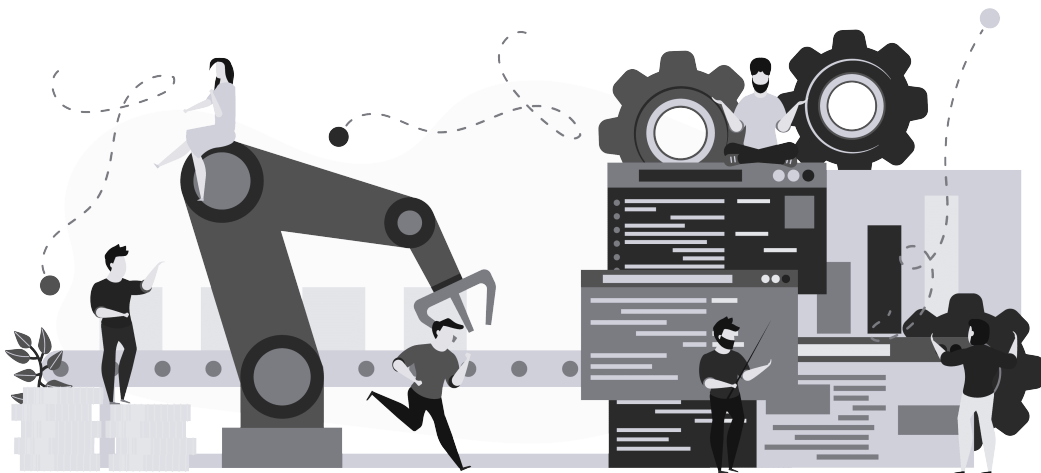# AUTOMATION AND PLANNING OF PRODUCTION SYSTEMS

Lecture notes

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Contents

Chapter 1

Introduction

> *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 **manufacturing 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.
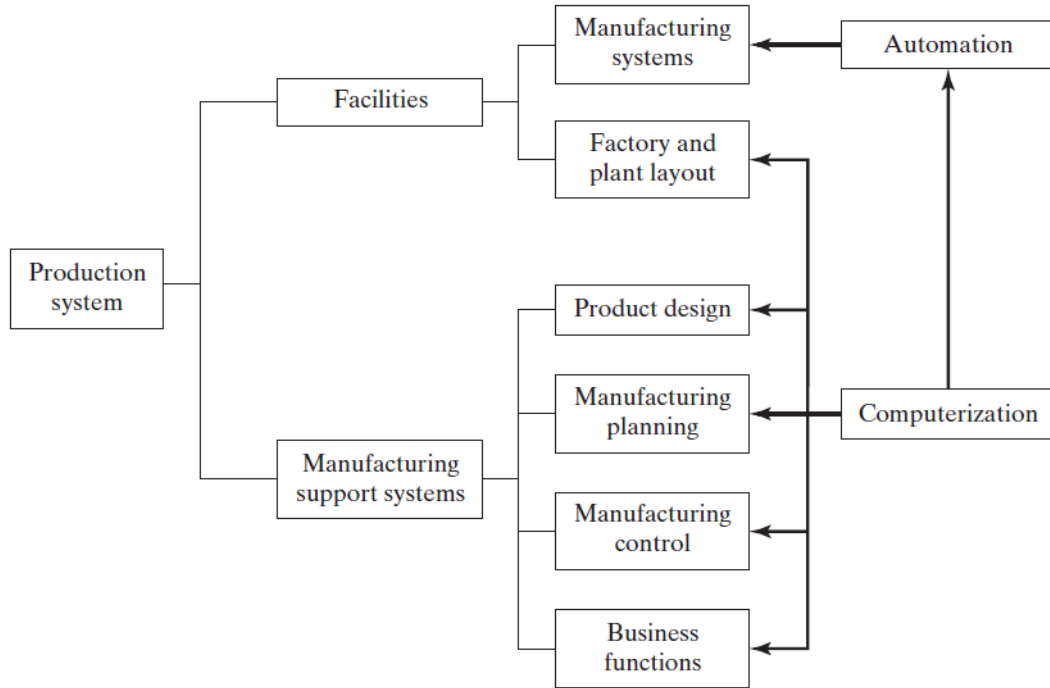
Figure 1.1: Production system structure and types of automation

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.
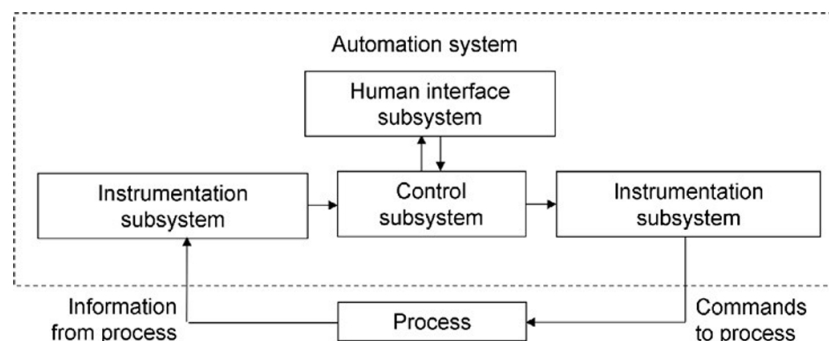
i) Instrumentation subsystem

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
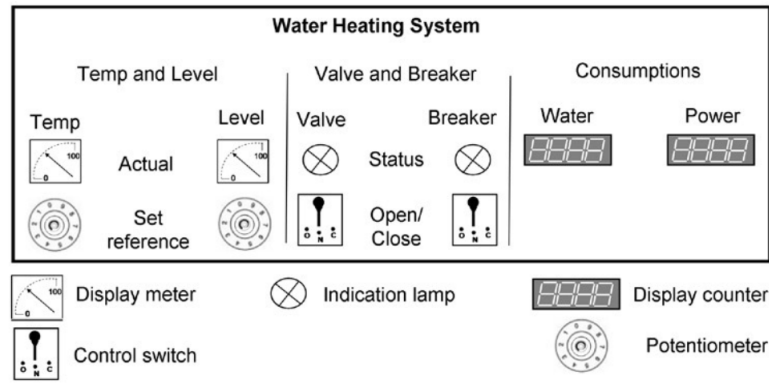
Figure 1.2: Human-Machine Interface

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.
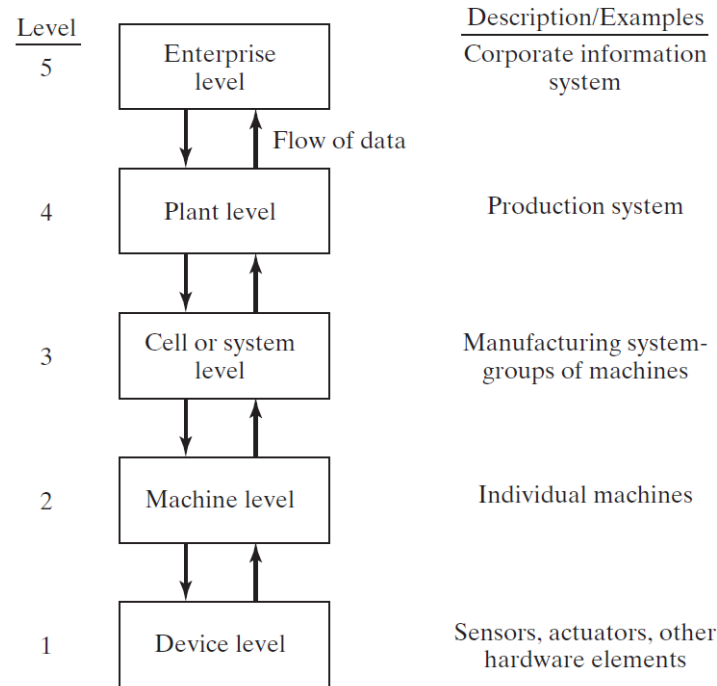
Figure 1.3: Different levels of automation

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:
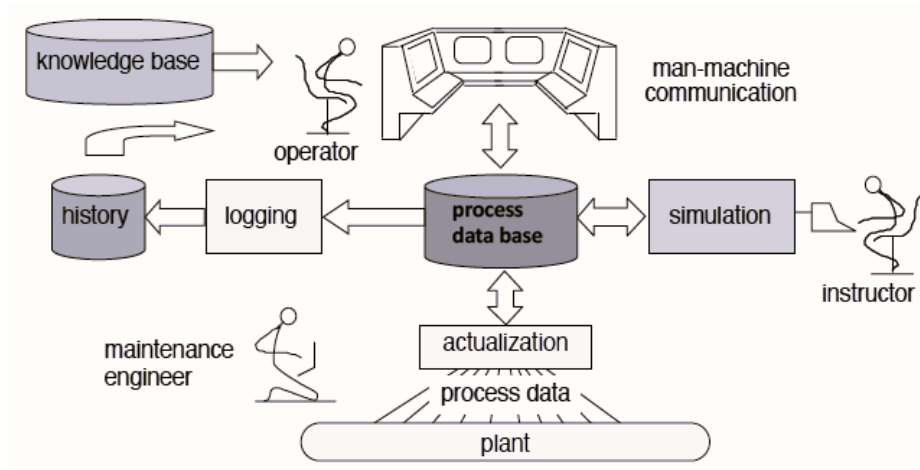
Figure 1.4: Databases in automated manifacturing system

- **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*).
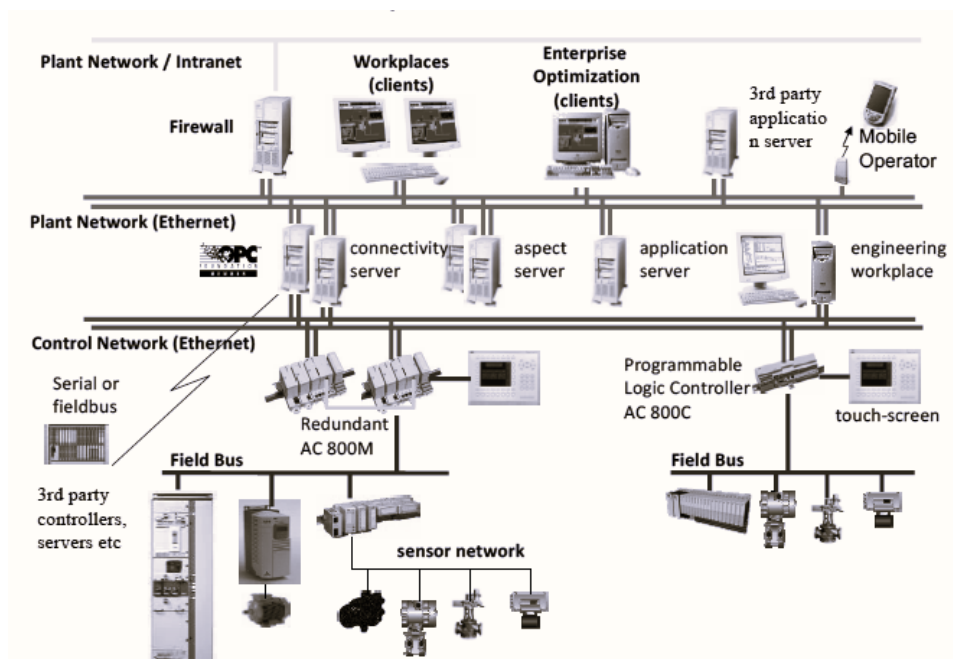

Figure 1.5: ABB Industrial IT

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.
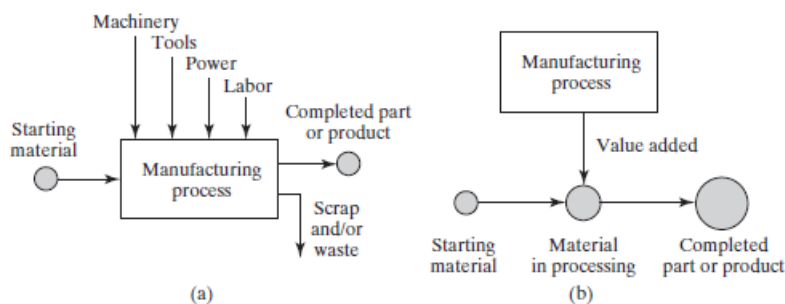

Figure 2.1: Manufacturing: economic and technological views

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[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 <u>uninterrupted</u>. 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.
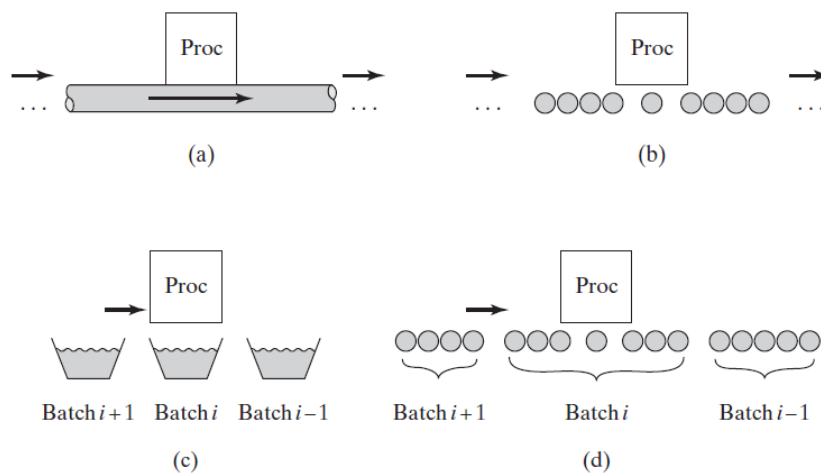
Figure 2.2: (Process/Discrete) vs (Continuous/Batch) production

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
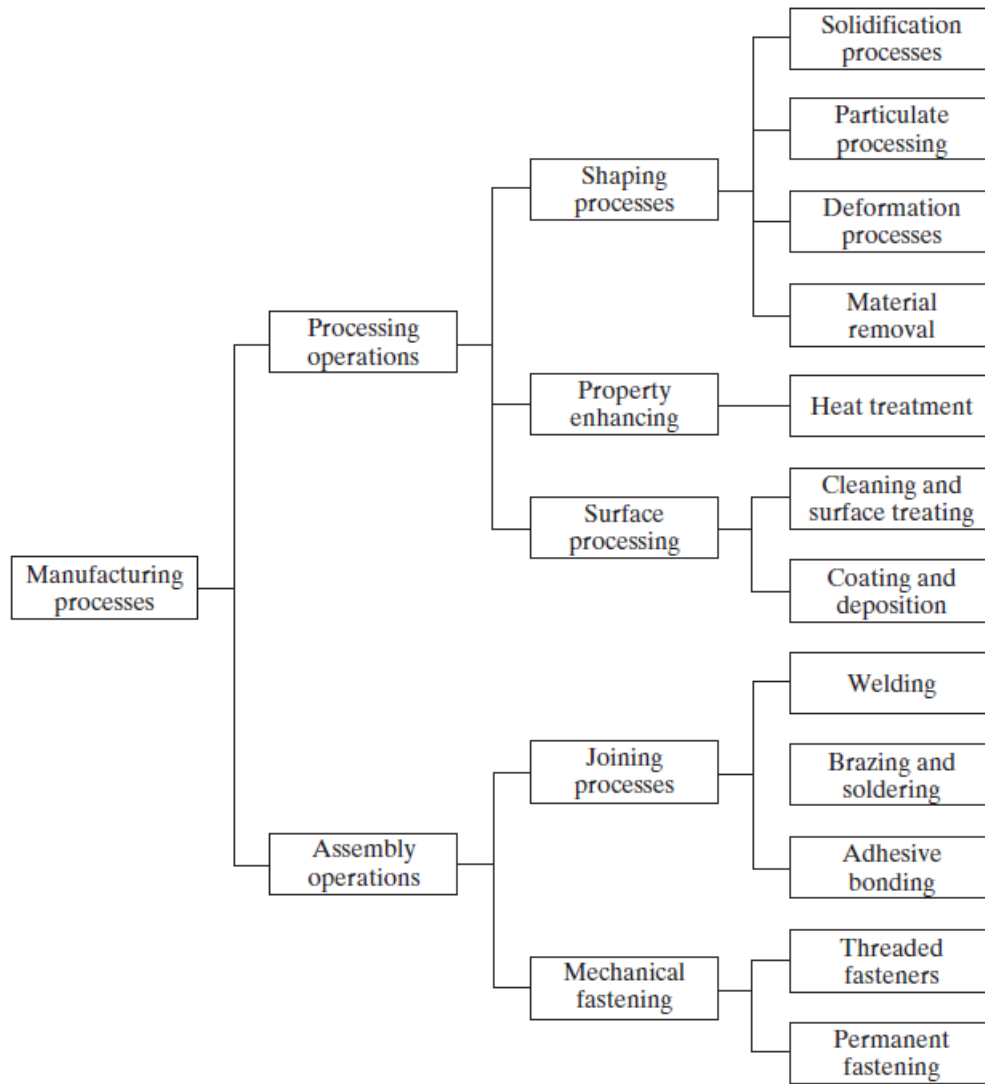
Figure 2.3: Manufacturing processes breakdown

properties are changed. On the other hand, ***Assembling operations*** are in order to put to-gether 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.
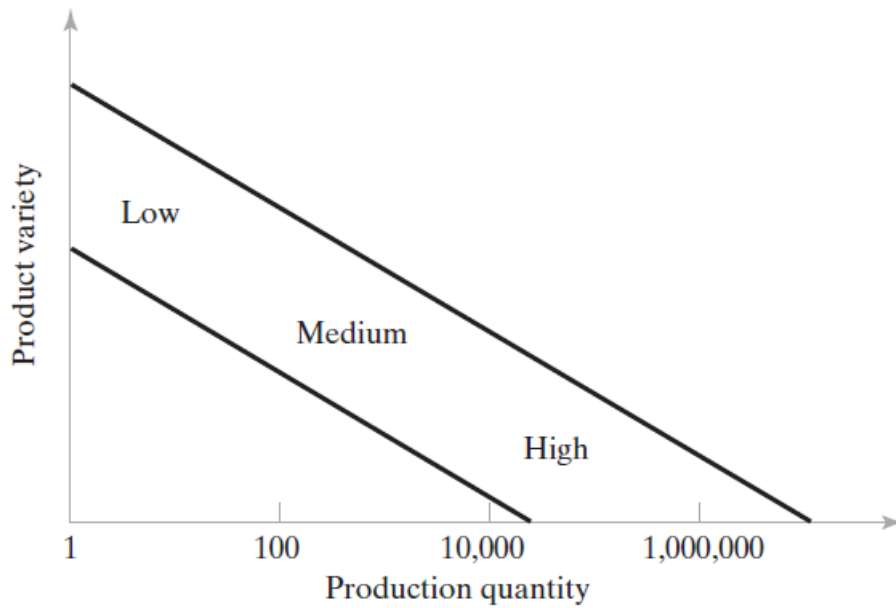
Figure 2.4: Quantity vs Variety plot

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.
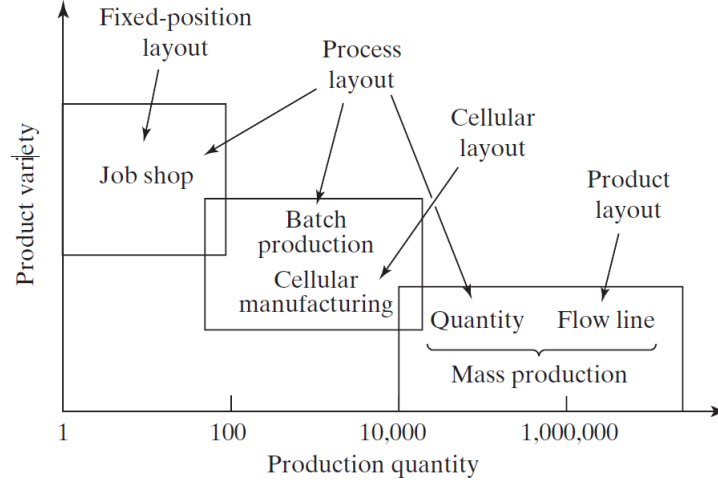
Figure 2.5: Production plants and related layouts

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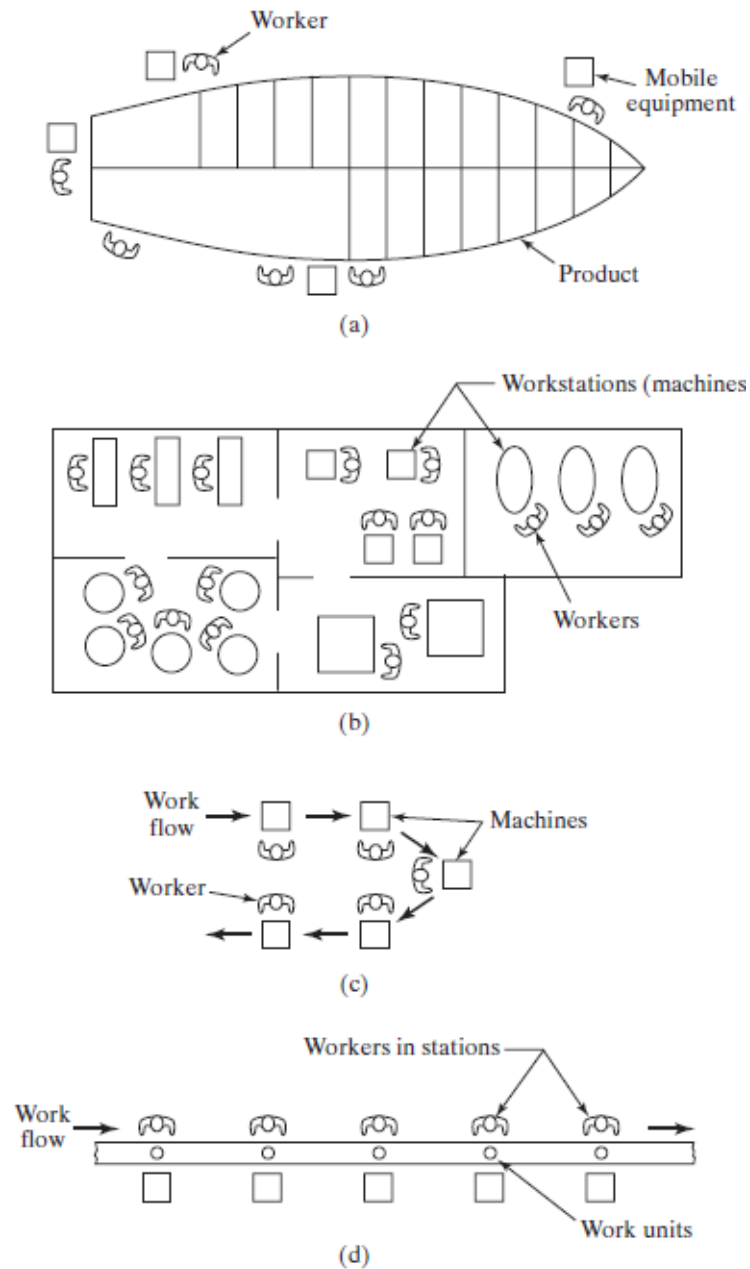
Figure 2.6: (a) fixed layout, (b) process layout, (c) cellular layout, (d) product layout

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
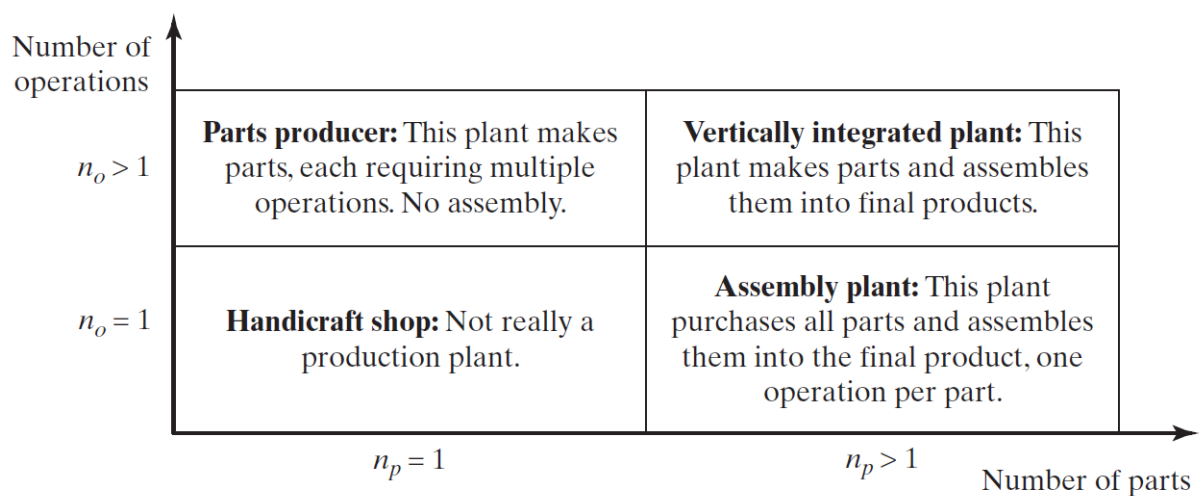
Figure 2.9: Production plants distinction according n_p and n_o

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.
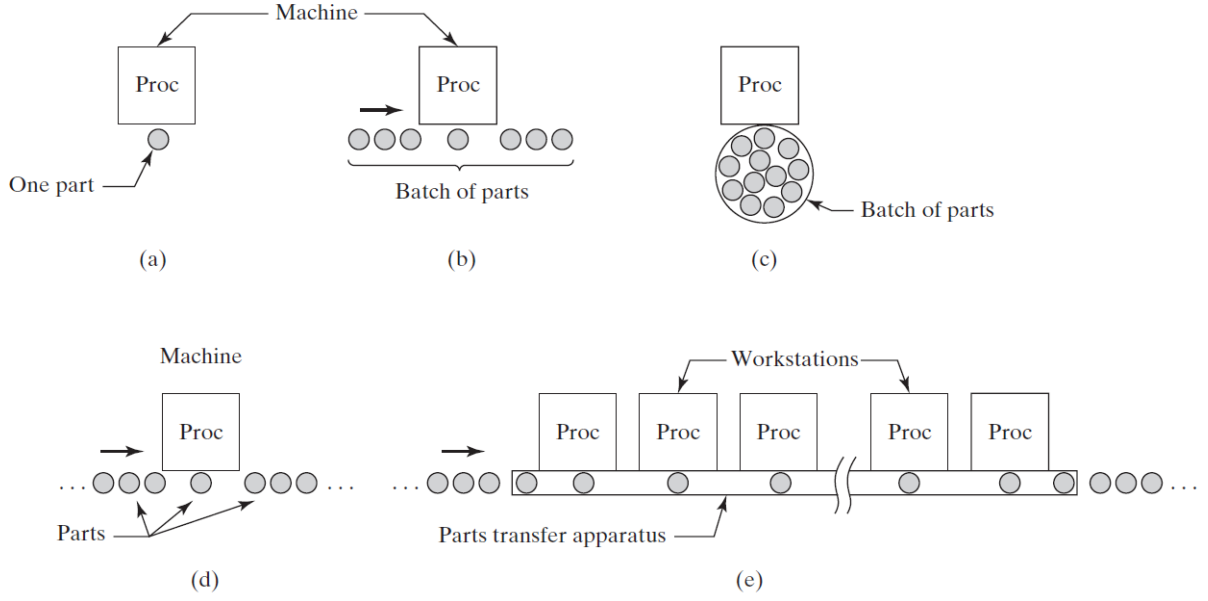
Figure 2.10: Different production plants for considering production rates

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.

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

Part	Machine 1		Machine 2	
	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 $WL = 2 \cdot H_{pw} = 2 \cdot 40 = 80$

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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 $MLT(\text{min})$ 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

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[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.
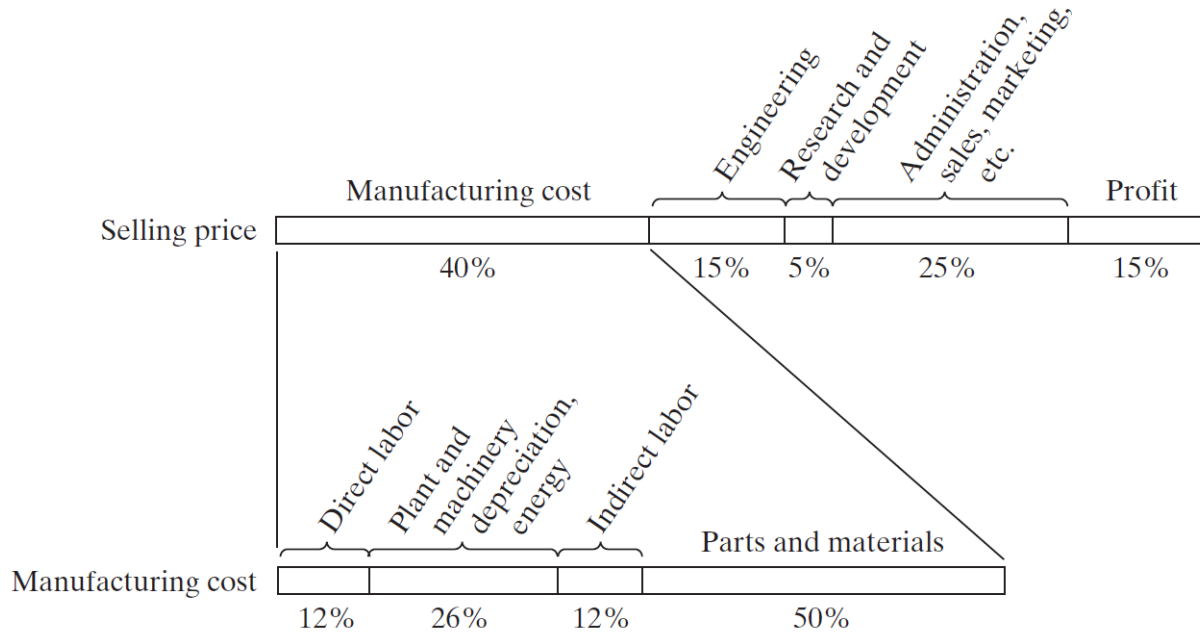
[3]aka *Work-in-progress*

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)