Preset* is reached. In the specific case, when the timer elapses the output B will be activated, and will be active until A will be active.
To be more precise and clear, look at Figure 3.12. After 3s the signal A is active for other 3s. Such a time is not sufficient to reach the Preset value (here we assume that the step is 1000ms, that is a 1 is added to the Accumulator each 1000ms). Since we are treating here a *(non-retaining) on-delay timer*, when A deactivate, Accumulator immediately goes to 0. Let us observe now the interval $[9, 13]$, here 5 seconds elapses, such interval is sufficient to reach Preset and for activating the output (EN).

Remark. Note that an auxiliary input `example.DN` is used in order to activate the output B, when the time interval elapses.

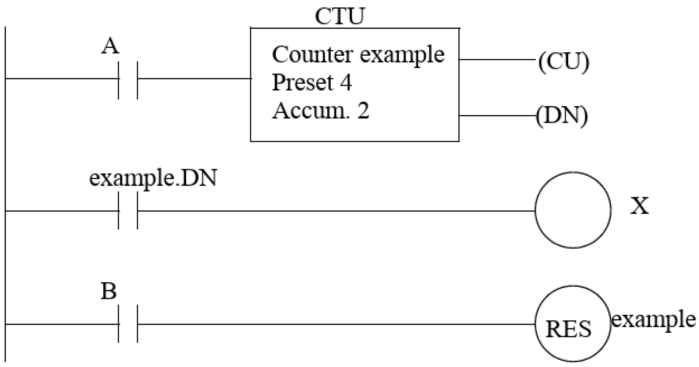


Figure 3.13: Example of *Count-up counter*

Counters

There are two types of counters: *count-up* and *count-down* one. The first when the input signal is active increment of a unit an Accumulator whatever is its duration[4].

Similarly than before, when the value of the Accumulator will reach the Preset value, (DN) will be activated. A counter-down, whether the input A is active decrement the accumulator of one unit. The timer showed in Figure 3.13 is a count-up counter whose with value of Preset and Accumulator equal to, respectively, 4 and 2. The output X will be active once the auxiliary input `example.DN` is active. On the other hand, when B will be active the Accumulator will be reset to 0.

Internal Bits

When dealing with simple program, (real) inputs can be used in order to set, (real) ouptut. When the situation becomes much harder, programs can use **memory locations** that are neither inputs nor outputs. These are also referred as *internal relays* or *control relays*. In modern PLCs they can be defined as *variables* of type BOOL. They are very useful in order to implement complex programs.

[4]Note that this is the same to state that counters (whatever its type is) is sensitive to the LOW-UP variation.

Chapter 4

Queueing systems