# Evolution of the intelligence of the production systems

- Industrial revolutions
- Mechanization / Automation
- How to put "intelligence" in manufacturing machines
- Tools for improving the machine intelligence
- Internet of Things

# Man has always been looking for something that works in his place

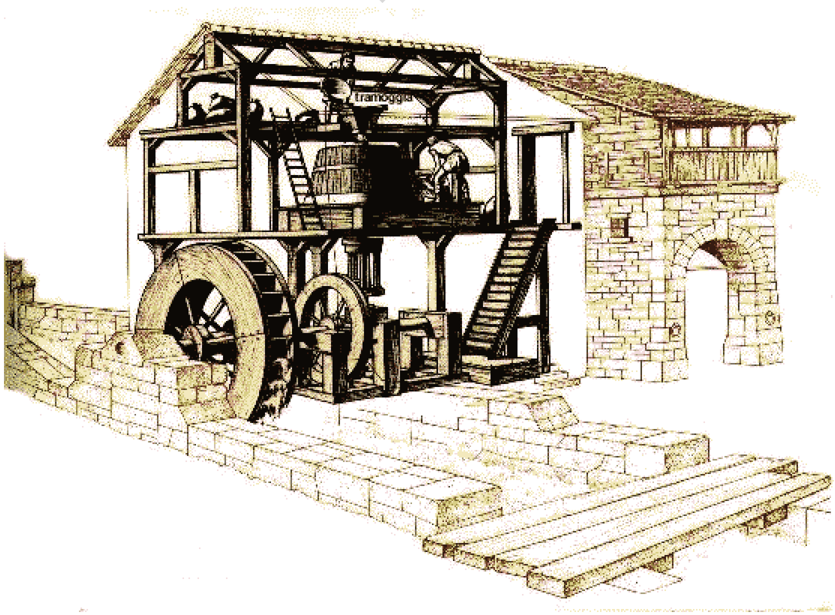
- Something that does the heavy work
- Something that does the boring work
- Something that does the repetitive work

- You need at least one **energy source**

- The mill is always and only a mill:
  it is useful only for grinding flour or running a hammer

- It would be nice to have something that can be **reprogrammed** to do something different

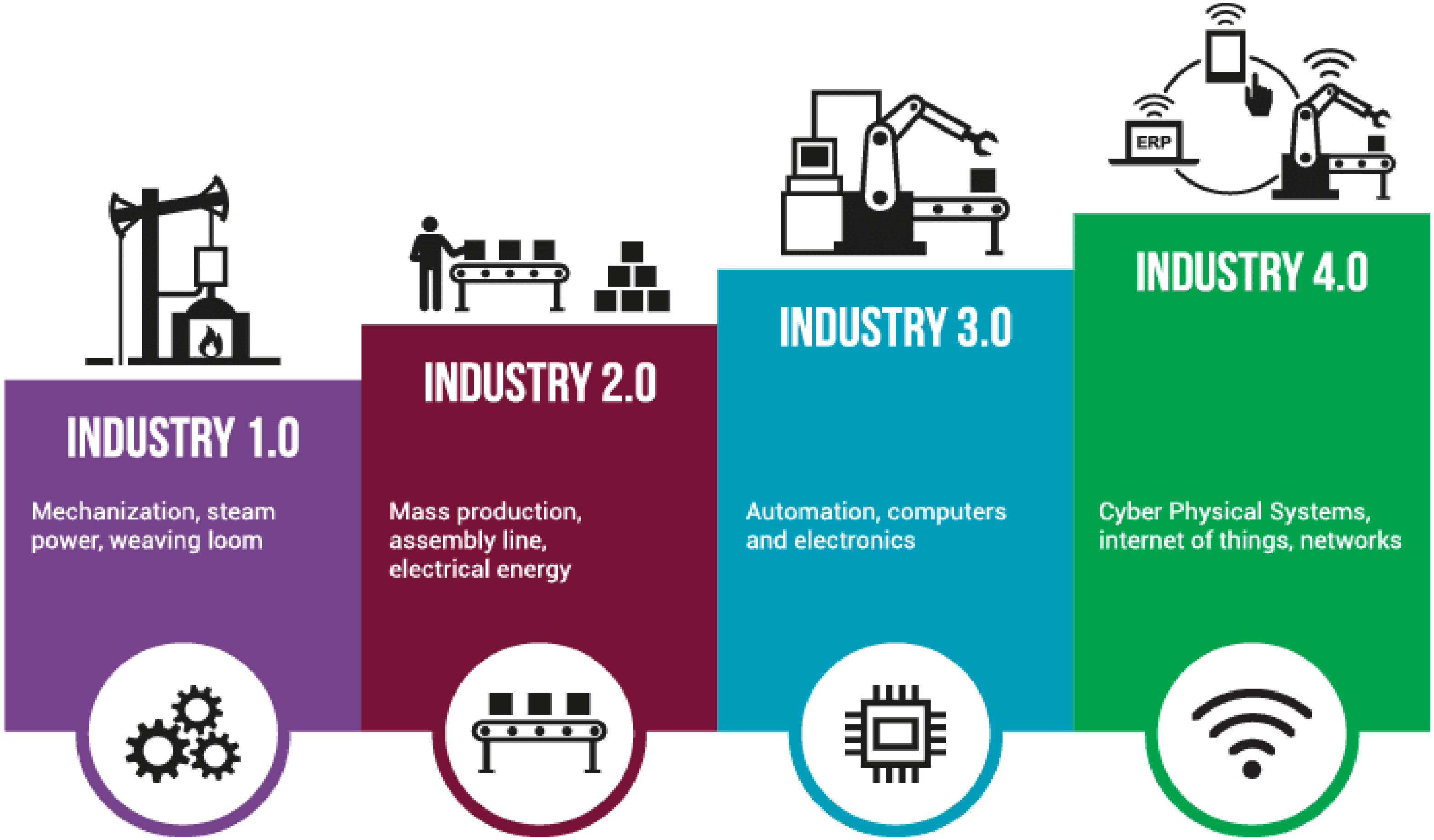
Grinding of cereals




What we need are flexible Production Systems

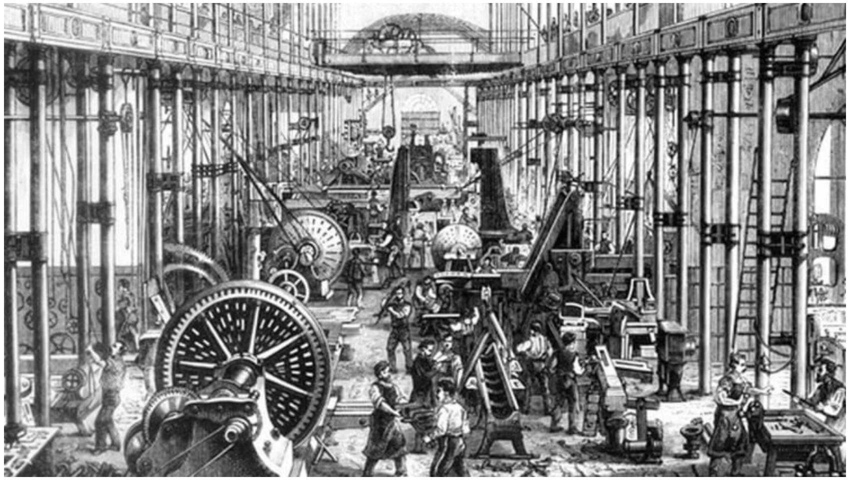
# Man and Technology

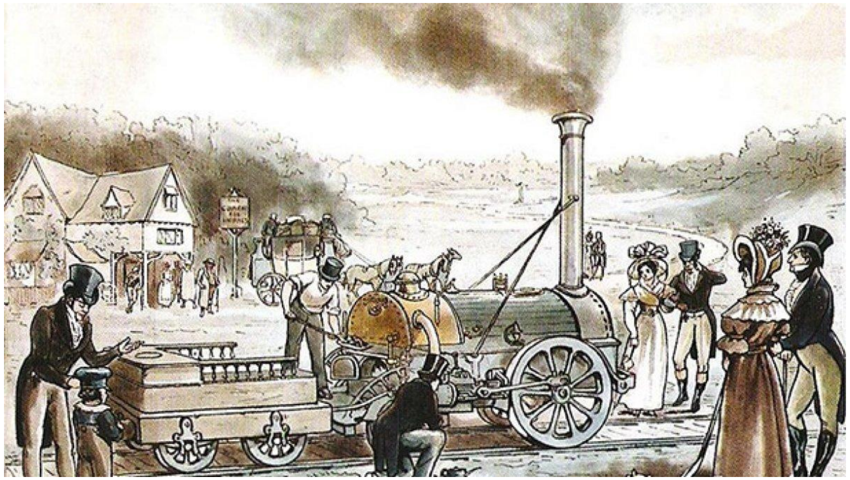
- Role of man in industrial revolution



# 1$^{st}$ Industrial Revolution

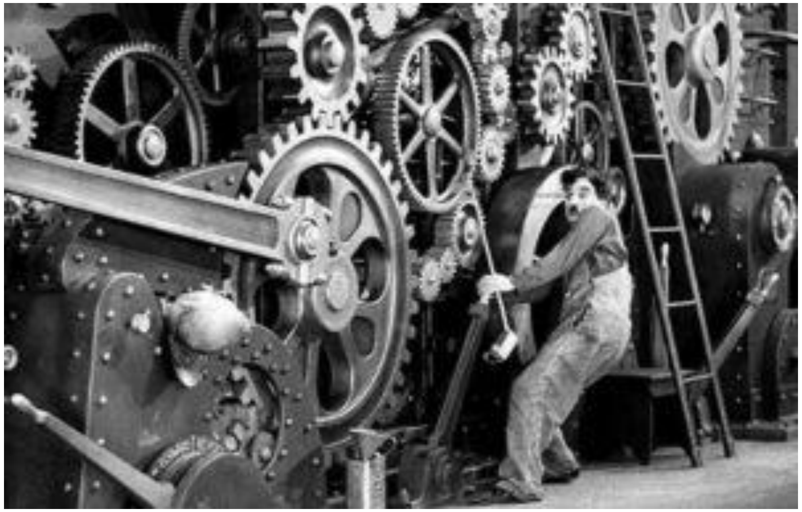
- Europe 1780 - 1830
- The invention of the steam engine changes the way of producing.
- It was from the mechanization of manufacturing
- The way of producing changes, the machines become the fulcrum of production but **are still completely dependent on man and his work**





# 2$^{nd}$ Industrial Revolution

- Between 1860 and 1900
- Exploitation of new energy sources such as electricity and oil
- The assembly line is introduced → mass production
- The man-machine relationship becomes more interdependent: the process only works **if man and machine work together**



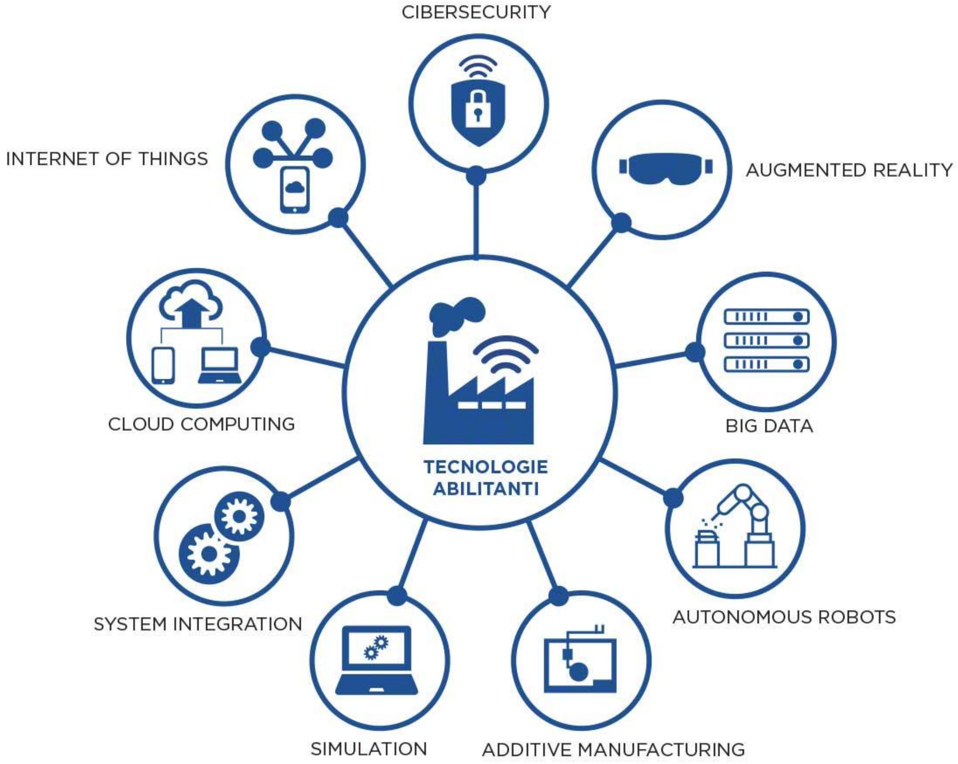
# 3rd Industrial Revolution

- Since 1950 with the birth of information technology, the introduction of computers and robots
- **Technological innovation and automated production**
- Revolutionary inventions, radical changes in the industrial world, in the way of working and lifestyle (internet, mobile telephony, etc.)
- The operator detaches himself more and more from the machine which operates autonomously
  → Human work moves more and more towards soft activities

# 4th Industrial Revolution I4.0

- Huge boost of technological innovation and scientific progress
- Planetary revolution linked to the interconnection of people and things thanks to the internet
  → We move from connected objects to intelligent systems (Smart Manufacturing)

- Industry 4.0 is characterized by autonomous decisions processed by intelligent machines and the use of so-called enabling technologies integrated with each other



# Limits of Traditional Production Systems

- Inefficient processing methods
- Difficulty maintaining standards
- Reconfiguration/tooling takes **a long time**
- Processing takes a **long time**

→ **<u>High labour costs</u>**

- We must:
  - improve efficiency
  - increase flexibility

# How to increase productivity: mechanization

- Mechanization in **production departments**:
  - It means managing a process or operation using:
    - mechanical, hydraulic, pneumatic, electrical, … devices

  - the operator controls directly the production process and must verify continuous performance of the machine

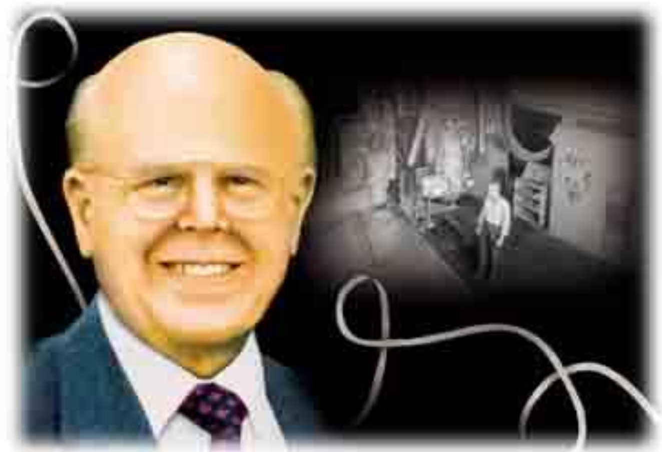
  - machines "know" how to do some things, but **always the same**

# The ability to work alone has increased, but ...

- Nice step forward, but convincing a washing machine to do something different, adapting to the hardness of the water, the weight of the load, the type of what there is to wash optimizing detergent and water temperature is still hard

# How to increase productivity: automation

- Automation has been developed thanks to the development of **electronics**
  - ... and with electronics: sensors, transducers, control systems, actuators, up to the PLC...



*Parson, creator of CNC machine tool in 1947 at MIT in Boston*

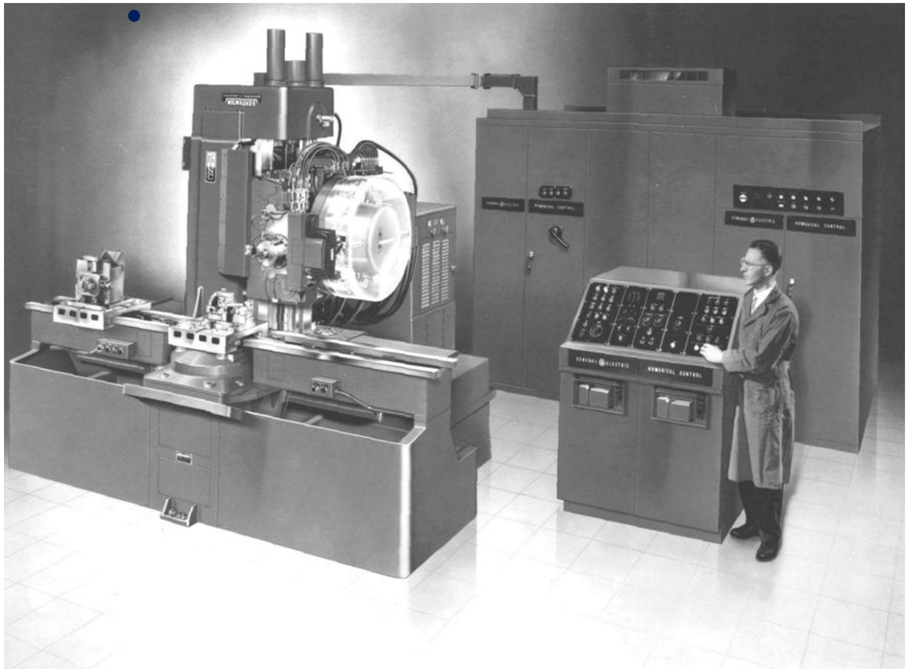
***CNC = Computerized Numerical Control***

- <u>Today we take everything for granted</u>

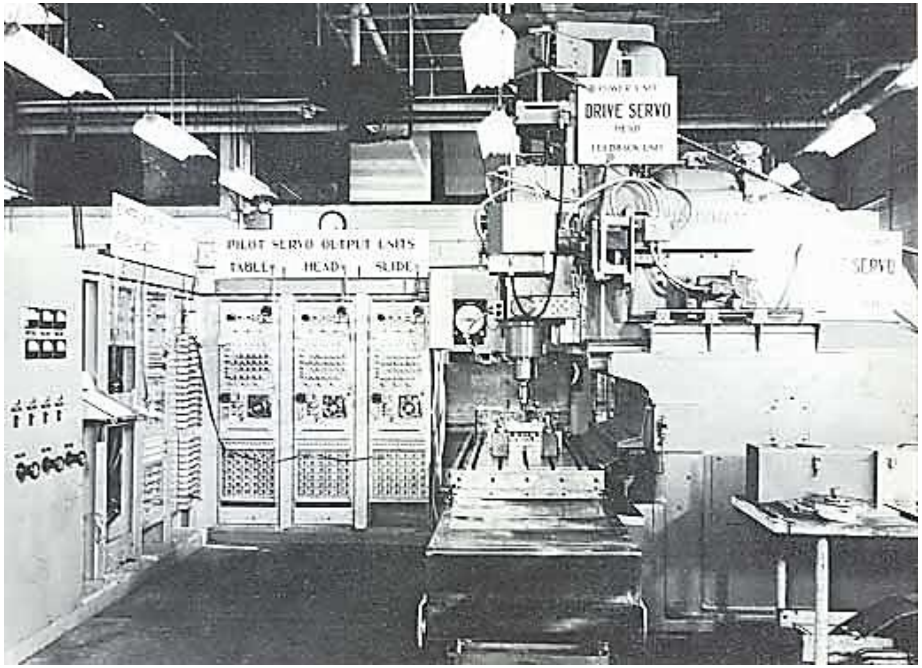
*Think about what it means to imagine a system that can be controlled with numeric instructions that are interpreted and convert into signals that can move the machine devices: you change the program and the machine does something different*

# Automation

- **<u>Definition</u>**:
  - technology that uses control systems (such as logic circuits or computers) to manage machines and processes **reducing the need for human intervention**
  -

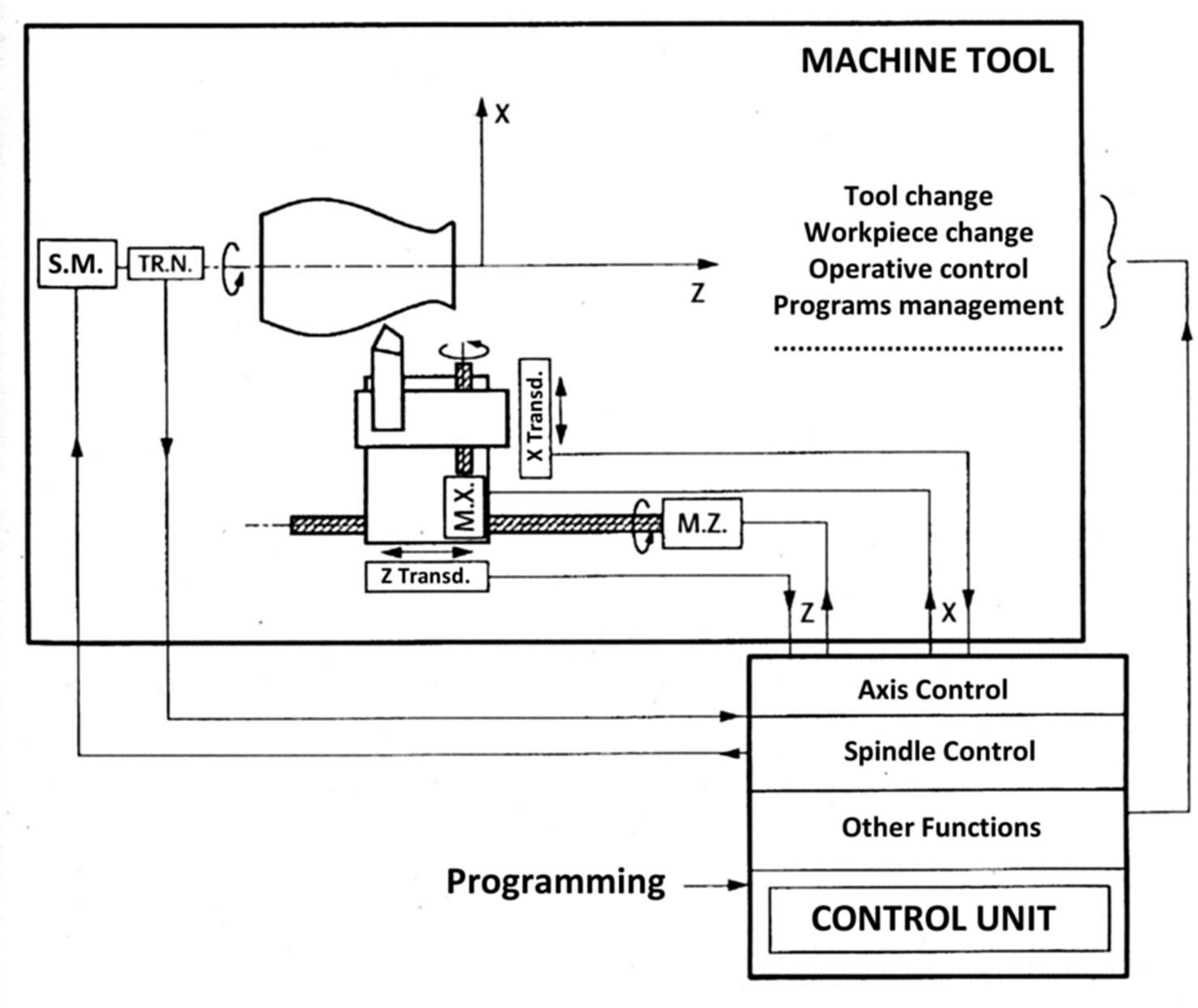


More for a laboratory than for a production department



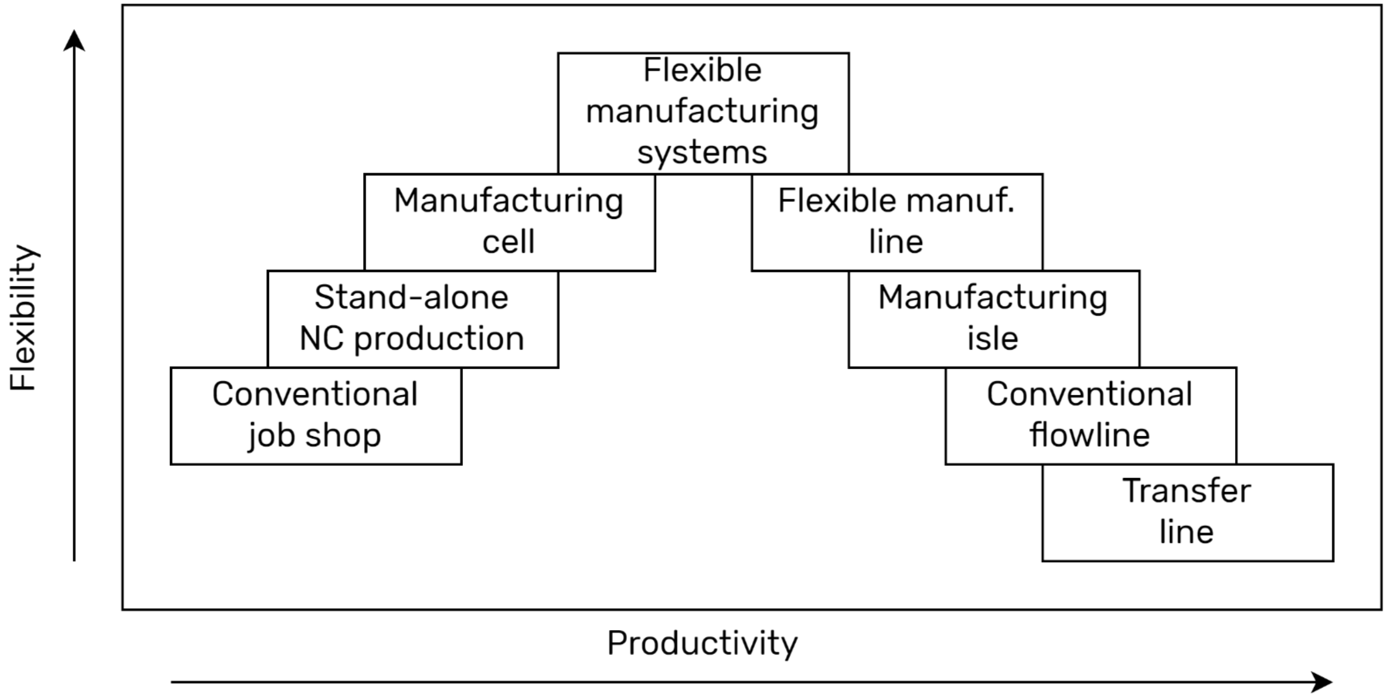

Chicago 1955
Machine Tool Show

# Scheme of a CNC Machine Tool



# Flexibility vs. Productivity

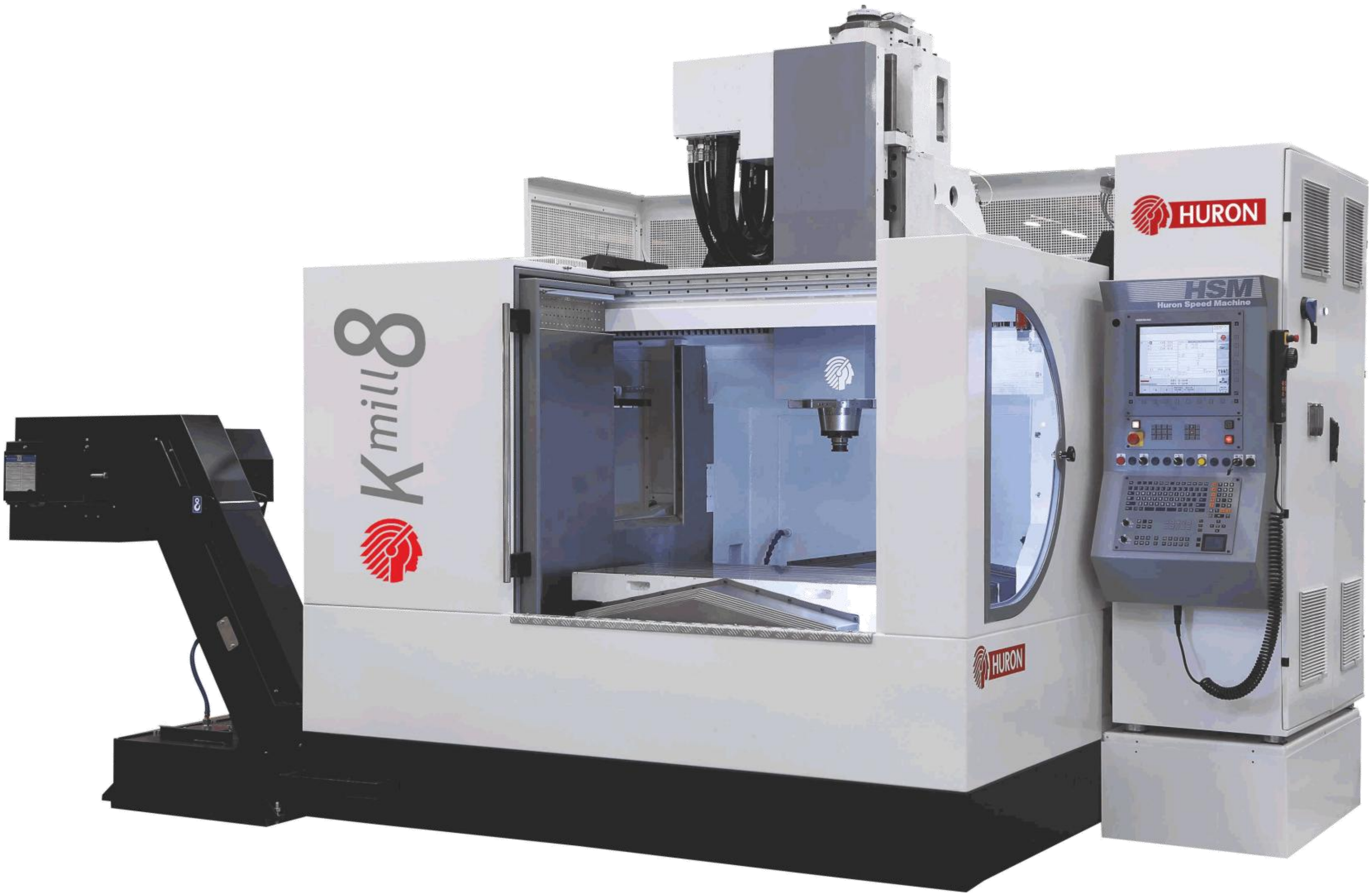
- **Flexibility** and **Productivity** of various types of production systems



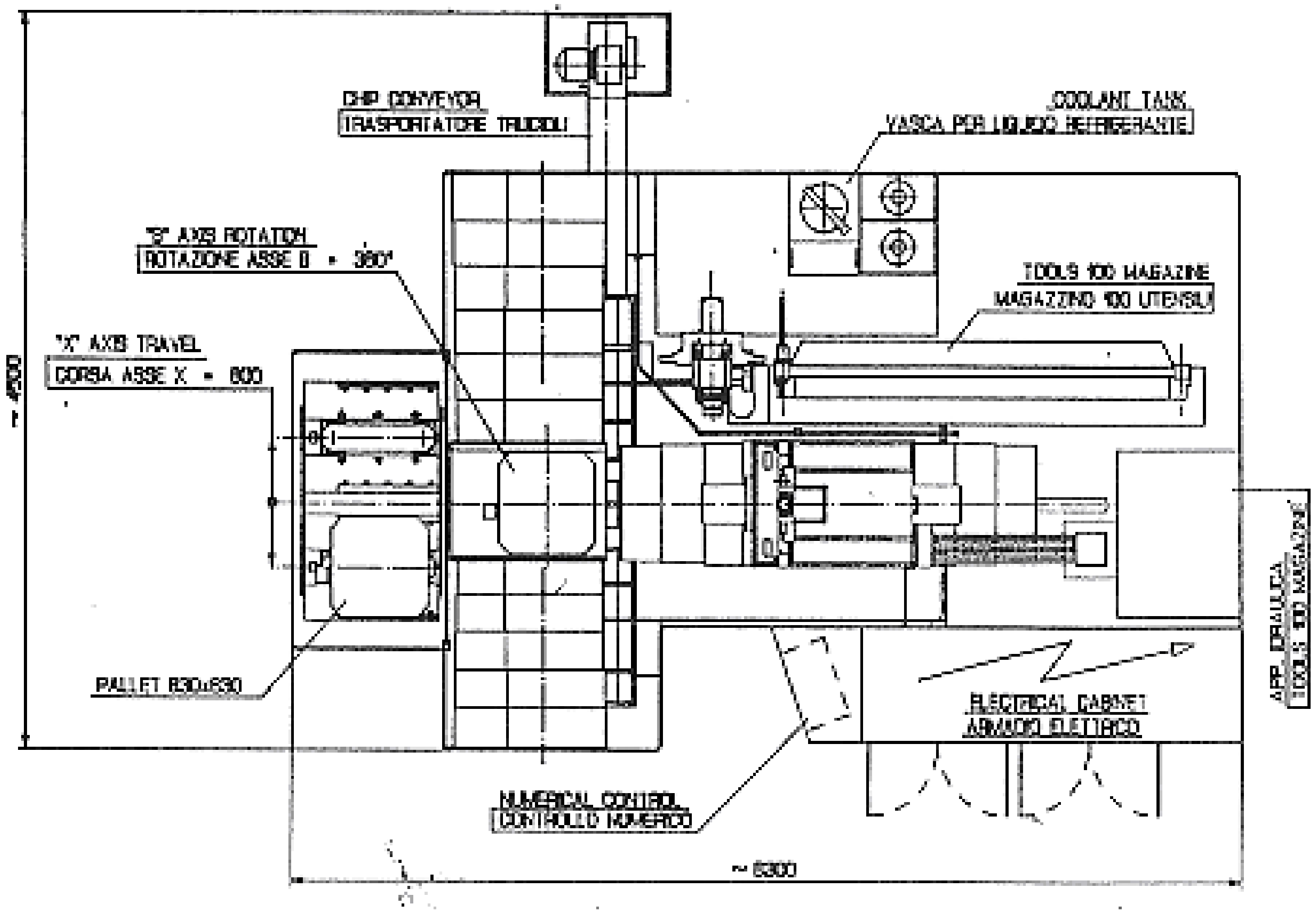
# Stand-alone NC production – Machining Center

- Suitable for many types of pieces not in large quantities
- It is the typical machining center, in general it is made with a single CNC module with integrated PLC
- It has tool management and pallet changer (1 or 2 pallets)

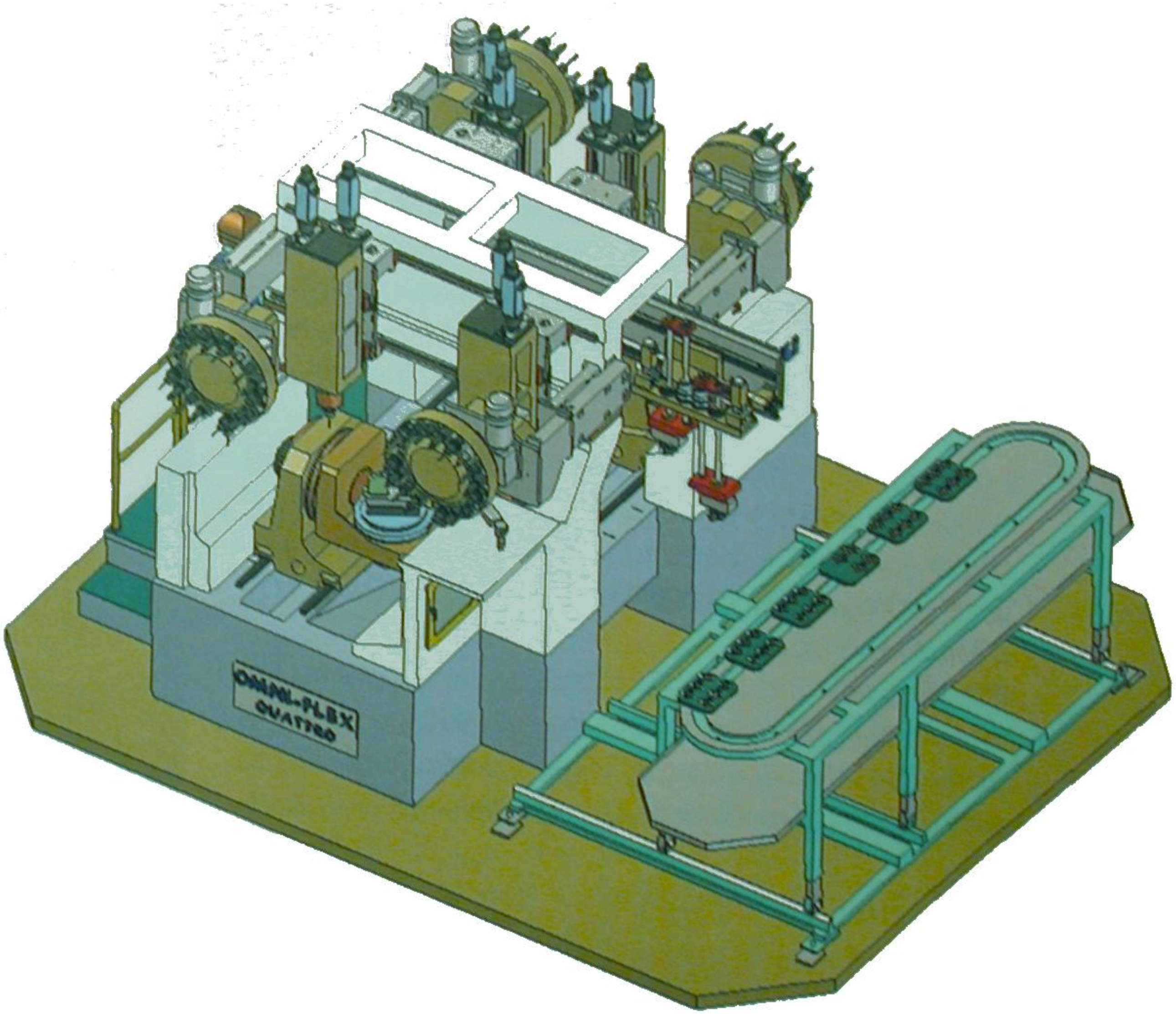
# Stand-alone NC production – Machining Center



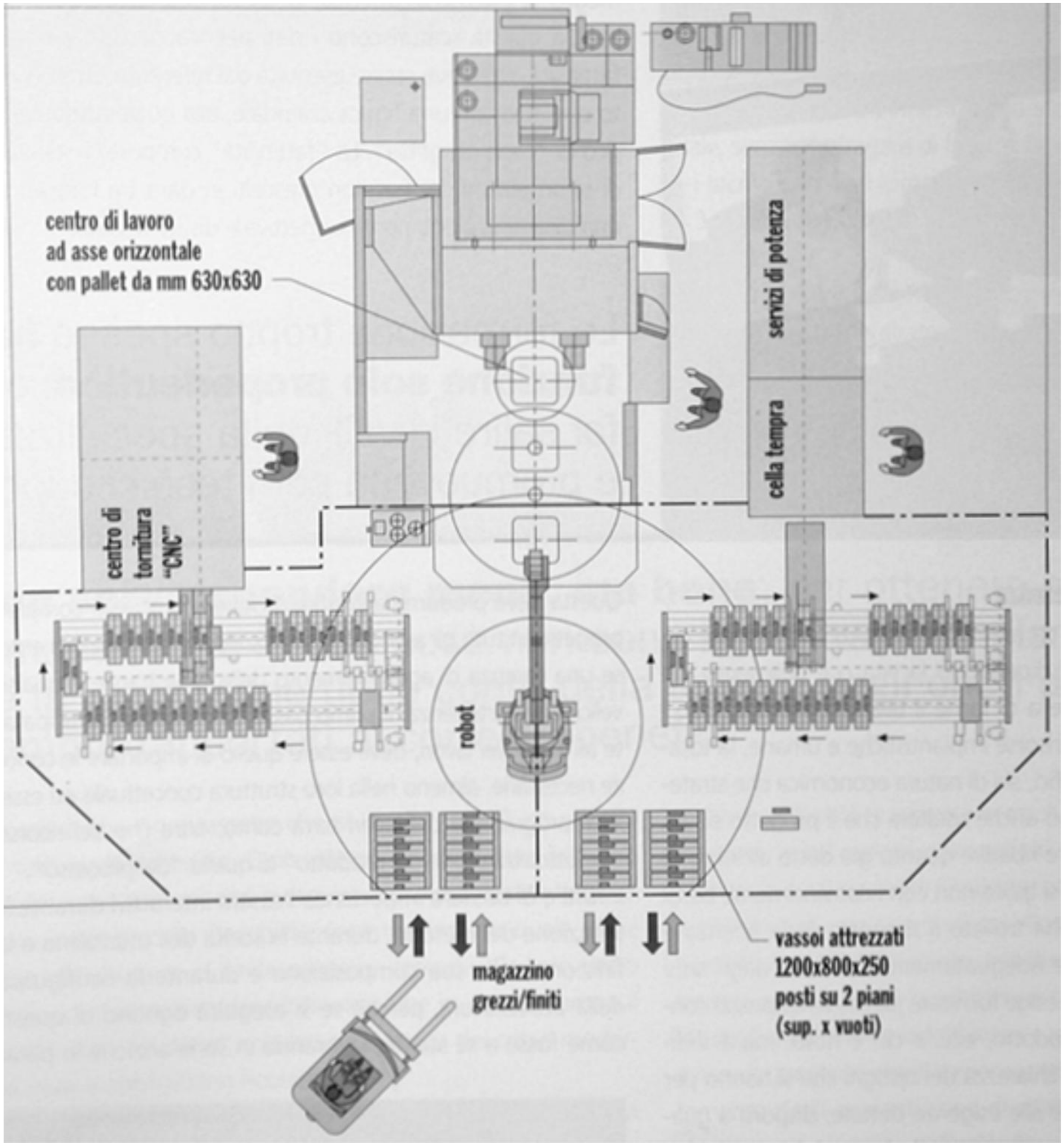
# Stand-alone NC production – Machining Center



# Stand-alone NC production – Machining Center



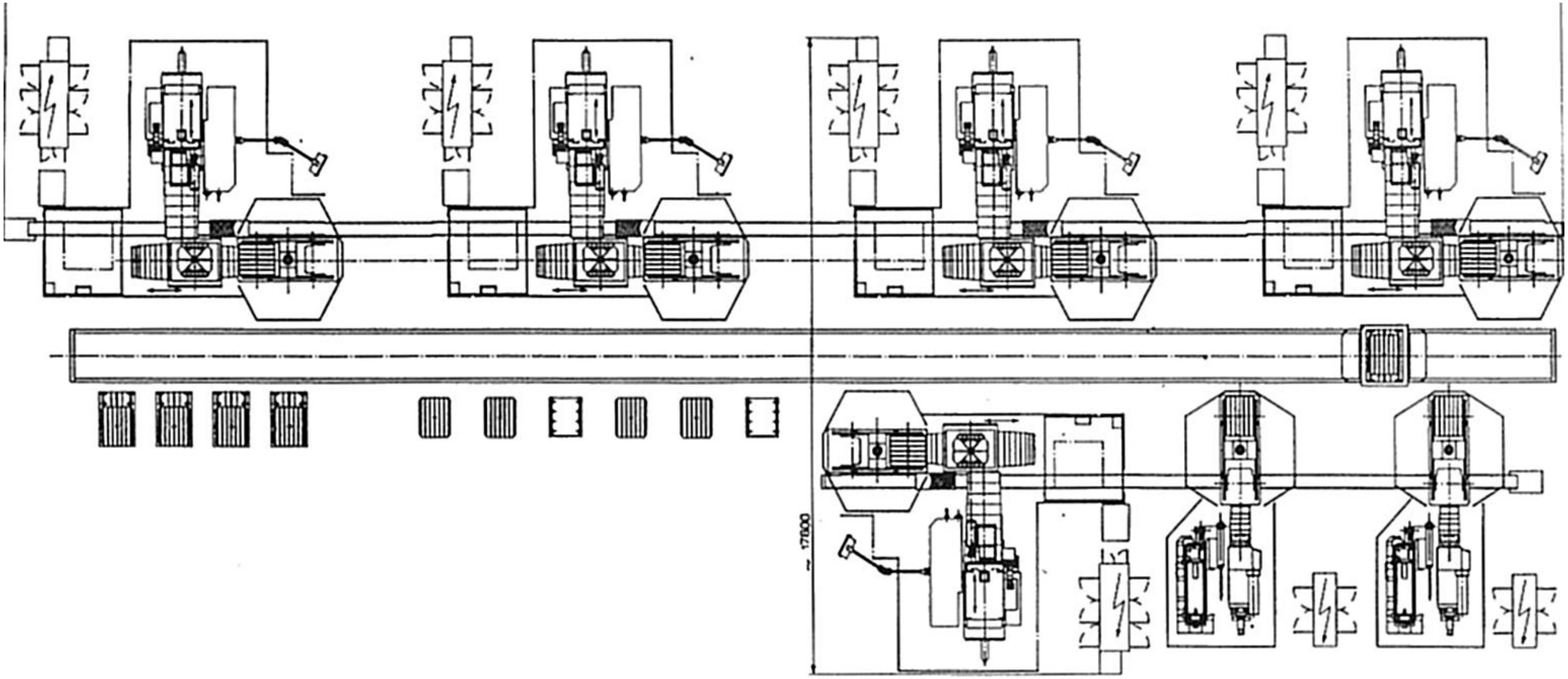
# Flexible Manufacturing Cell



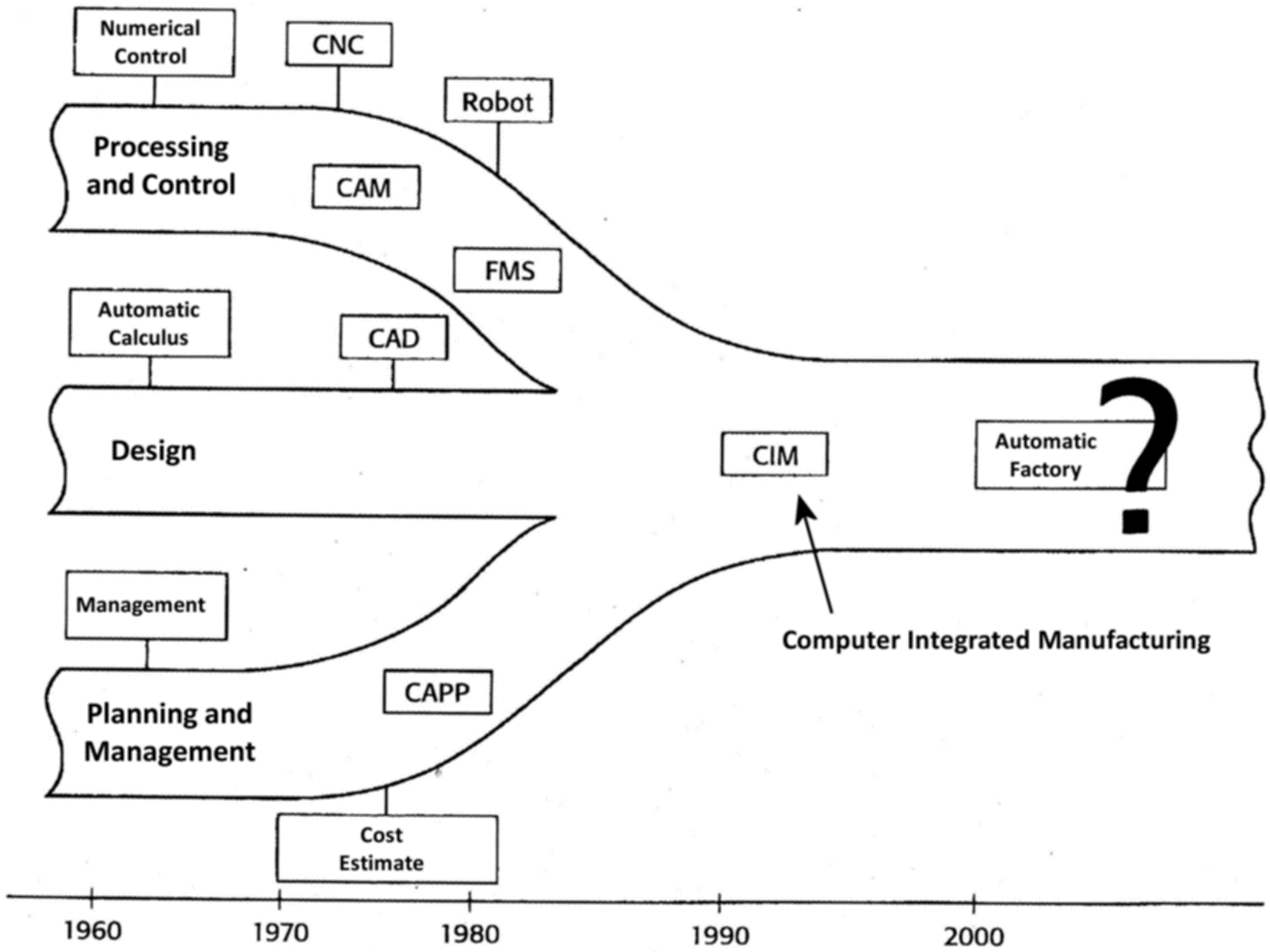
# Flexible Manufacturing Systems

- Suitable for many types of pieces in large quantities
- It is made up of several production cells or in any case of several production units of different types
- It has various parking spaces for pallets and several parts loading/unloading stations
- Sometimes the automatic distribution of tools with shuttle or robot is also realized
- The distribution of the pallets is carried out with 1 or 2 shuttles
- The pallet-pieces management module (WPF) has video units both at the loading / unloading stations and in the supervisor box
- The connection to the Host is established with the possibility of dialogue with the factory network (LAN)

# Flexible Manufacturing Systems

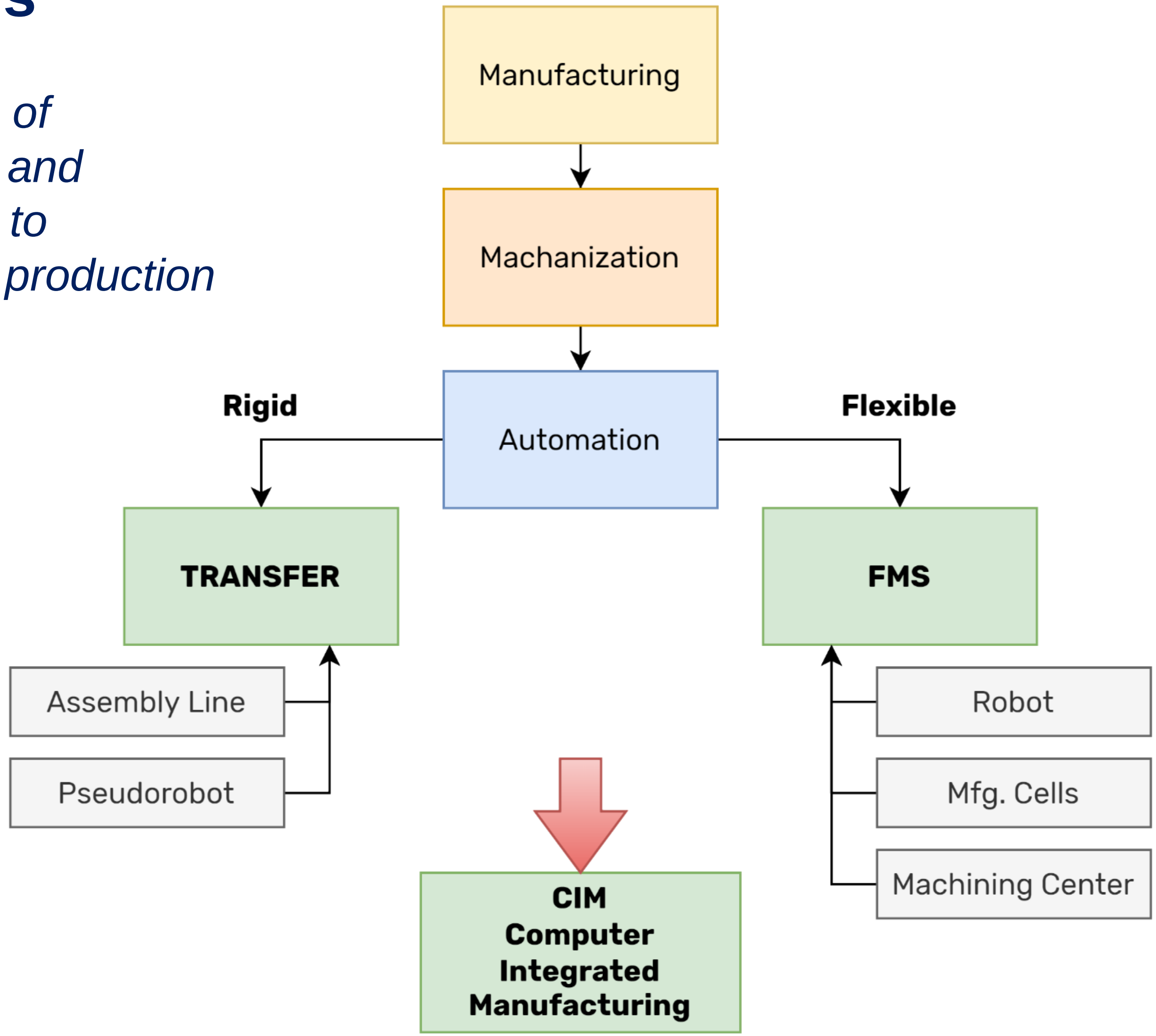


# Production Systems Evolution as seen in the past



# Automation in the Production Systems

- ***Definition:*** *application of mechanical, electronic and computerized systems to implement and control production in place of the human operator*



# Benefits of Production Systems Automation

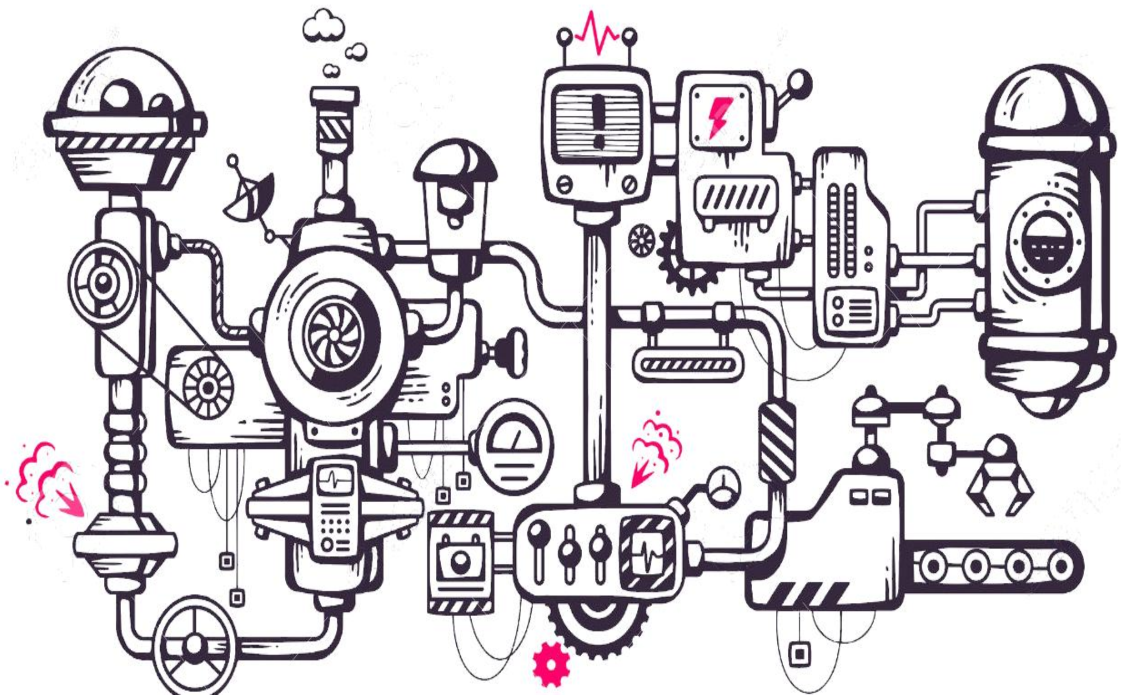
- Reduction of processing costs
- Improving product quality
- Reduction of the total production time of a single piece
- Execution of processes that cannot be done manually
- Reduction of negative effects from lack of manpower
- Improvement of general working conditions
- Improvement of operators' safety conditions

# Now the question is:
# "Is it enough to introduce a CNC machine?"

- Nice phrase:
  "*you change the program, and the machine does something different*"
- We are facing a more complex system that no one has ever seen **before**
- It is true only if you also change the way of designing, drawing, managing production, using tools, doing maintenance, the operator-machine relationship ...

- It is also necessary to change the head to make it suitable for the new system

Training



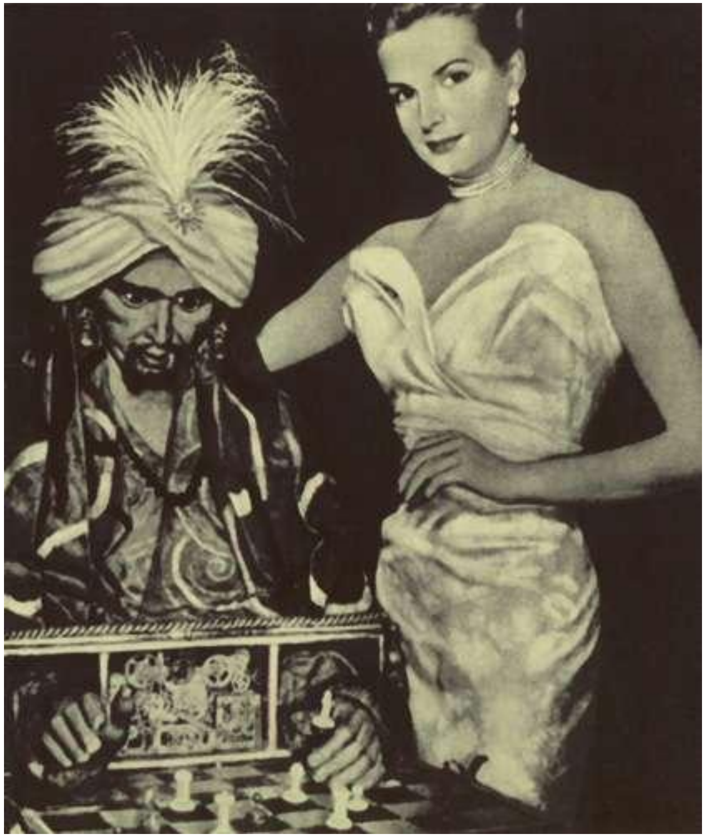
# Is automation enough today

- To look carefully, the level of automation of the most advanced MU is at least **one generation later** than that achieved in other fields (avionics, aerospace, robotics, automatic driving systems ...)
- A new MT should also **make decisions based on the gathered information**
- To take a further step forward, is it necessary to have a **material** or **cognitive intervention**?

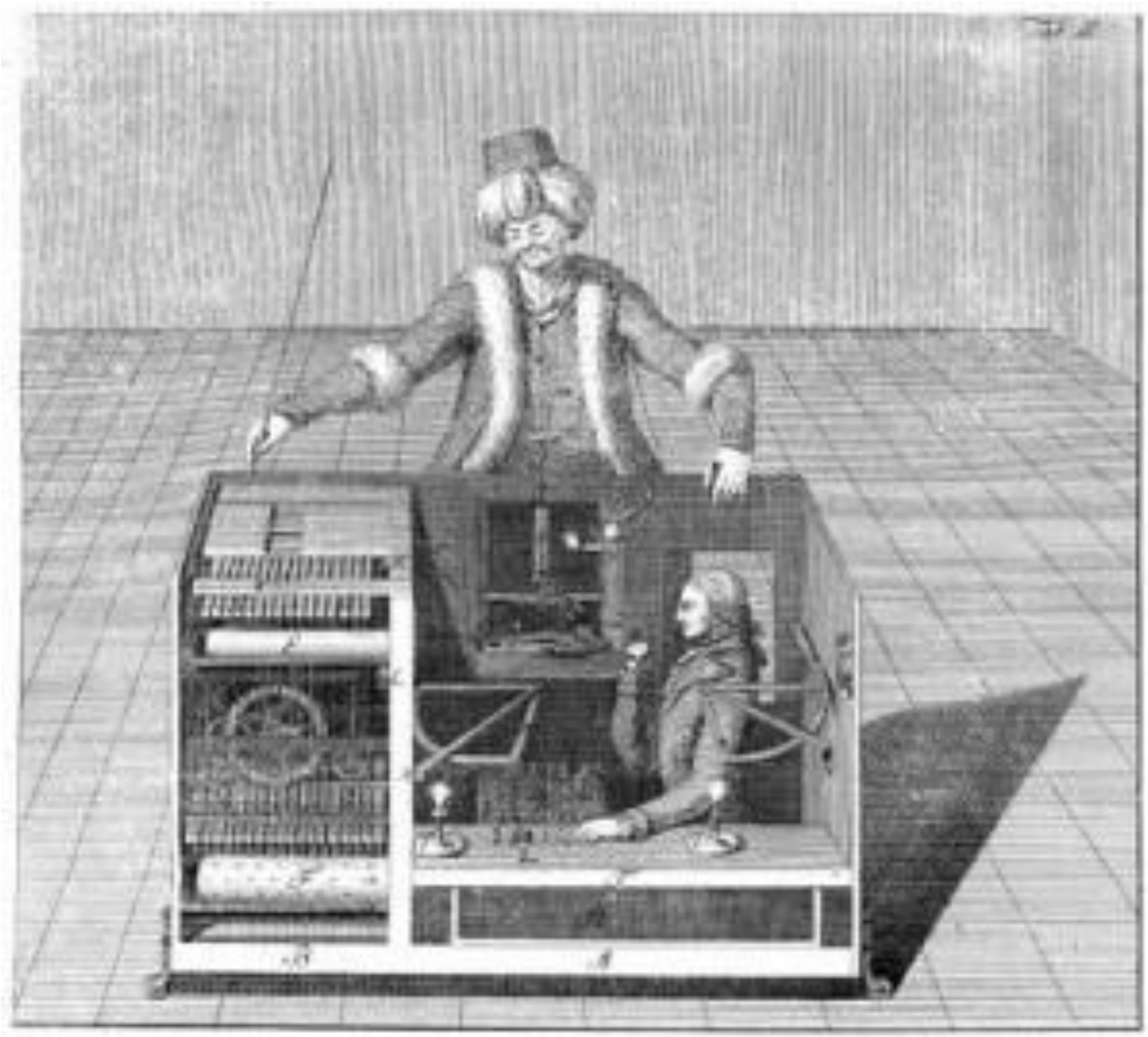
# First example of "intelligent machines"

- <u>The chess player</u>:

  The **Turk** was a **chess machine** created in 1769 by Baron Wolfgang Von Kempel

# In reality, intelligence was put by a man



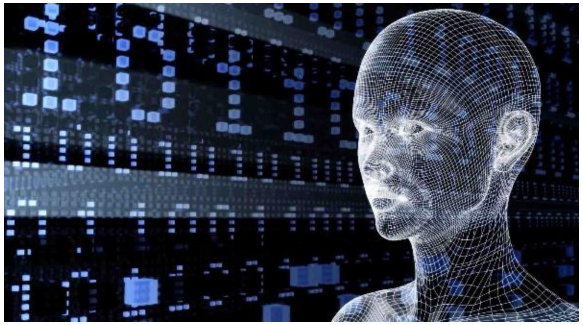
# It would be nice..

- It would be nice to have something that:
  - is programmable, but flexible
  - to whom it is possible to give precise tasks, but intelligent enough to be able to adapt to situations
  - yet complex , but easy to program
  - that can also make mistakes, but can learn
  - ...

- Not only "intelligent", but also "smart", that is: with a **witty intelligence**

# Intelligent machines

- The structure of a system should be open and not too customized so that it can be used and adapted to an entire supply chain



- **Objective**:

  increase the degree of automation and intelligence in machine tools by transferring process knowledge and learning skills from the operator to the machine control system

# Intelligent Machine Tools

- The goal is **to insert in the Machine Tools sufficient "intelligence" to obtain higher and more stable product quality levels, symptoms of robust and reliable process**, by means of:
  - the introduction of mechatronic systems with an increase in the level of automation
  - insertion of self-diagnosis functions
  - adaptability to workload conditions
  - adaptability to work situations
  - correction of machining errors
  - …

# Intelligent Machine Tools

- The recipe:

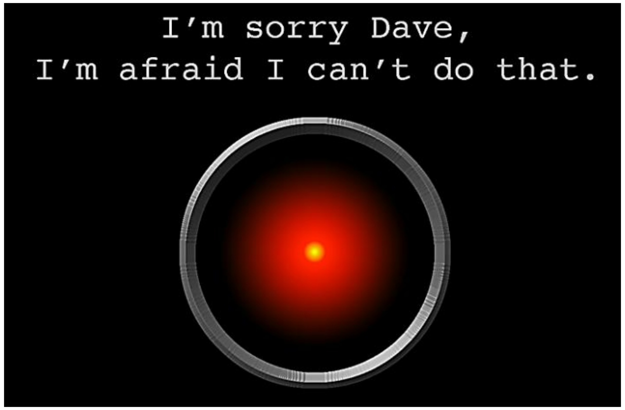
Hardware
- *Mechanics*
- *Microelectronics*
- *Sensors*

Software
- *Management algorithms*
- *Control and correction algorithms*
- *Knowledge Acquisition Systems*
- *Inference engines*

# Levels of automation – by "Anatomy of Automation"

| Livello Autom. | Funzione umana sostituita | Esempio |
|---|---|---|
| A0 | Nessuna | Utensili manuali |
| A1 | Energia | Macchine ad energia animale, ad acqua, a vapore, ecc. |
| A2 | Destrezza | Automazione a ciclo singolo, trapano a colonna |
| A3 | Diligenza | Ciclo ripetuto, controllo numerico a loop aperto, linee transfer |
| A4 | Giudizio | Controllo numerico a loop chiuso, retroazione |
| A5 | Valutazione | Analisi e ottimizzazione automatica di processo |
| A6 | Apprendimento | Correzione incrementale, autoapprendimento |
| A7 | Ragionamento | Ragionamento induttivo, intelligenza artificiale |
| A8 | Creatività | Sviluppo di soluzioni originali in autonomia |
| A9 | Dominio | HAL in 2001, A Space Odissey |

G. Amber, P. Amber - **Anatomy of Automation**, Prentice-Hall



# Artificial Cognitive Systems

- **Today's machine tools and production systems** are mainly located at level **A4**, with some characteristics typical of level **A5**

- **The artificial cognitive systems**, levels **A6** and **A7**, are currently in advanced development and are realized in some applications by introducing the complete ability of Assessment, Learning and Reasoning

| | | |
|---|---|---|
| A4 | Giudizio | Controllo numerico a loop chiuso, retroazione |
| A5 | Valutazione | Analisi e ottimizzazione automatica di processo |
| A6 | Apprendimento | Correzione incrementale, autoapprendimento |
| A7 | Ragionamento | Ragionamento induttivo, intelligenza artificiale |

# A solution for intelligent MU: the EPC

- **EPC – Evaluation and Perception Controller**

- A key element is the acquisition of the techniques of:
  - **perception/sensor fusion**
  - **decision/autonomous planning**

  available or in advanced development in various areas:
  - mobile robotics
  - autonomous vehicles
  - automatic vision systems
  - optimal control theory
  - …

# A solution for intelligent MU: the EPC

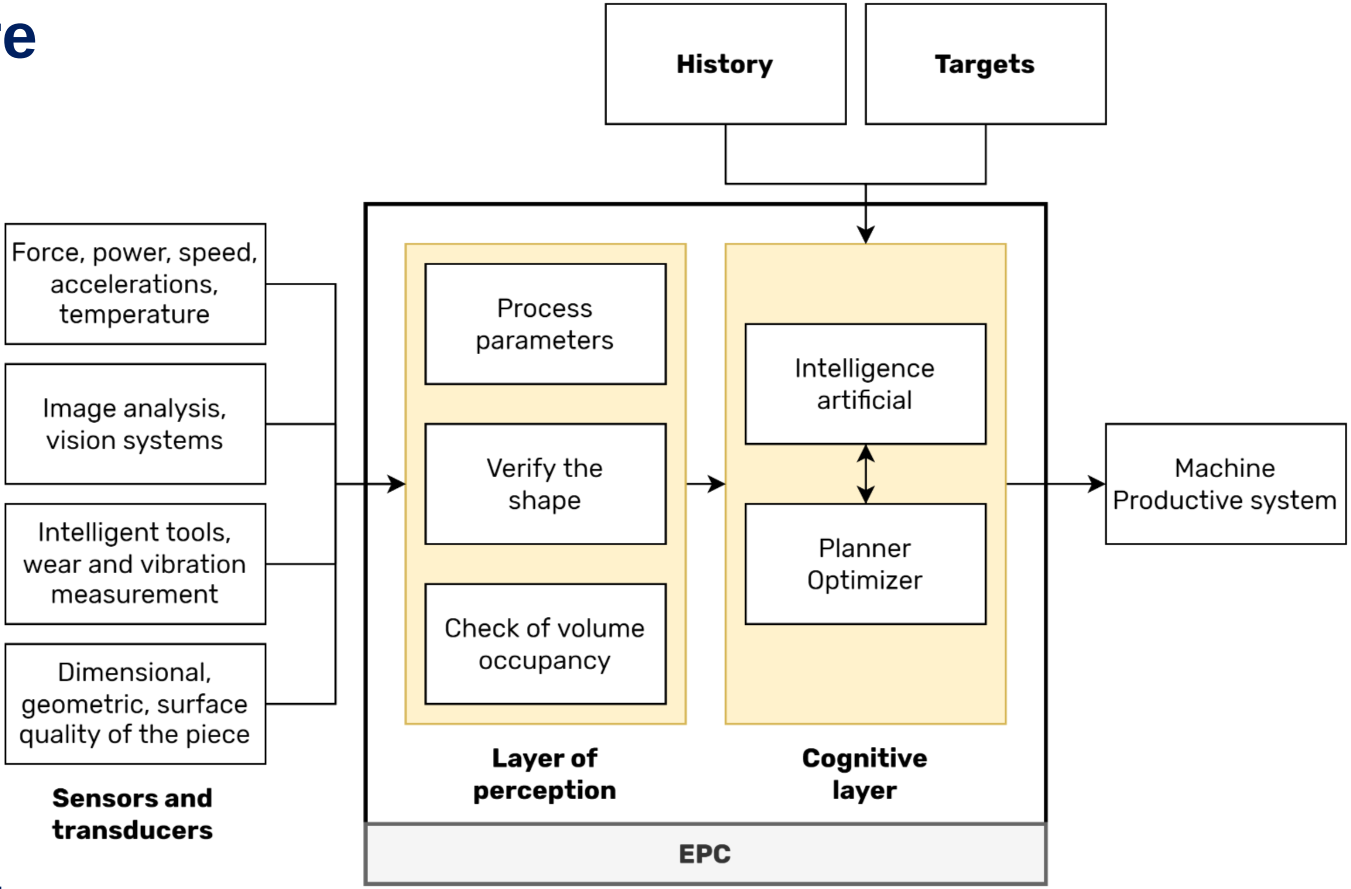
- It is the second "brain" that joins the CNC of the machine tool taking care of high-level functions:
  - reconstruction of the **ego state**
  - **active correction** of process parameters
  - tool trajectory **replanning**
  - error **compensation**
  - **learning** and **self-learning**

# EPC Architecture

It is not a classic **feedback loop**

The set of **sensors** plus the **analysis logic** is called an **adaptronic system**

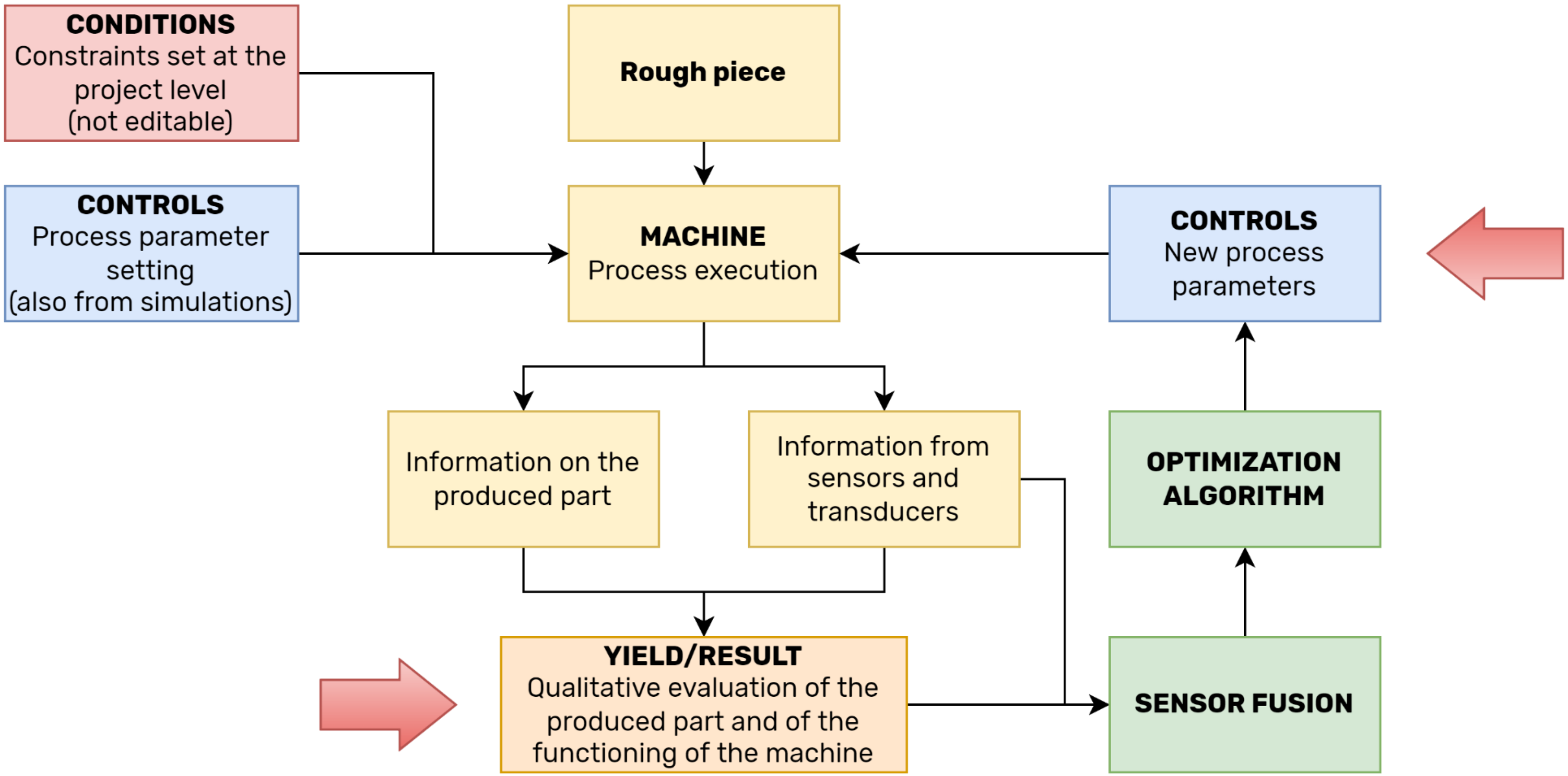
**Sensor fusion techniques** produce a **model of the scenario** (***ego state***)
→ DIGITAL TWIN




**Functions of the EPC:**

1. **Perception:** reconstruction of the scenario through sensor fusion techniques
2. **Evaluation:** comparison of the current state with objectives and constraints imposed on the process and evaluation of the operating conditions of the machine
3. **Optimal scheduling:** planning based on simplified models of the different manufacturing processes and information coming from the evaluation status
4. **Learning:** to use the experience as a support to functions 2 and 3

# Definition of links between "yield" and "controls"



# Benefits of EPC

- Increased accuracy
- Process time reduction (thanks to optimized toolpaths)
- Cost reduction (thanks to less stress on tools that reduce wear);
- Decreased energy consumption and consequent lower environmental impact
- Reduction of rework and waste
- Better surface quality
- Greater safety for the operator, the workpiece and the machine, thanks to the lower risk of collisions
- Autonomous optimization of the processes given the status, the objective to be achieved and/or the ability to independently decide some processing parameters

# Adaptronic modules

- **Adaptronic modules** are integrated subsystems consisting of:
  - a measuring system
  - a microcontroller for acquisition/control/communication
  - and, where appropriate, a compensation actuator

- The adaptronic modules simplify the sensor fusion layer, delegating to distributed microcontrollers the task of acquiring and preprocessing the measurement signals (vision module, spindle monitoring module, ...)

# Example of possible solutions

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **P1** | Velocità di taglio | Avanzamento per dente | Larghezza truciolo | Sovrapp. Passate | Mass. Acc./ jerk | | | | | | | |
| | 28.2% | 25.6% | 17.9% | 10.3% | 17.9% | | | | | | | |
| **P2** | Velocità di taglio | Avanzamento per giro | | | | Carico radiale | | | | | | |
| | 36.8% | 31.6% | | | | 31.6% | | | | | | |
| **P3** | Velocità di taglio | Avanzamento per dente | Larghezza truciolo | Sovrapp. Passate | Massima accelerazione | | | | | | | |
| | 19.7% | 24.2% | 19.7% | 19.7% | 16.7% | | | | | | | |
| **P4** | | Velocità di avanzamento | Step size | | Massima accelerazione | | Temperatura pezzo | Tipo percorso | Velocità di strisciamento | Raggio ut. relativo | | |
| | | 15.2% | 21.2% | | 6.1% | | 16.7% | 24.2% | 6.1% | 10.6% | | |
| **P5** | | | | | | | | | | | Pressione max acqua | Curva di pressuriz. |
| | | | | | | | | | | | 28.6% | 32.1% |
| **TOT** | Velocità di taglio | Avanzamento per dente | Larghezza truciolo | Sovrapp. Passate | Mass. Acc./ jerk | Carico radiale | Temperatura pezzo | Tipo percorso | Velocità di strisciamento | Raggio ut. relativo | Pressione max acqua | Curva di pressuriz. |
| | **84.7%** | **96.6%** | **58.8%** | **30.0%** | **40.7%** | **31.6%** | **16.7%** | **24.2%** | **6.1%** | **10.6%** | **28.6%** | **32.1%** |

| | | |
|---|---|---|
| **Sensors** | on line | Dynamometer table |
| | on line | Accelerometers |
| | on line | Position transducers |
| | on line | Pressure transducers |
| | on line | Wattmeter |
| | on line | Thermocouples |
| | off line | Ultrasound |
| **In addition** | off line | Analysis of the usage of the working volume for the definition of the *occupation grid* |

| | |
|---|---|
| **Algorithms** | CAM path variation to adapt to errors |
| | Variation of the cutting speed to adapt to vibration |
| | Maximization/minimization of the objective function |
| | Compliance with maximum or minimum values of working parameters imposed by machine structure |

# Modeling and simulation environment development

- EPC development and design **requires the ability to simulate both the process and the dynamic behavior of the machine tool**

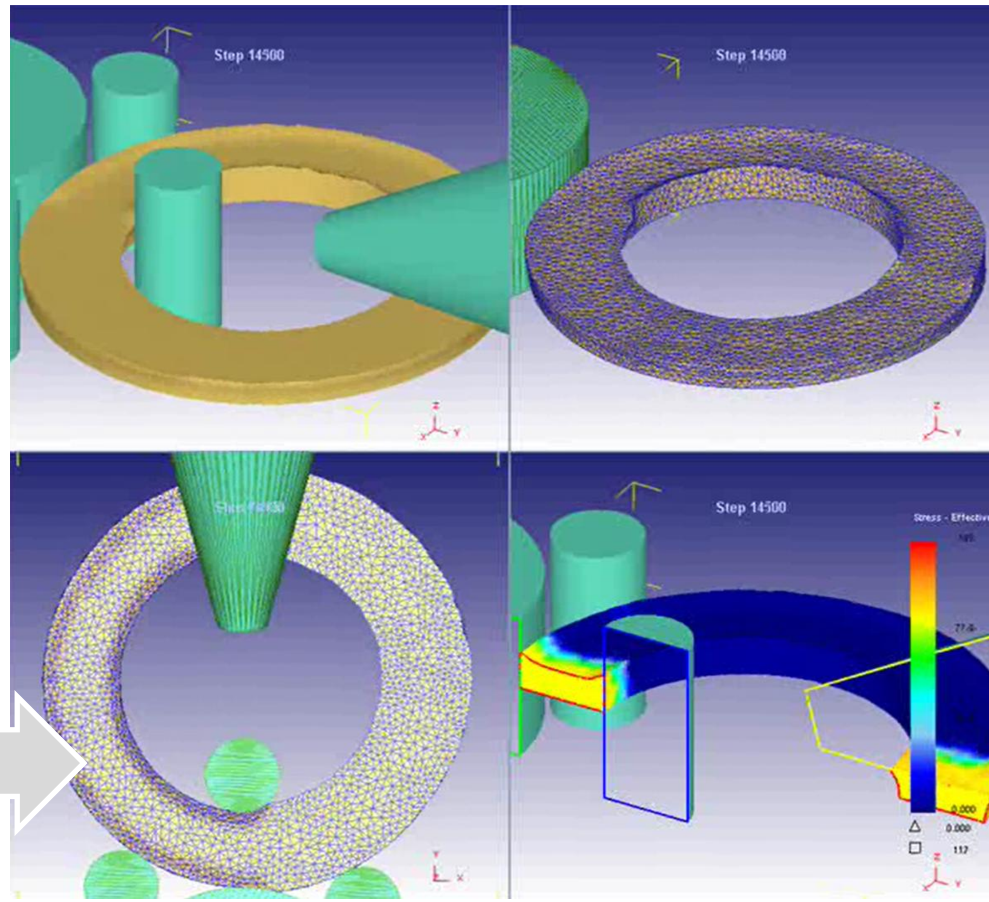
- **Process simulation** is required to support the development of the machining process reference model employed by the planning and optimization layer

- The **simulation of dynamic behavior** of MT is necessary, for example, for the verification and optimization of the operation of the EPC

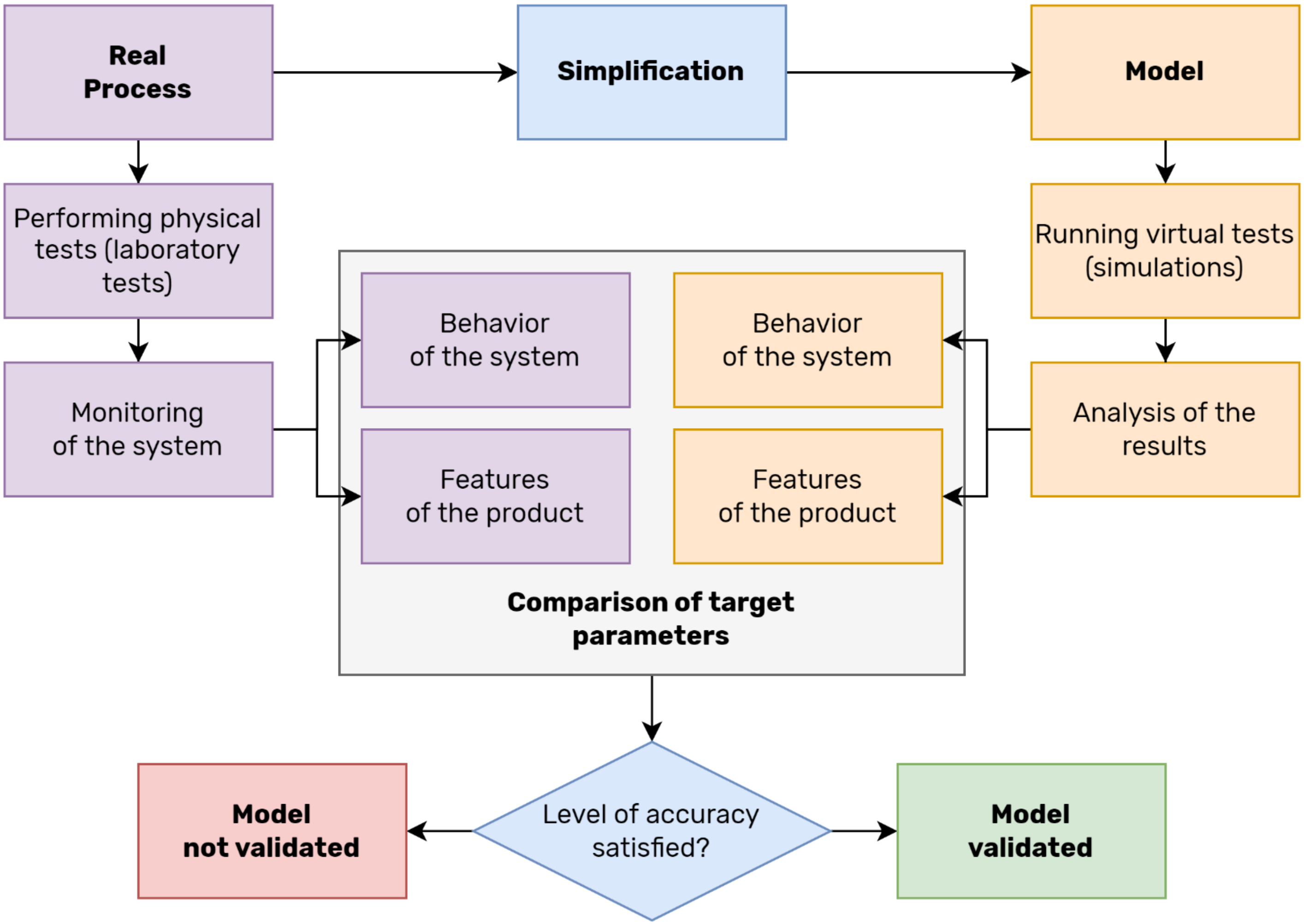
# Model validation

- A model is a virtual environment in which it is possible to verify the behavior of systems under known conditions and under control

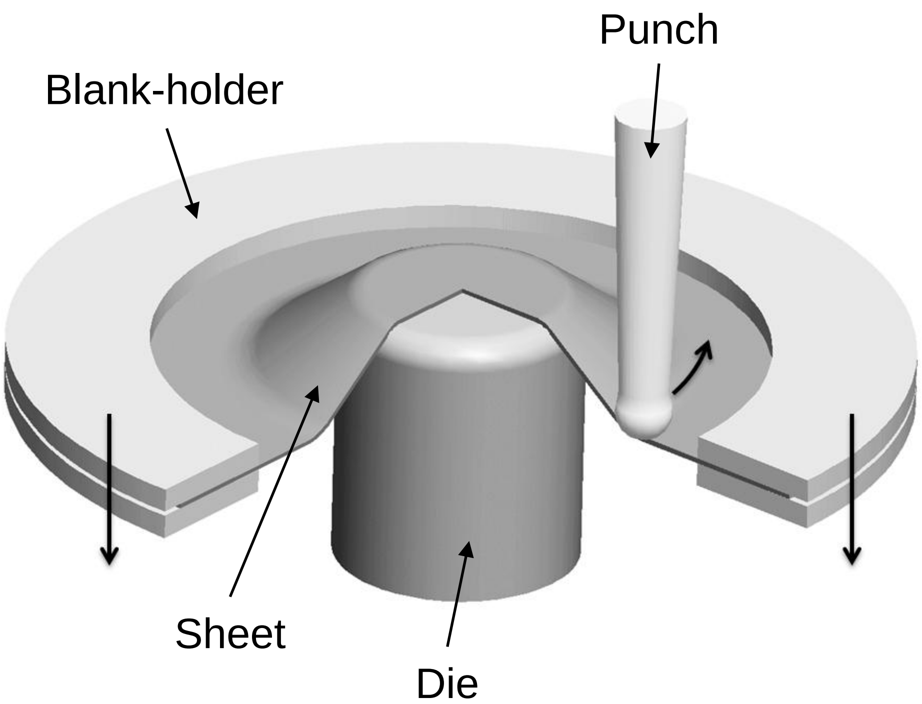
- **Models are simplified representations of reality**
  - Validation is important to evaluate the level of approximation of the model

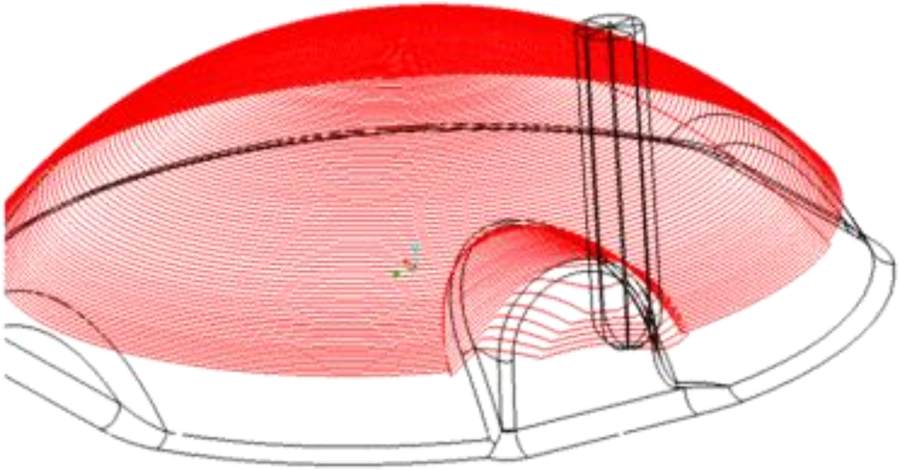


# Model validation



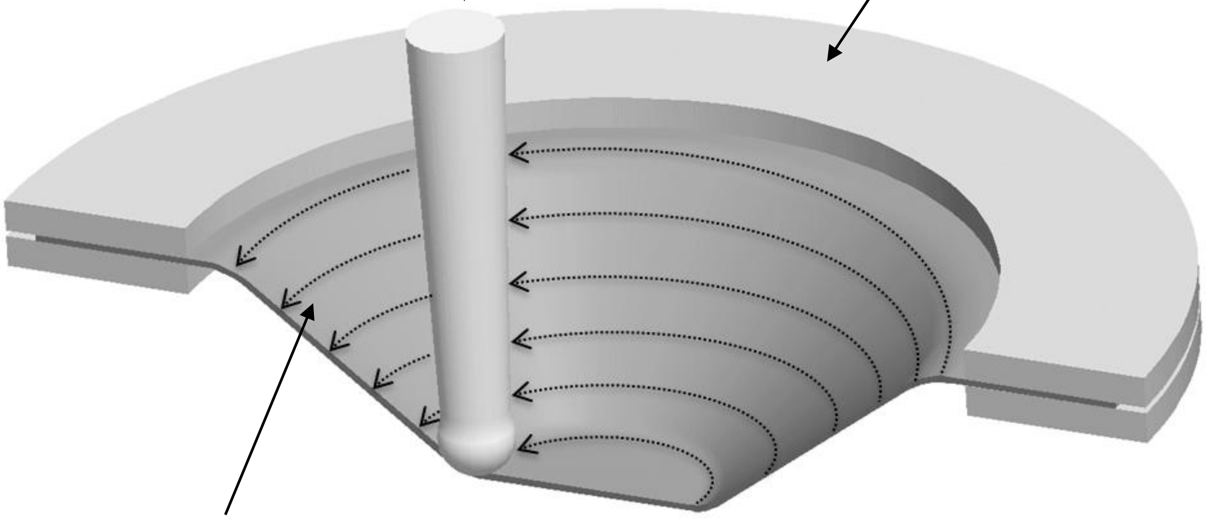
# An example:
# Incremental Sheet Forming



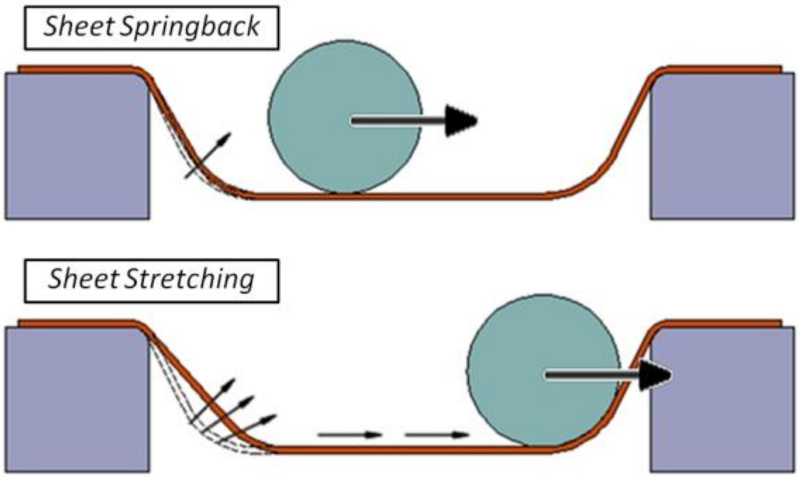
# An example:
# Incremental Sheet Forming

CAD model
↓
CAM
↓
Part-program
↓
Machine tool →



# Limits of the technology

1. The possibility of obtaining the desired product **without causing the sheet to break** due to **excessive thinning** typical of products with too much inclined walls
2. **Respect for the desired geometry**, that is difficult to comply for the double effect of **springback** (the sheet is worked with local deformations) and the fact that while the punch works at increasingly depth values, the action of the punch causes the deformation of the sheet (**for pulling actions and for the torques that are generated**) even where it has already been machined (ie on smaller depths)



# It is necessary to correct the ISF toolpath

- **To develop a software to perform a correct modification of the tool path** in incremental forming processes in order to obtain a part in tolerance after shake-off and profiling

- **To compensate the elastic return of the material** (in the machine, after shakeout and after profiling)

- **To measure the real part** and estimate the geometric errors with respect to the CAD model: it is necessary to define a strategy for measuring the part and analyzing the profiles considering the next path modification algorithm (e.g .: STL → profiles along constant Z sections)

- **It is necessary to compensate the geometry of the part and not directly the tool-path**

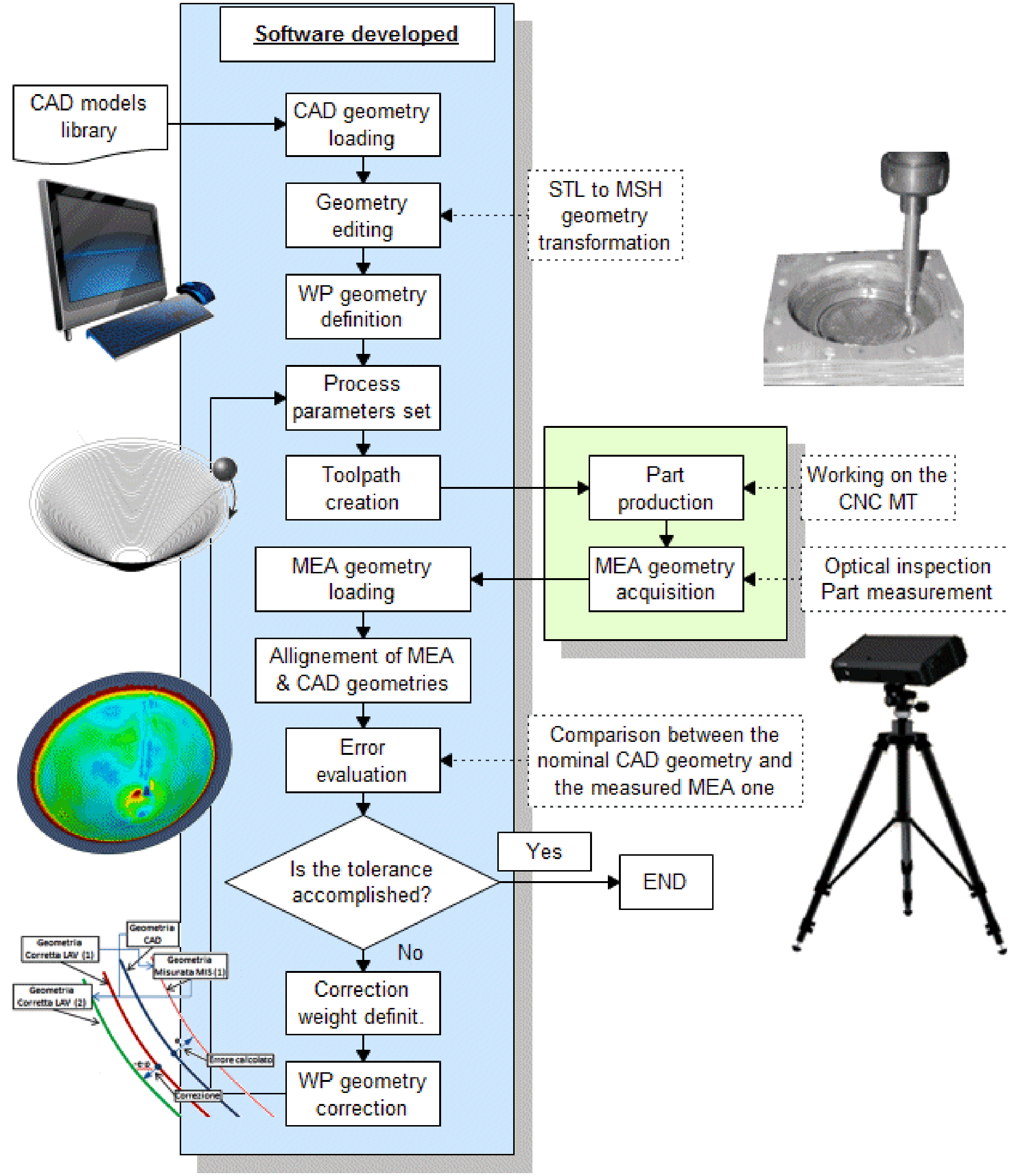
# Overview

Part to be produced

ISF process

Geometry detection

Dimensional error reduction
through **ILC**
↑
**Iterative Learning Control**

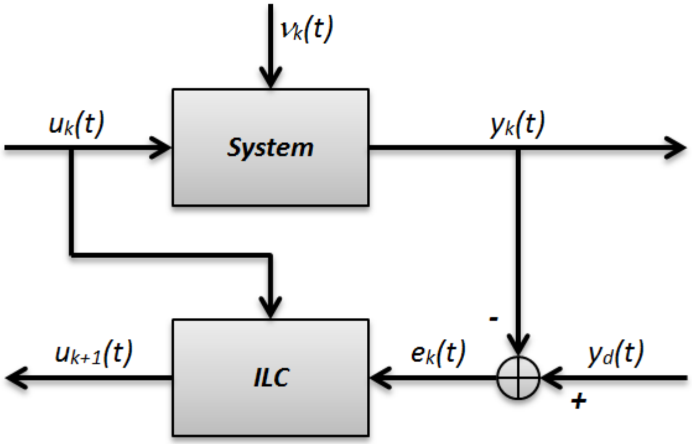


# The core of the toolpath optimization: Iterative Learning Control – ILC

- The problem of iteratively learn and control a system, can be expressed as to iteratively find the system input minimizing the output error as the difference between what is obtained with respect to what one wants to obtain

- This type of problem is normally called Tracking Iterative Learning Control (TILC) problem. This type of approach does not require any a priori knowledge of the system under control and can be applied to all the cyclic processes

- In fact, ILC is so called because it acts iteratively on a system, it learns for each cycle by deriving information from the system and it controls the system by using the collected information



# The core of the toolpath optimization: Iterative Learning Control – ILC

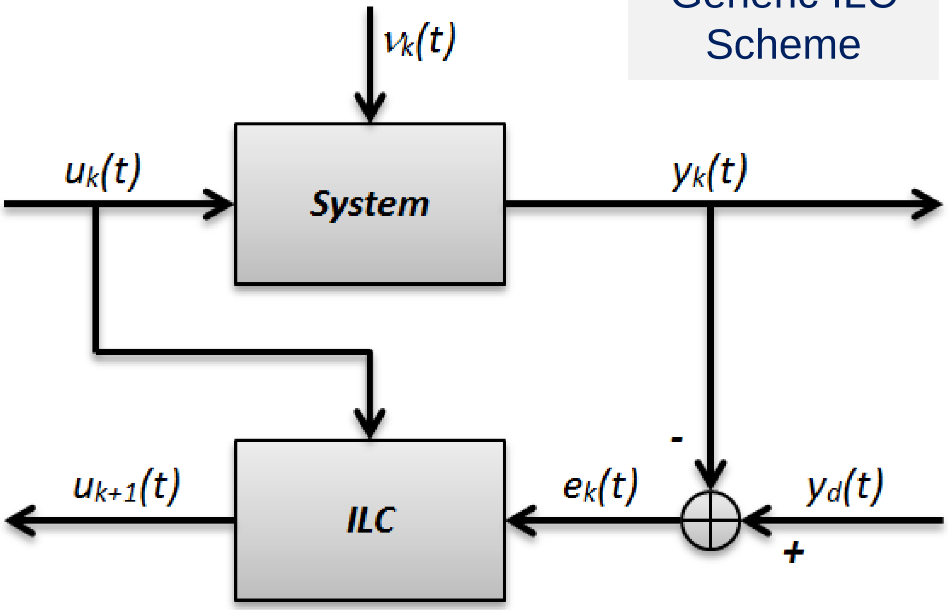
- The most interesting aspect of the ILC is related to the fact that it is possible to implement a control law acting between one cycle and the subsequent one
- To do this, it is necessary to store the errors and to respect the **basic hypothesis**, i.e. the initial condition of each cycle of the process are always the same
- This latter, even if is a heavy hypothesis, in the case of ISF is easily satisfied since the worked material and the initial shape of the sheet is the same for each repetition

# The core of the toolpath optimization: Iterative Learning Control – ILC

- The schematic of an ILC procedure is reported in figure where it is possible to see the **system** and the **learning controller**, which are the core elements
- Between them several signals are passed
- All the signals are defined in a limited time interval $t \in [o, t_f]$ that can assume either continuous or discrete values

- The subscribed *k* indicates the repetition number (*k* = 0 means the initial value)

Generic ILC Scheme



# The core of the toolpath optimization: Iterative Learning Control – ILC

- In practice, during the *k-th* cycle the $u_k(t)$ input is applied to the system which gives $y_k(t)$ as output
- The two signals are recorded in order to be utilized, at the end of the cycle, for the calculus of the next system input $u_{k+1}(t)$
- This signal is recorded for the next cycle

- If $y_d(t)$ represents the desired output signal of the system, the tracking error for the *k-th* cycle $e_k(t)$ can be expressed as:

$$e_k(t) = y_d(t) - y_k(t)$$

- The generic iterative control law can be expressed as:

$$u_{k+1}(t) = f(e_k(t'), u_k(t')) \qquad \text{where: } t, t' \in [o, t_f]$$

- The final goal of the ILC is to minimize the error *e(t)*, i.e.:

$$\lim_{k\to\infty} u_k(t) = u^*(t) \qquad \forall t \in [o, t_f]$$

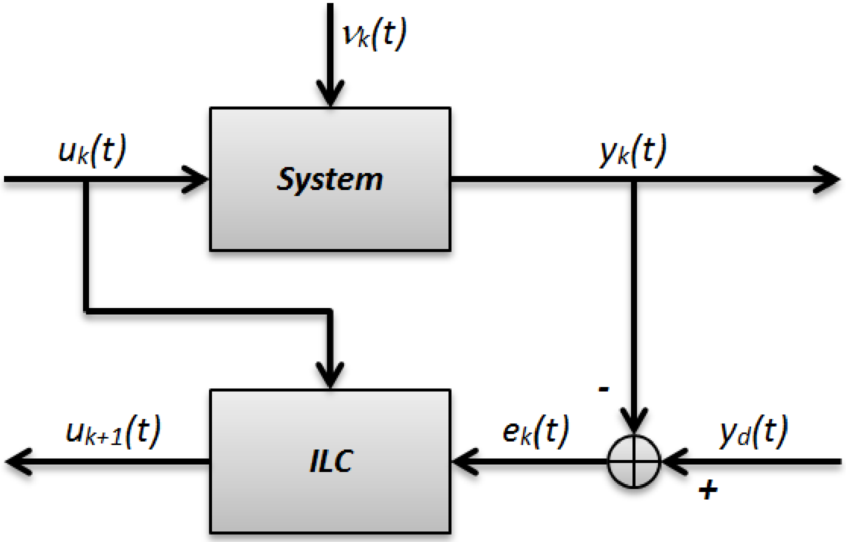
- where $u^*(t)$ is the input signal minimizing the norm of the error:

$$\|y_d(t) - y_k(t)\|$$

- The problem formulation can be seen as to determine the ILC law:

$$u_{k+1}(t) = f_{ILC}\left(y_d, u_{k-m}, y_{k-j}, y_{k+1}\right)$$

where: $j, m \geq 0$



- Between all the different algorithms available in literature, a linear first order algorithm was chosen. In this algorithm it is necessary to store the error of the previous cycle only:

$$u_{k+1}(t) = f_{ILC}(y_d, u_k, y_k)$$

and the ILC function is linear, hence:

$$u_{k+1}(t) = T_u(z) \cdot u_k(t) + T_e(z) \cdot e_k(t)$$

where $T_u(z)$ and $T_e(z)$ are linear operators in $z$, the system variable

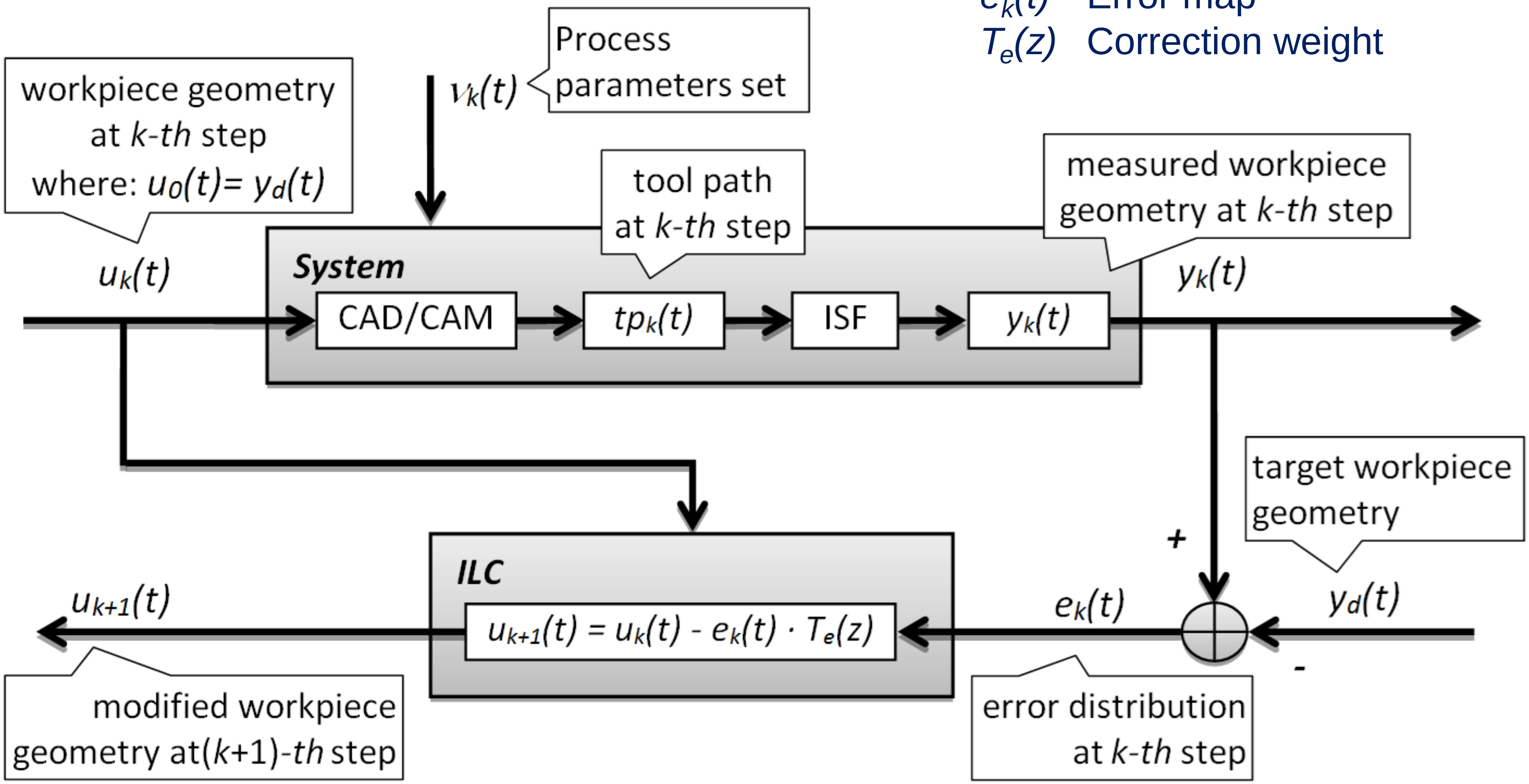
- In the studied case $T_u(z)$ was set equal to 1 while $T_e(z)$ was considered as a weight (0,1] applied to the calculated error
- In such a way the new control signal $u_{k+1}(t)$ is modified with respect to $u_k(t)$ by an amount proportional to the error. Value of $T_e(z)$ greater than 1 should lead to a non-convergence of the system
- The correctness of choosing $T_e(z)$ equal to 1 can be proved comparing the output signal after the first cycle and after the second one applying the first compensation

- The ILC most important aspects are:
  - It is necessary to fix a first trial input signal $u_0(t)$ for the first cycle
  - It is supposed that the initial conditions are always the same for each cycle
  - It is supposed that the cycle length $t_f$ is constant
  - The error should converge to 0; It is supposed that the system is stable during the time; this is very important since the ILC algorithm is able to better the system performance and not to stabilize it
  - The convergence characteristics are independent on the desired signal $y_d(t)$; for this reason, the ILC controller, once implemented and correctly configures, should be able to self-adapt to the new situation

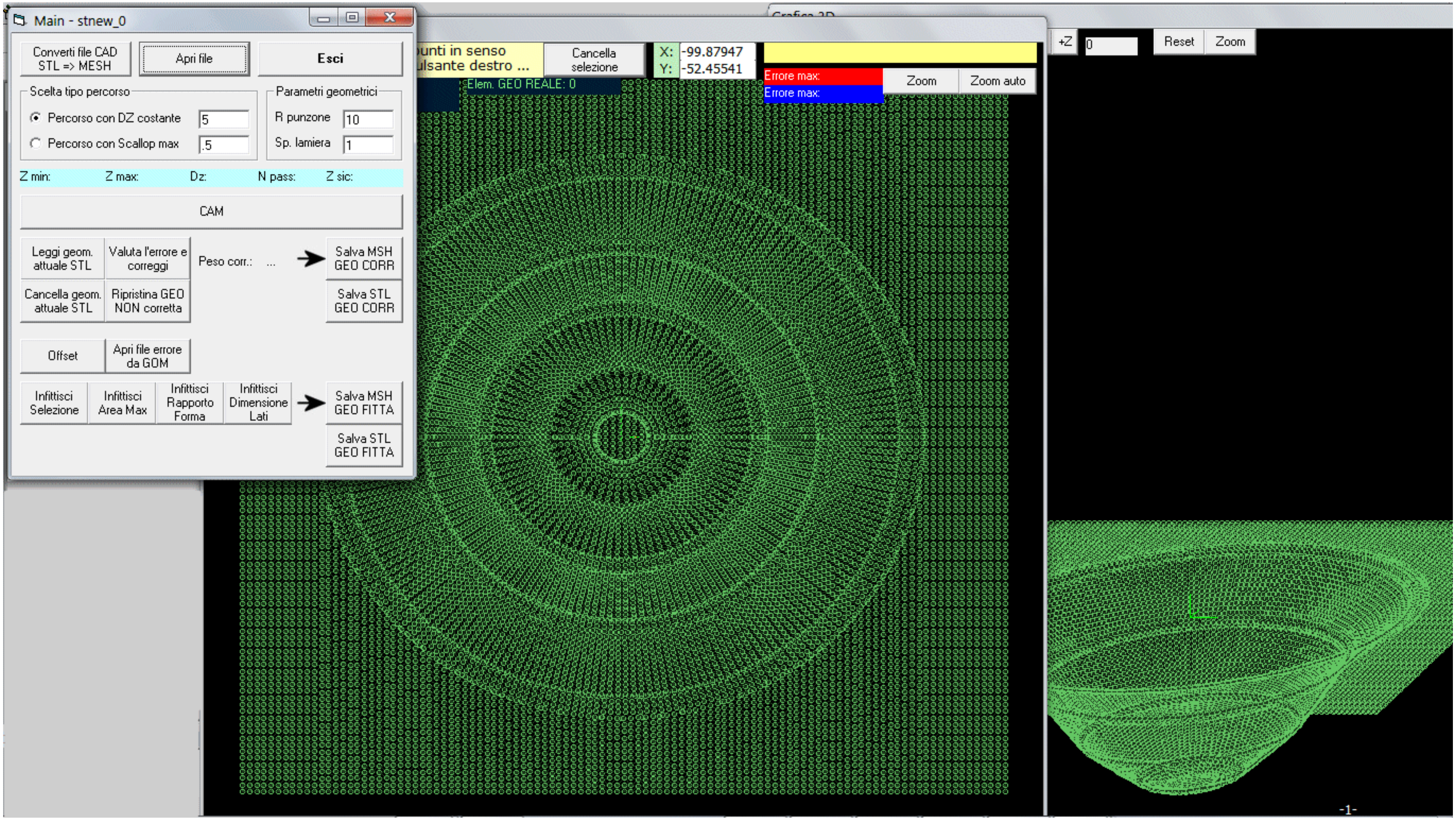
# Error reduction by means of ILC

$u_k(t)$ Part geometry (corrected)
$v_k(t)$ Process parameters set
$tp_k(t)$ Toolpath
$y_k(t)$ Obtained geometry
$y_d(t)$ Target geometry
$e_k(t)$ Error map
$T_e(z)$ Correction weight

Scheme of the ILC applied to ISF

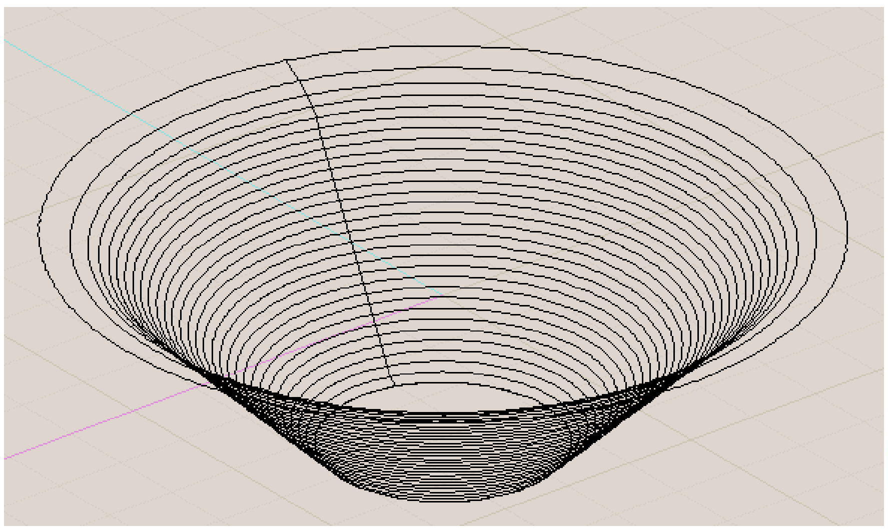


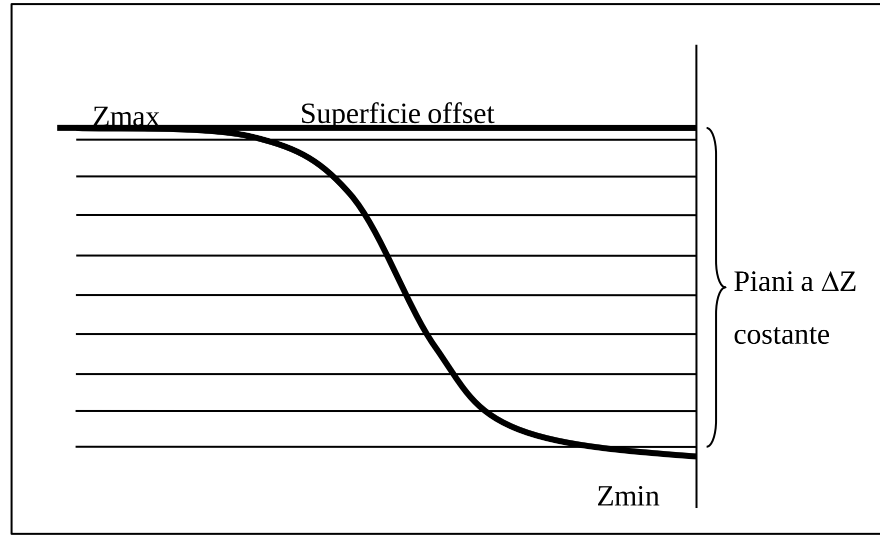
# Developed program – Geometry loading

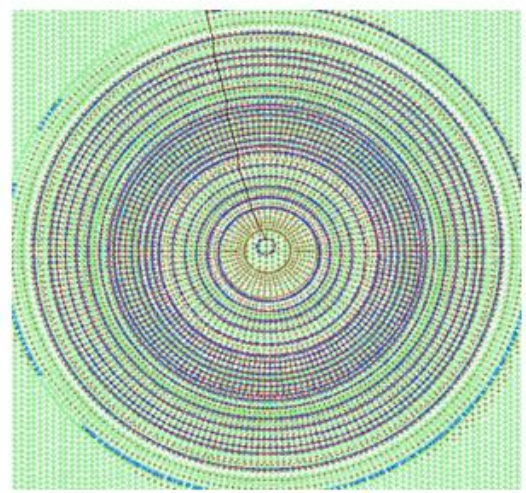


# Developed program – CAM module

- Developed CAM for toolpath definition at constant Z levels
- From CAD/LAV to Part Program

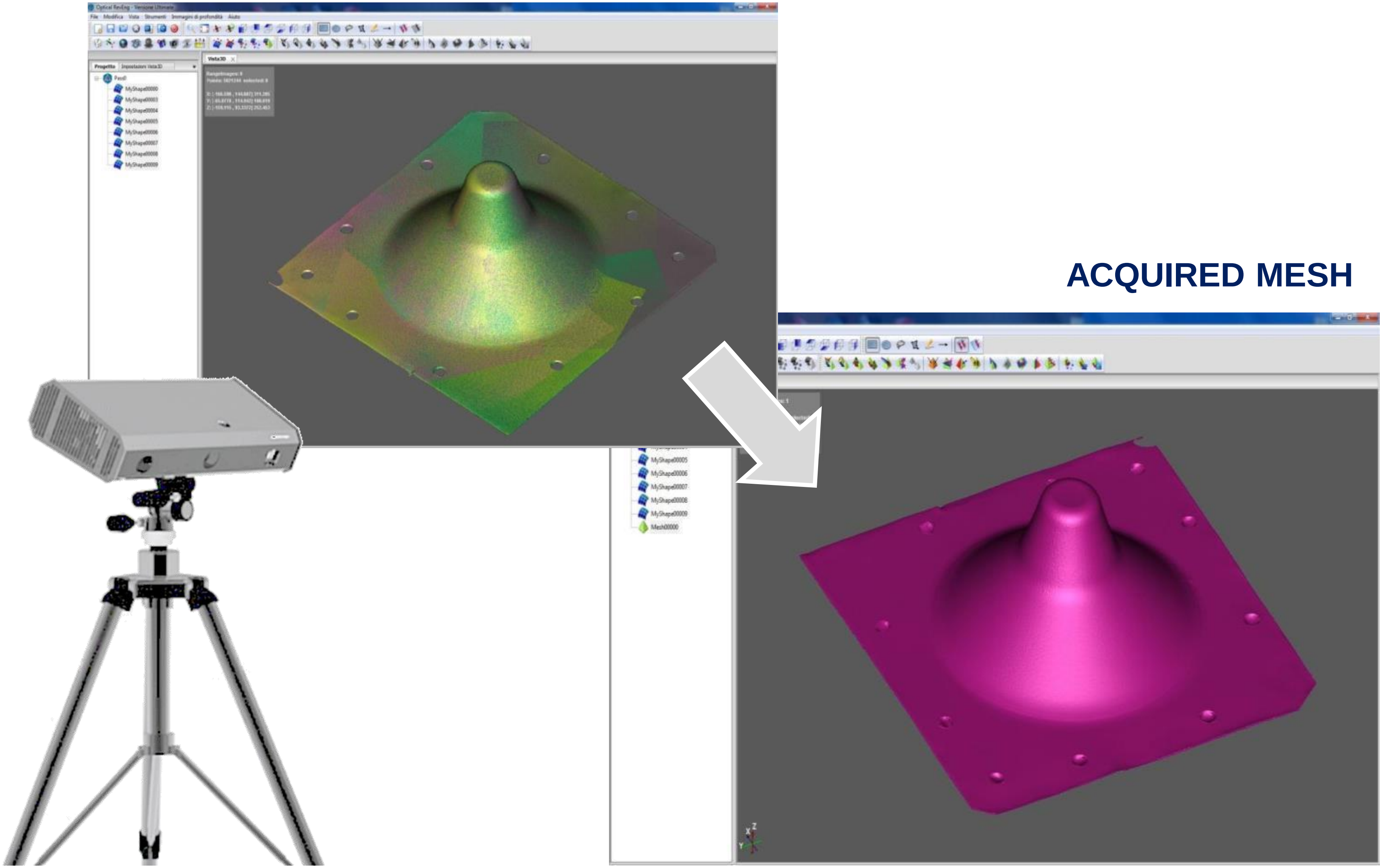




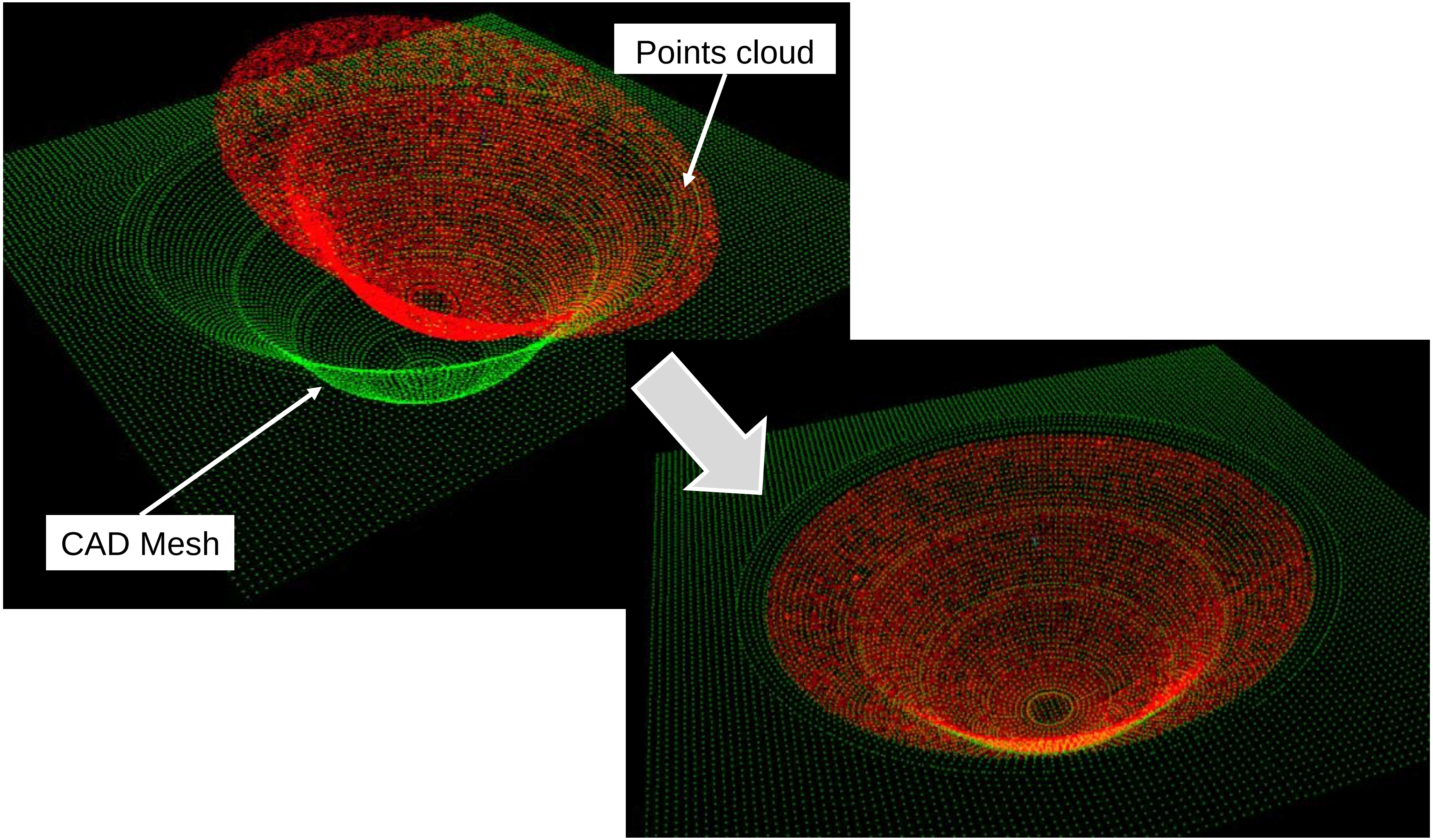



```
$ - stnew
$ - R.punzone: 7
$ - Sp.lamiera: 1,5
$ - Delta Z cost.: 0,39812636361
X81.841 Y-12.385 Z8.441
X81.954 Y-11.434 Z8.441
X82.003 Y-11.073 Z8.441
X82.196 Y-9.541 Z8.441
X82.236 Y-9.179 Z8.441
X82.393 Y-7.644 Z8.441
X82.424 Y-7.281 Z8.441
X82.548 Y-5.742 Z8.441
X82.571 Y-5.378 Z8.441
X82.659 Y-3.833 Z8.441
X82.657 Y-3.447 Z8.441
X82.744 Y-1.923 Z8.441
X82.728 Y-.389 Z8.441
X82.749 Y.001 Z8.441
X82.699 Y1.575 Z8.441
X82.695 Y1.918 Z8.441
X82.672 Y3.470 Z8.441
X82.659 Y3.834 Z8.441
X82.571 Y5.379 Z8.441
```

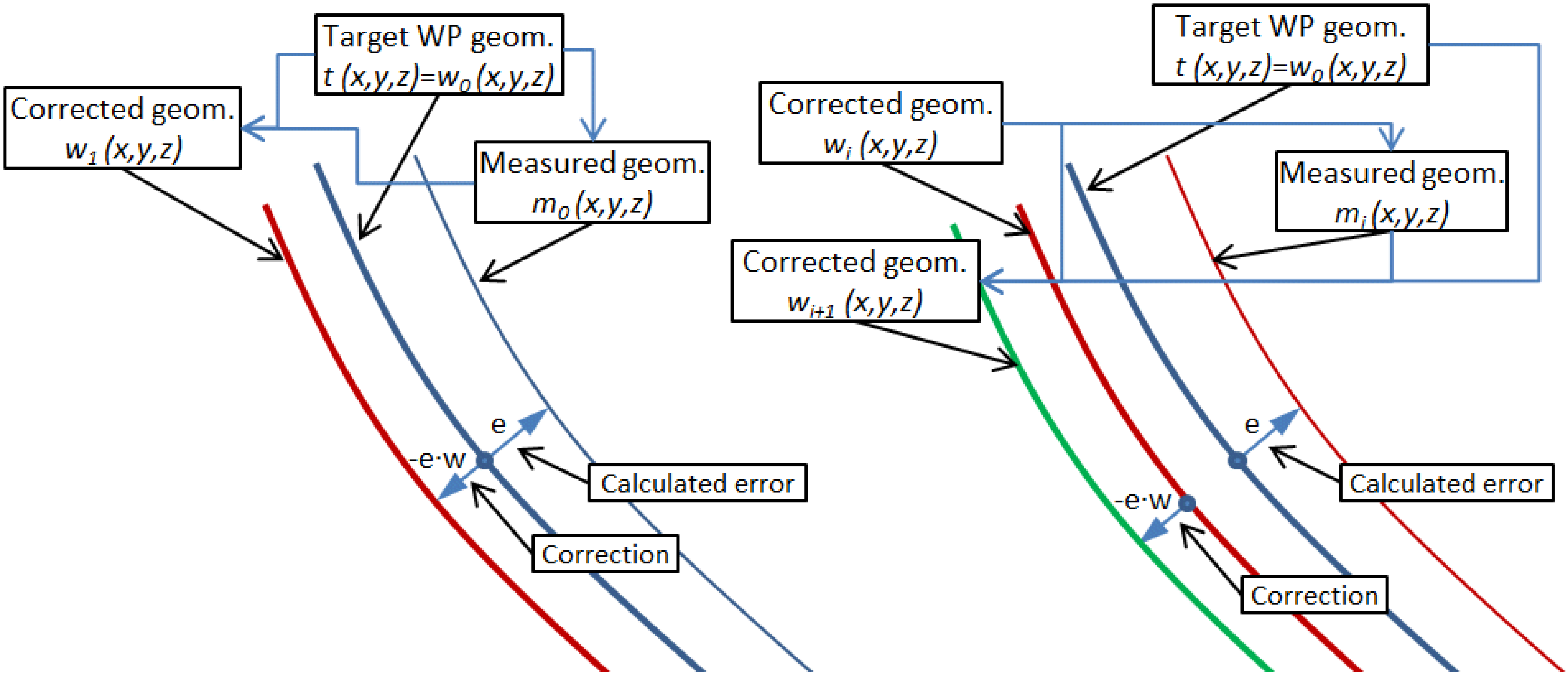
# Produced part measure – Mesh acquisition



# Alignment of the measured geometry with respect to the theoretical one

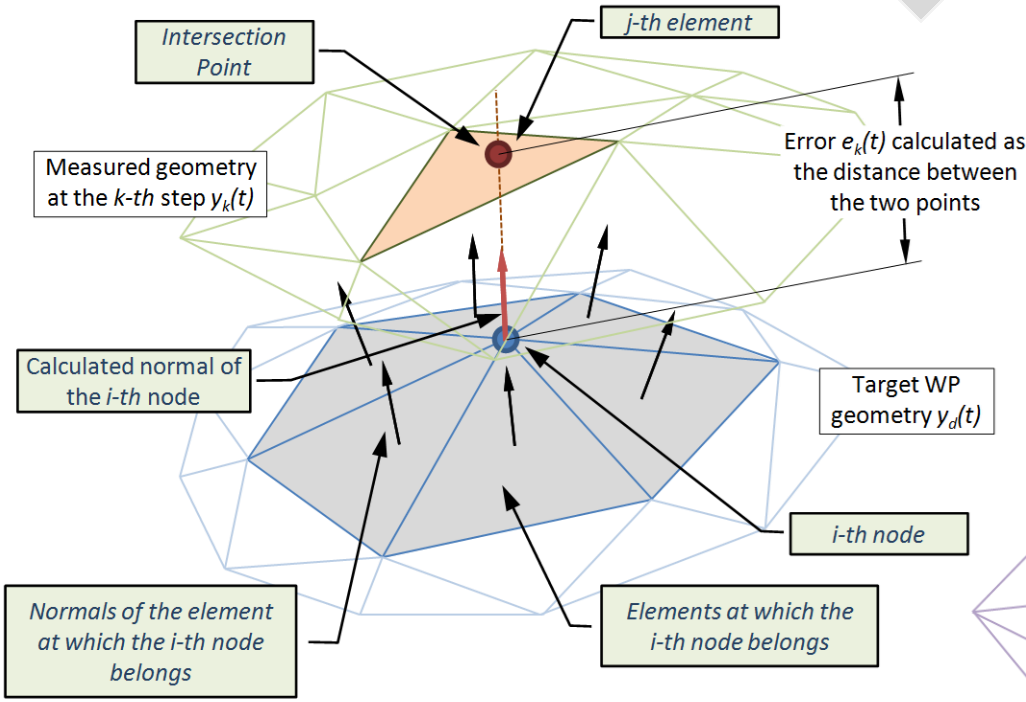


# Error reduction by means of ILC

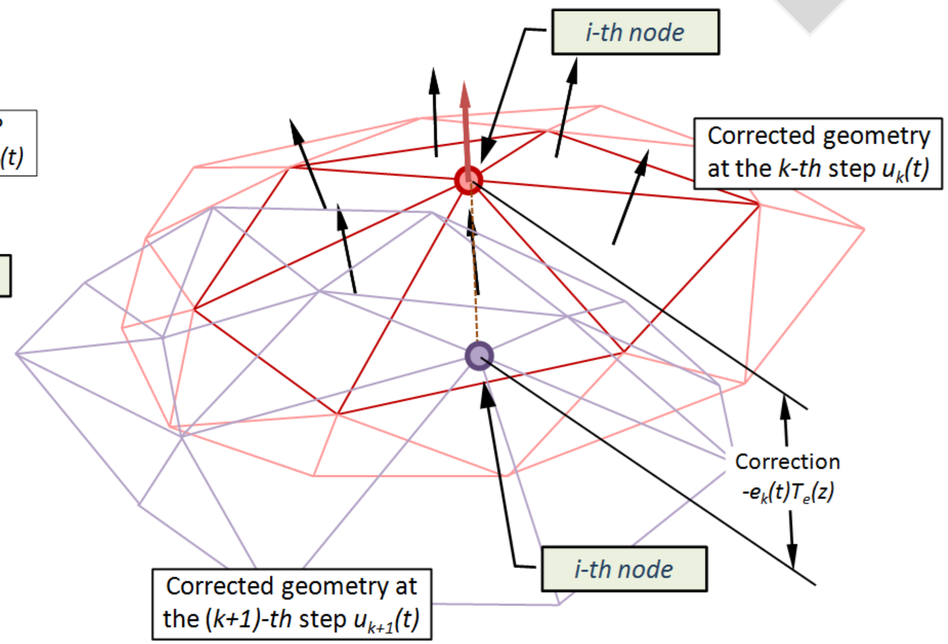


# Error reduction by means of ILC

## Calculation algorithm of the geometric error $e_k(t)$




## Compensation algorithm



# Preliminary experimental tests

Geometry: axisymmetric with variable angle

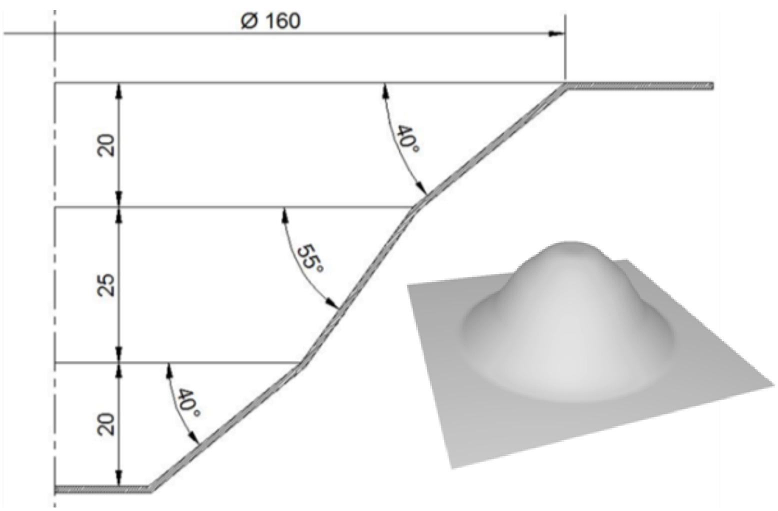
Sheet: Al1050A - 1.5mm

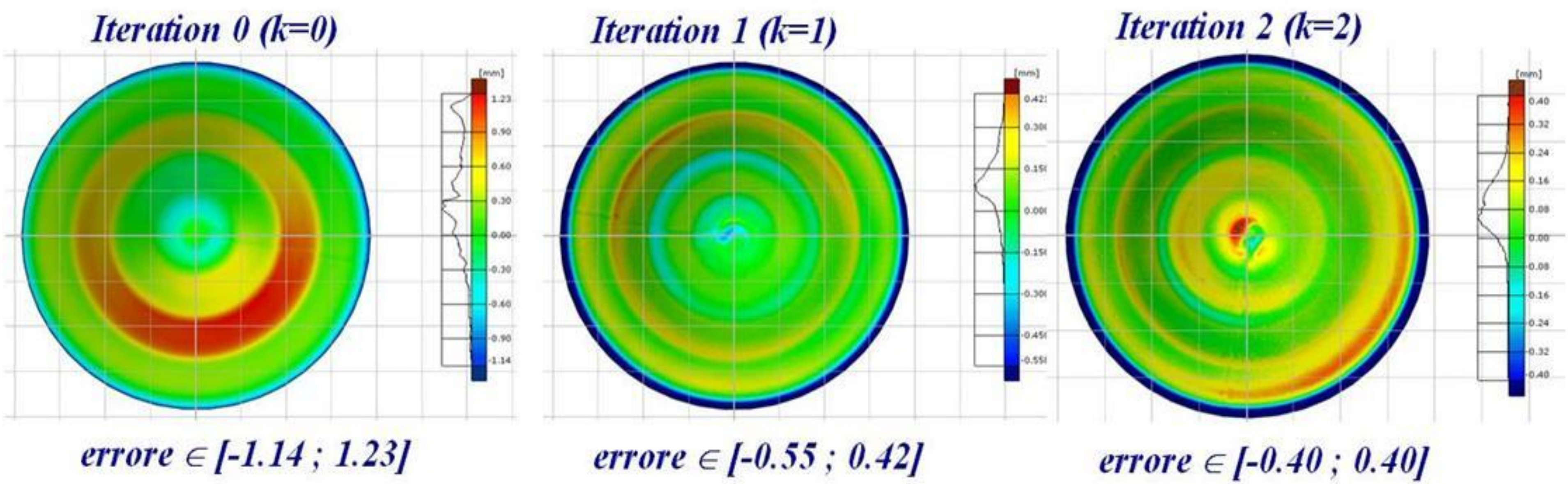
Toolpath: $\Delta Z$ = 0.4 mm

Correction weights: $T_e(z) \in (0;1]$

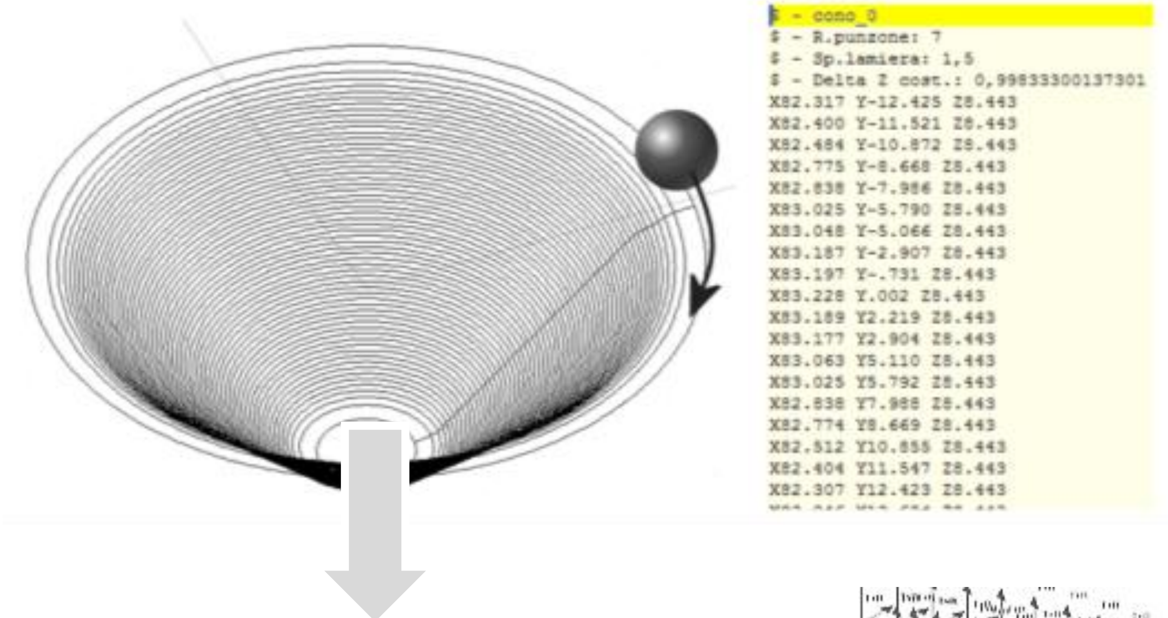
<u>**Oss**</u>: - optimal value $Te(z) = 1$

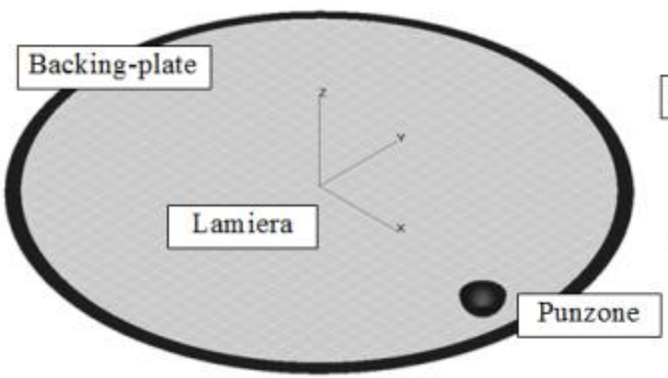
- significant geometrical error reduction

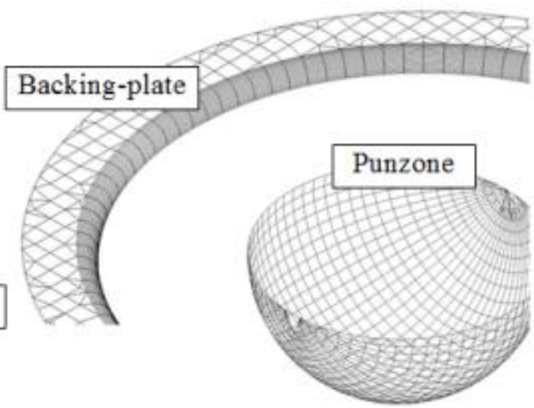


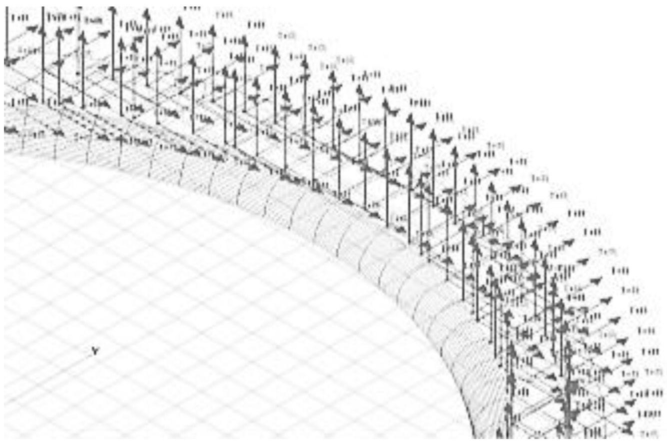



# Development of a model of the process to verify the capability of the method

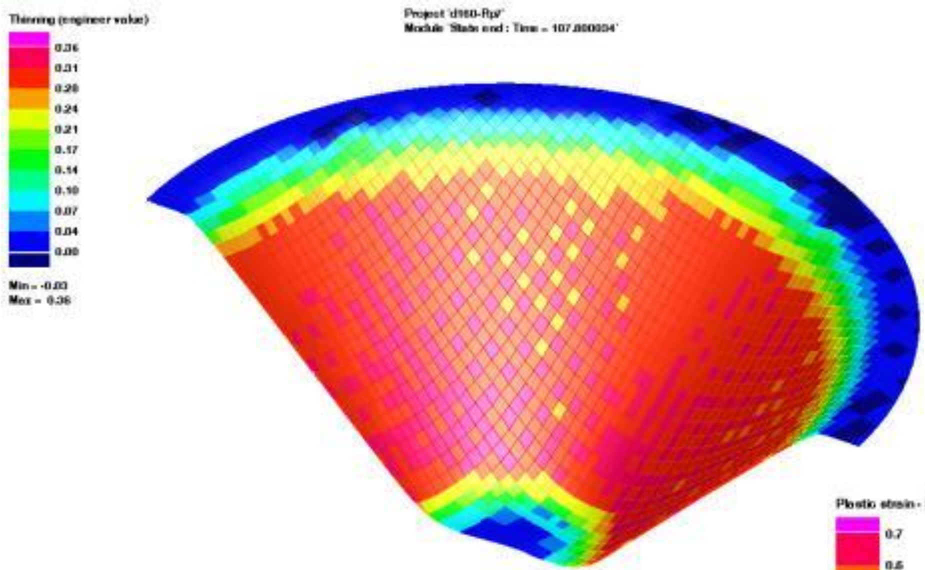


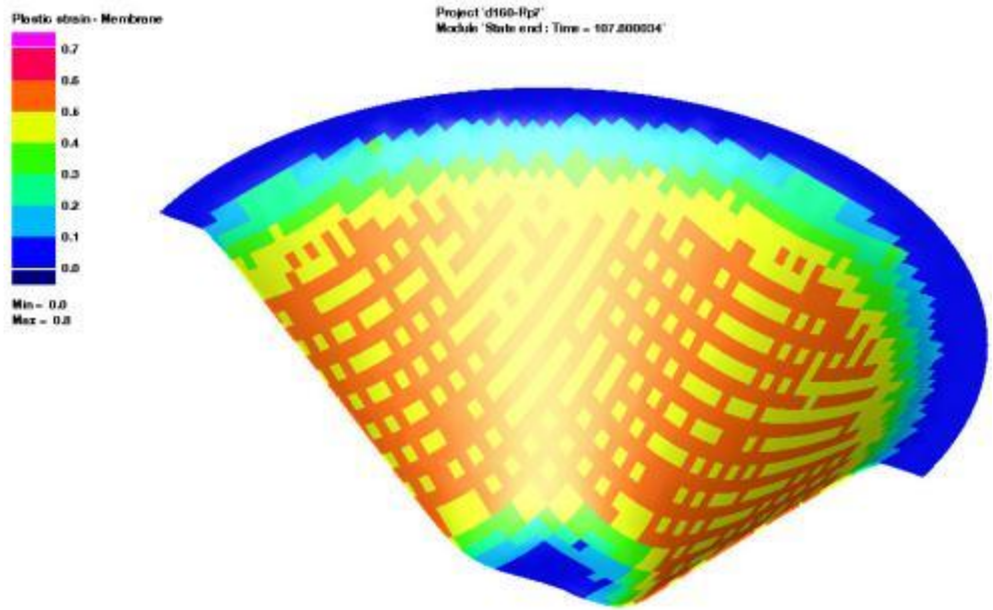



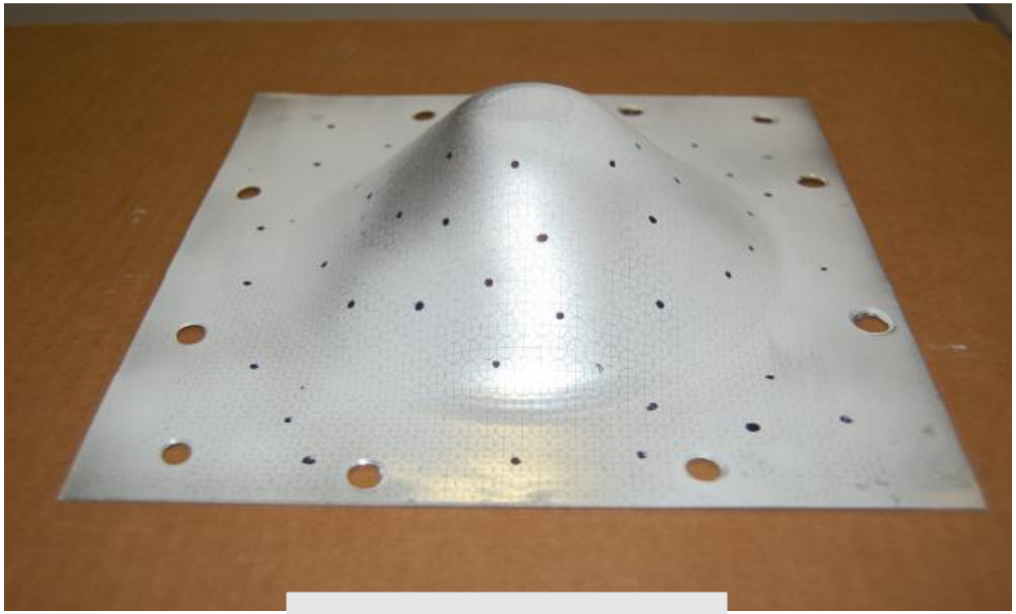
# FEM



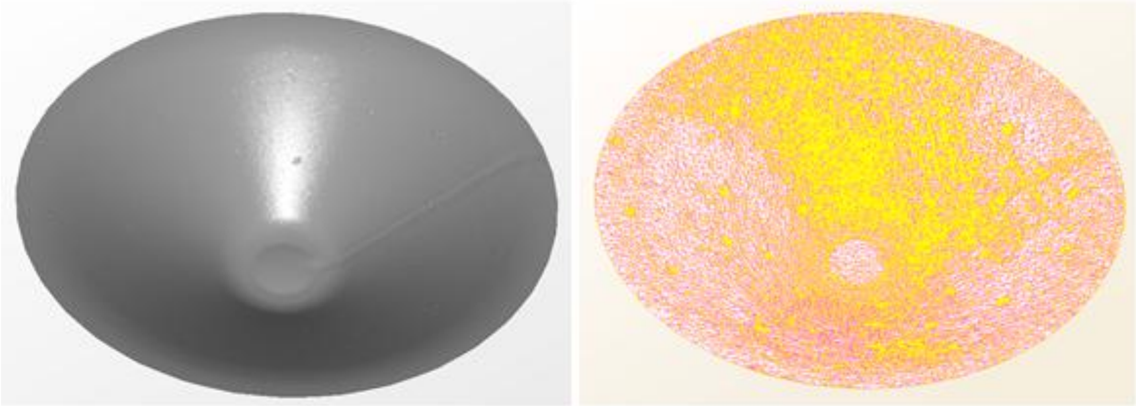

Output FEM



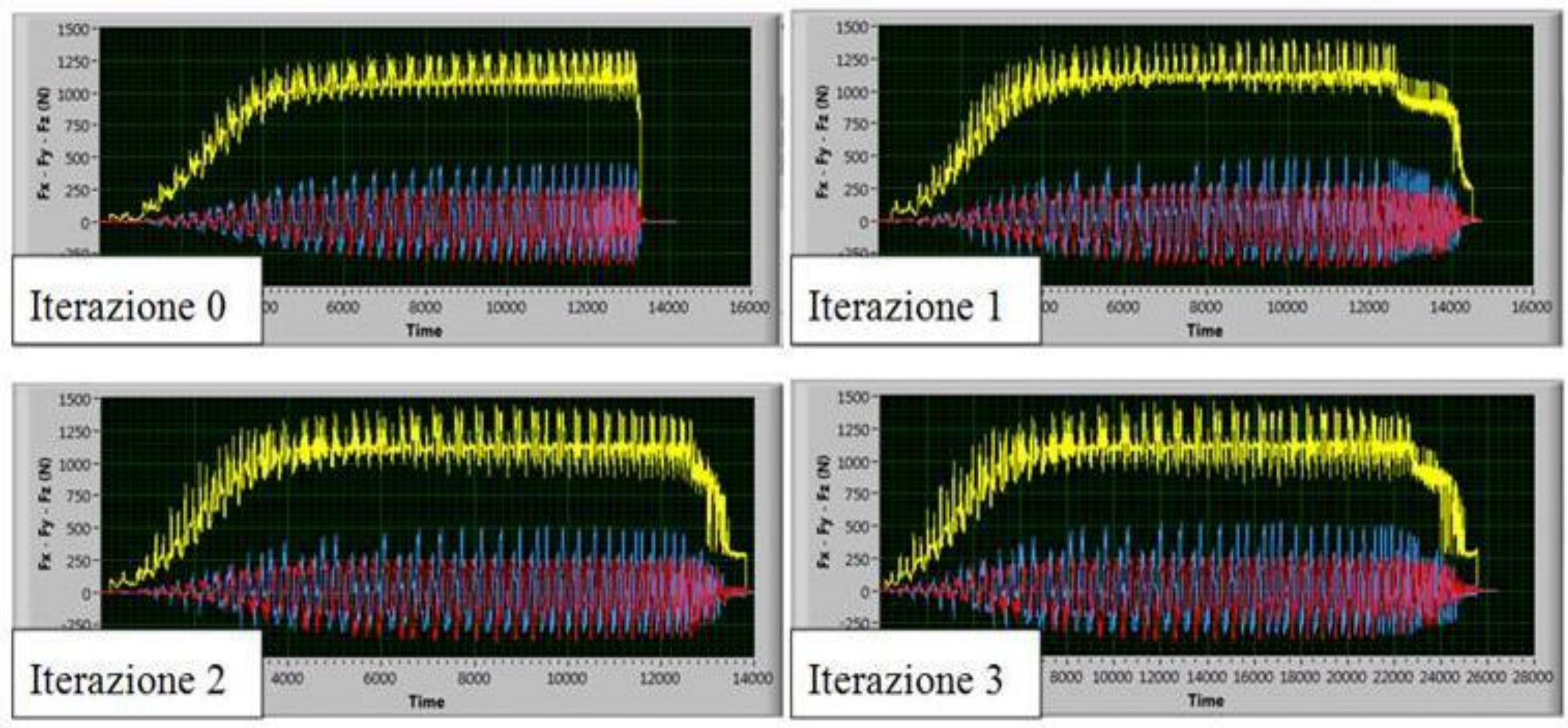
# Experimental test for validation



Part scan



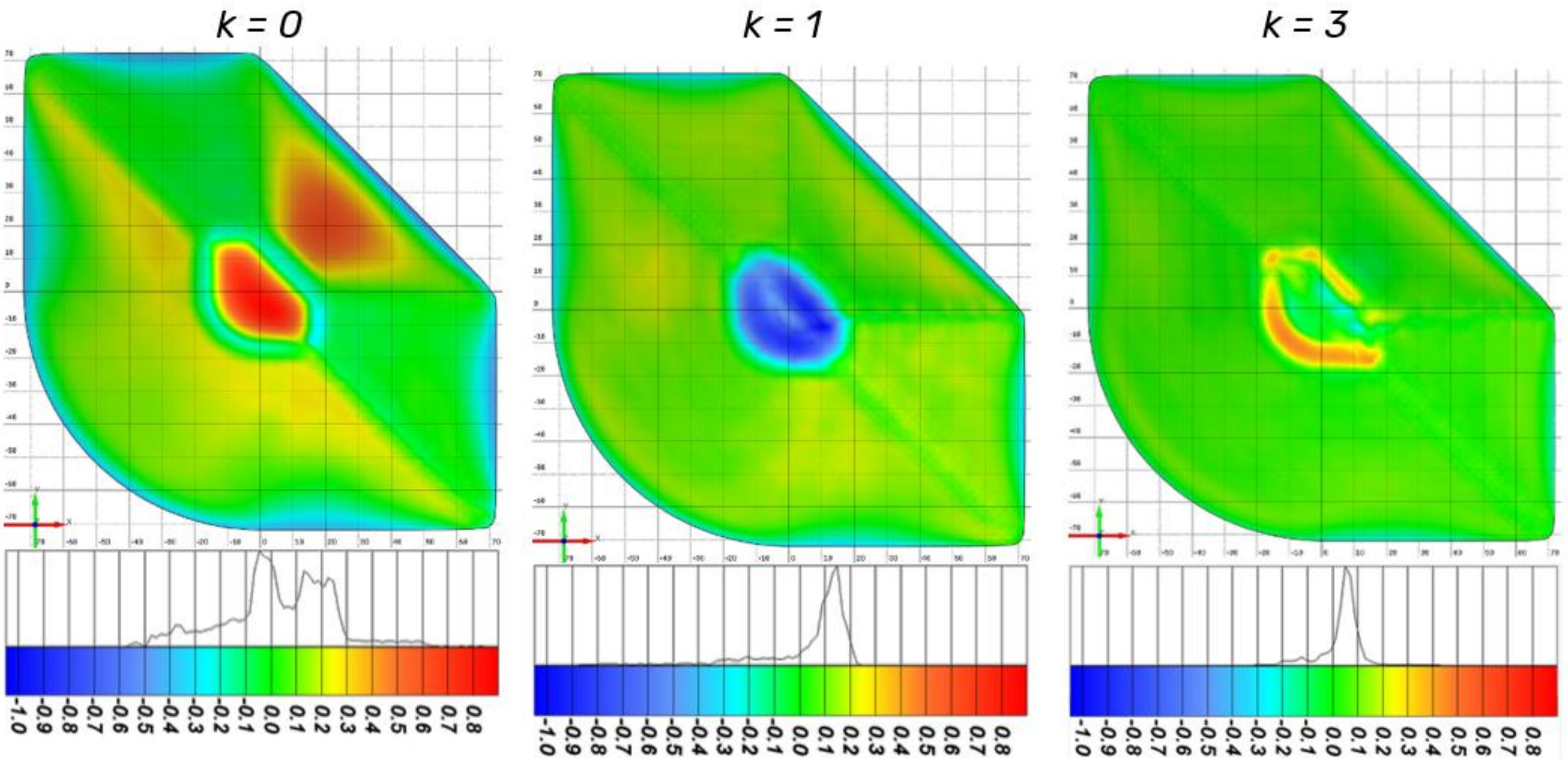
# Forces analysis




**Online forces monitoring**

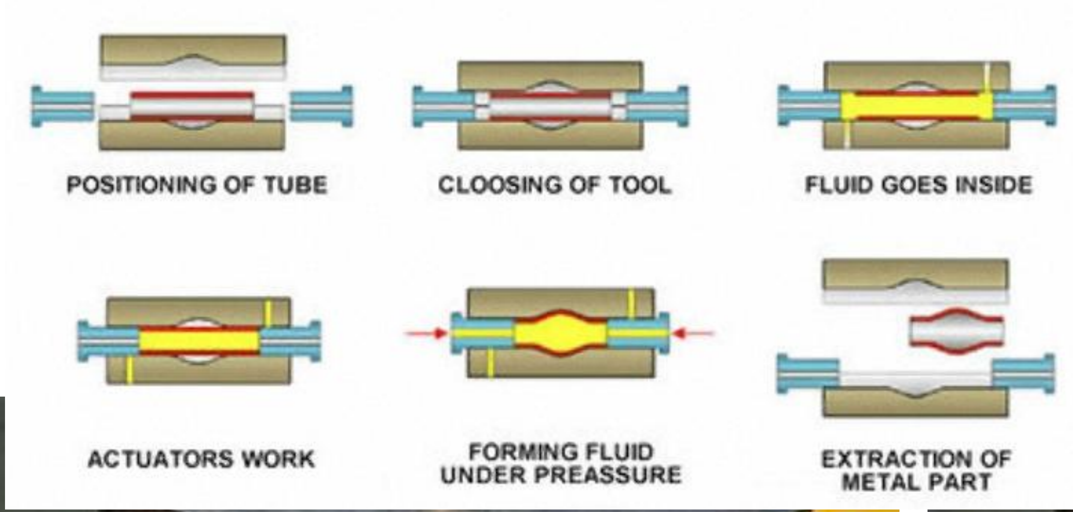
- The reduction of the forces occurs in the event of breakage of the workpiece
- This control can be implemented with a control system that interrupts the processing avoiding any damage to the equipment

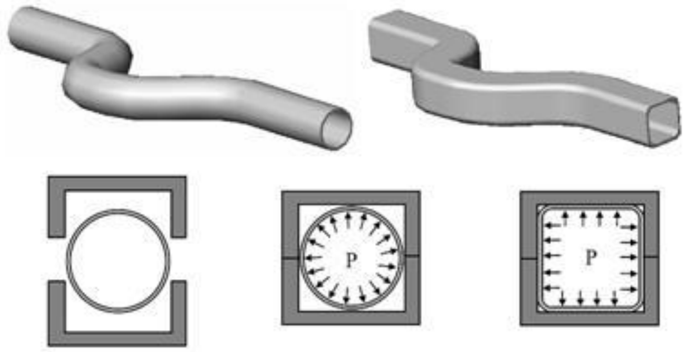
# A non axisymmetric part

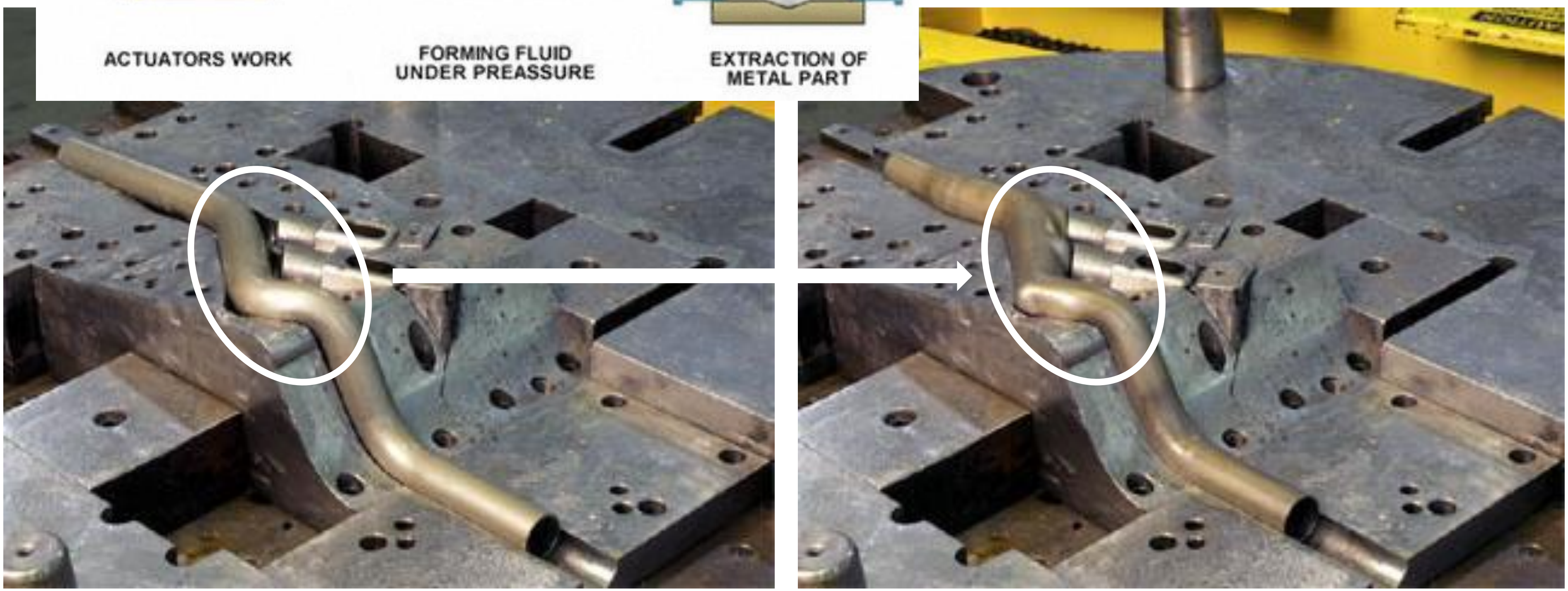



Geometrical error of the part (map and frequency distribution) at the k-th iteration step of the ILC for Al 1050A alloy

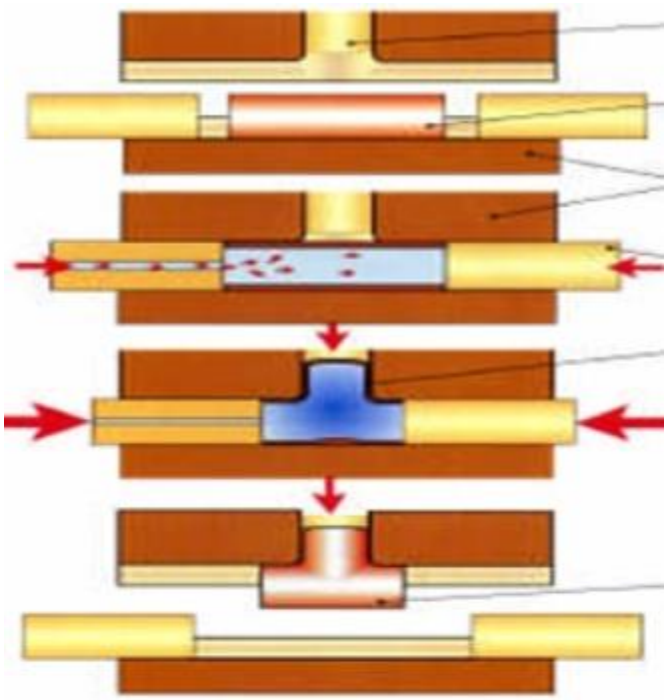
# An example:
# Tube Hydroforming



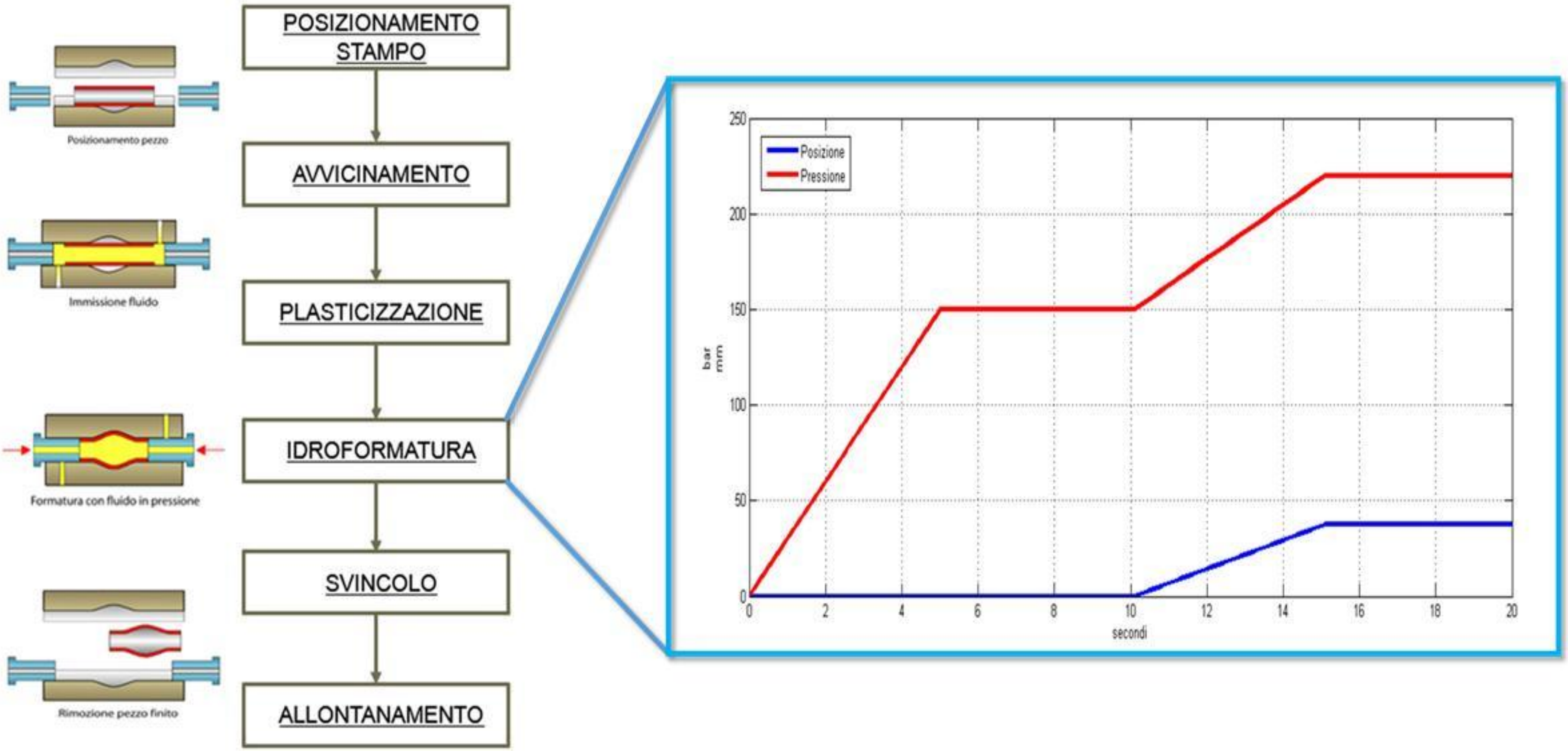



# Tube hydroforming

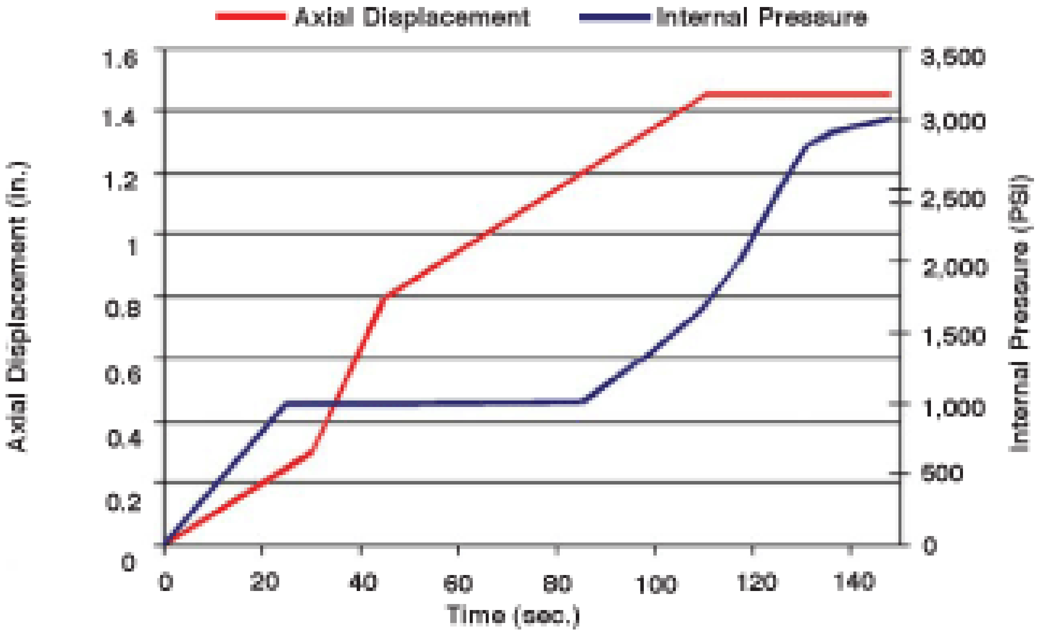


# The hydroforming process



# Problems

- Manage pressure curves and feeding curves of the actuators in a coordinated way to avoid effects such as:
  - burst
  - wrinkles
  - excessive thinning

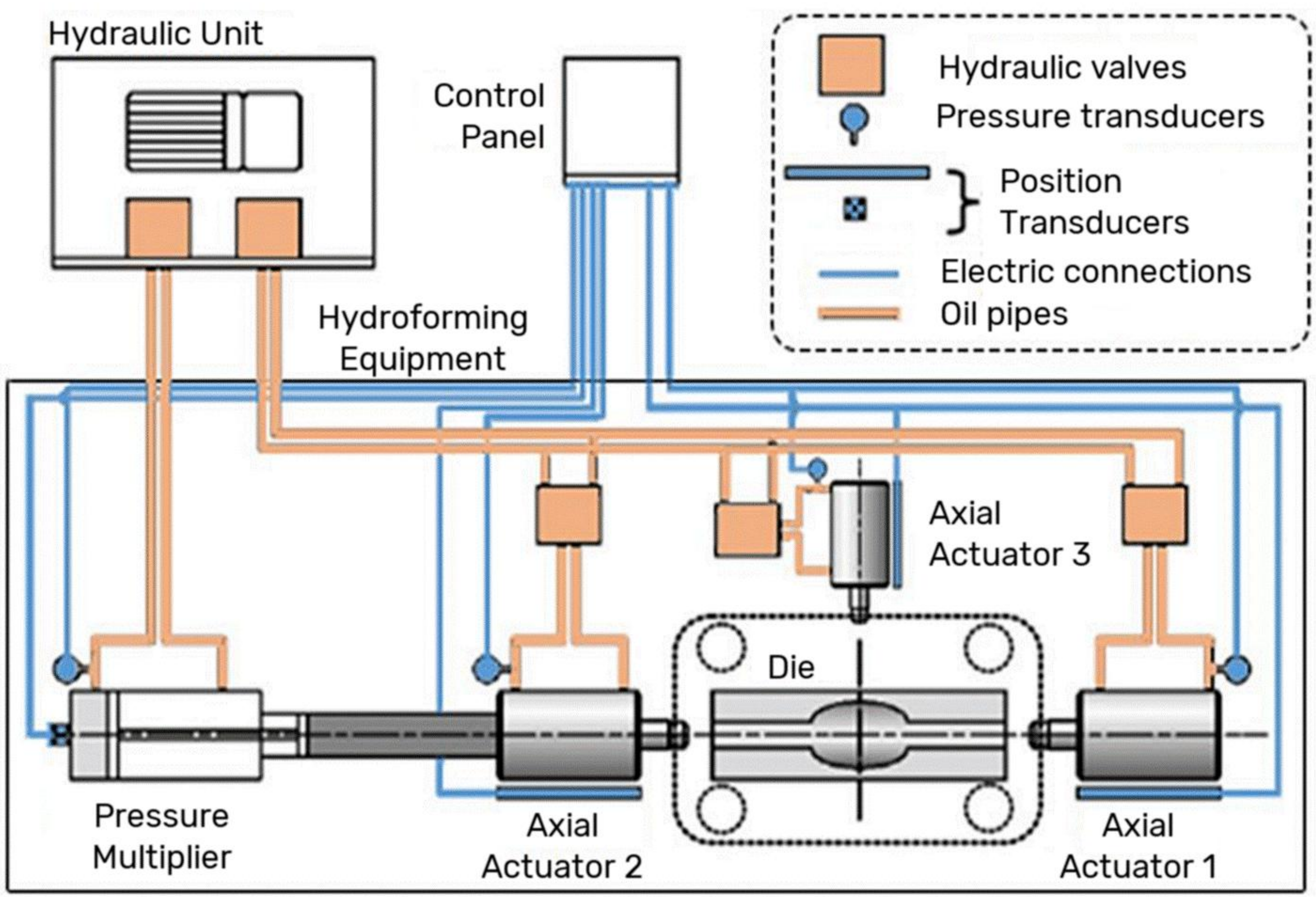



# Tasks

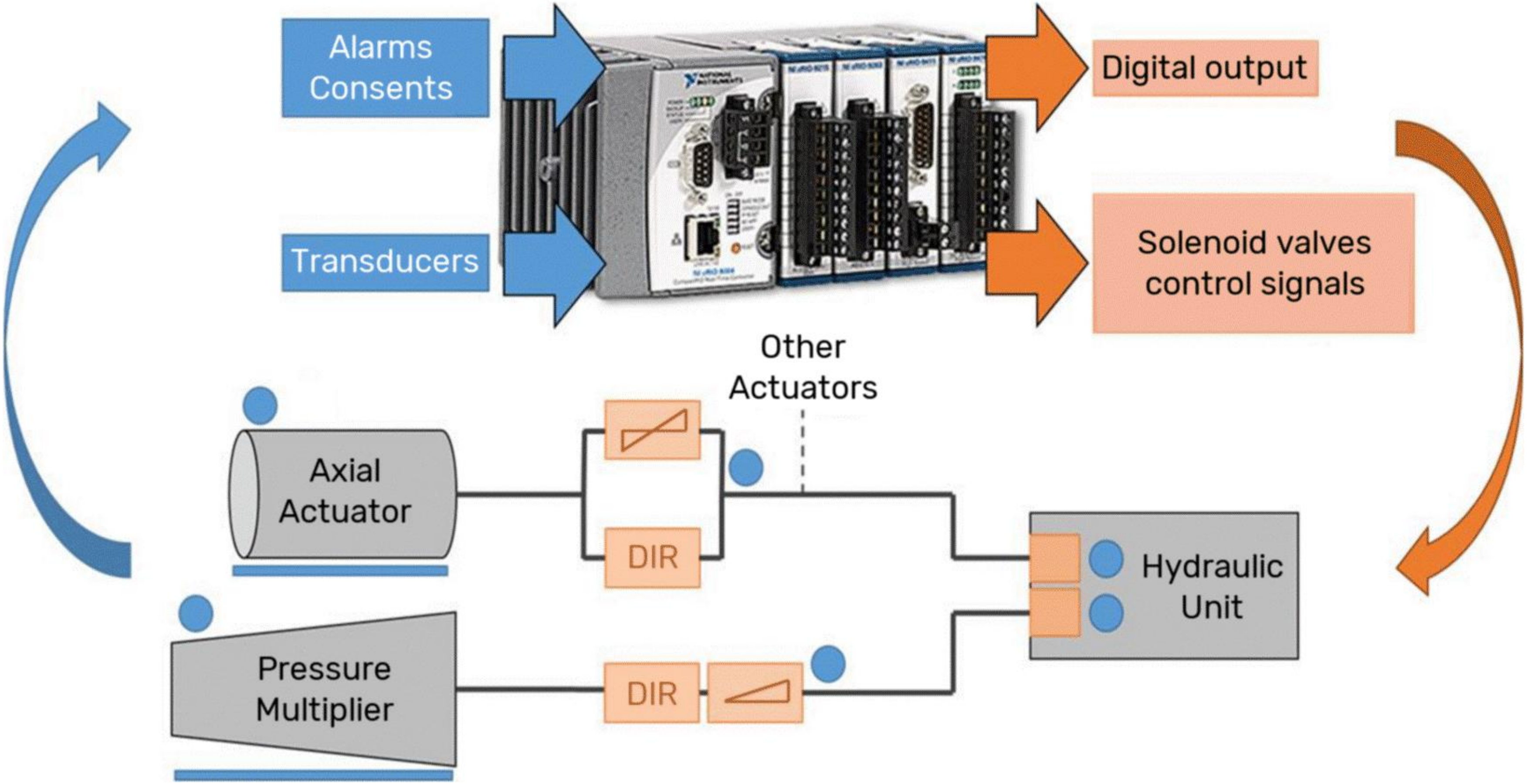
- Designing flexible and intelligent equipment
  - Define the technical specifications of the equipment
  - Define the signals and sensors to be used to control the process
    - Stroke actuators
    - Fluid internal pressure
  - Define the interface for machine management
  - Define the technical solutions used in the machine
    - Die closing system
    - Pressure multiplier
    - Actuators
- Define the work cycle of the machine
- Define the validation criteria of the developed approach

- Possibility of optimizing process parameters and adapting to specific situations

# Layout of Hydroforming Equipment



# Control logic
# Coordinated valve control

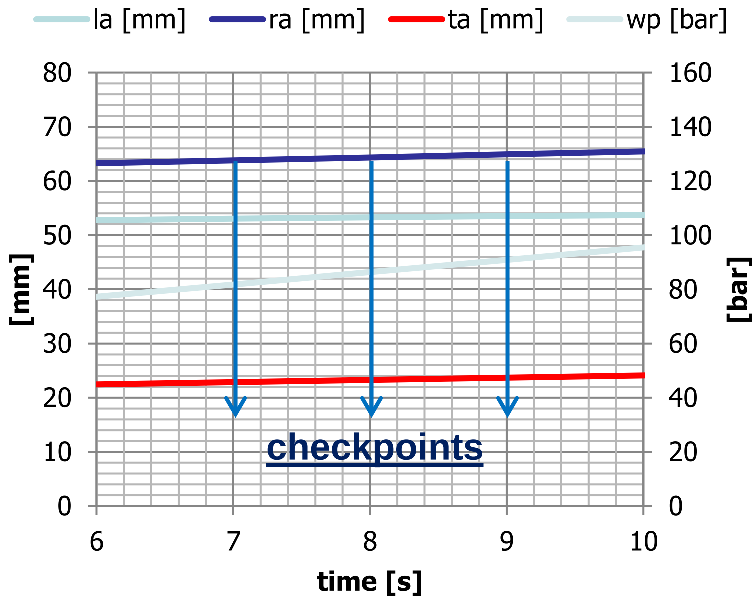


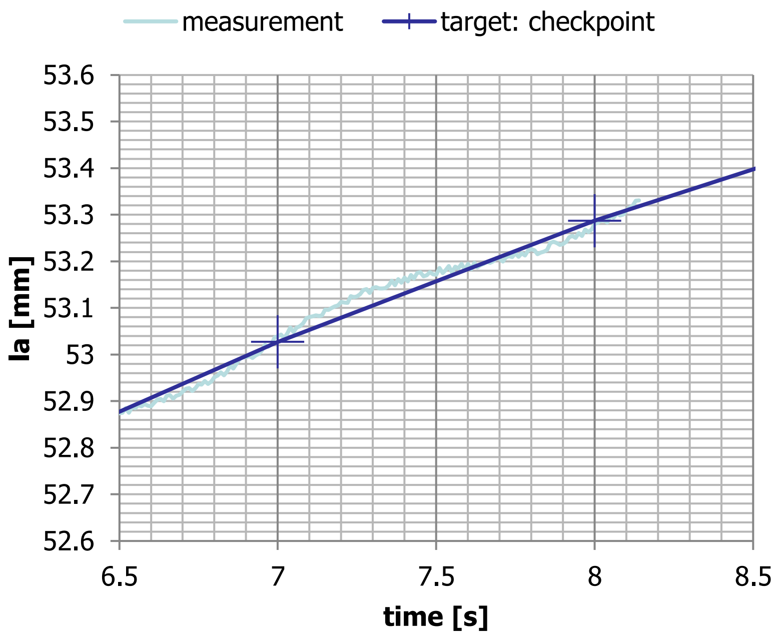
# Control logic
# Coordinated work cycle

- **Working cycle:**
  - Motion laws of actuators
  - Pressure law required

- The laws required over time are sampled at fixed intervals
- A "checkpoint" is carried out at the primary setpoints so the axial movement laws are postponed until the setpoint has been completely reached

- **Optimization:**
  - Tested values from 10 up to 1000 ms
  - Optimal value: **50 ms**



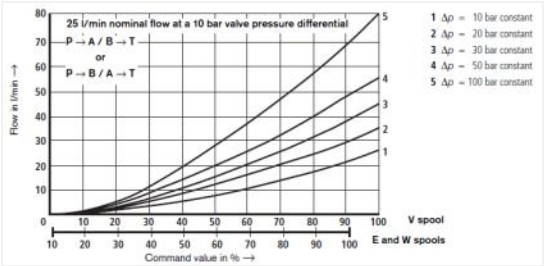
# Control logic
# Solenoid Valves Characteristic Tables

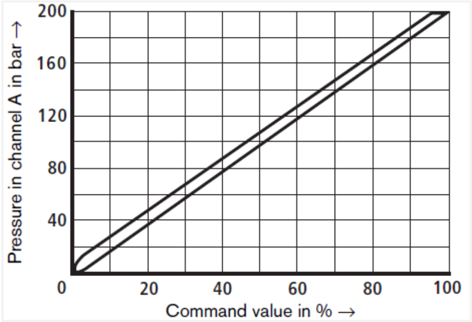
- **Axial actuators and pressure multiplier**
  - The response of the actuators depends both on the control operated on the valves and on the pressure difference across the proportional valves
  - Instead of using the characteristic tables of the valves provided by the manufacturer, they have been obtained experimentally

DOWNSTREAM PRESSURE

UPSTREAM PRESSURE

CONTROL VOLTAGE




FLOW

FEED RATE

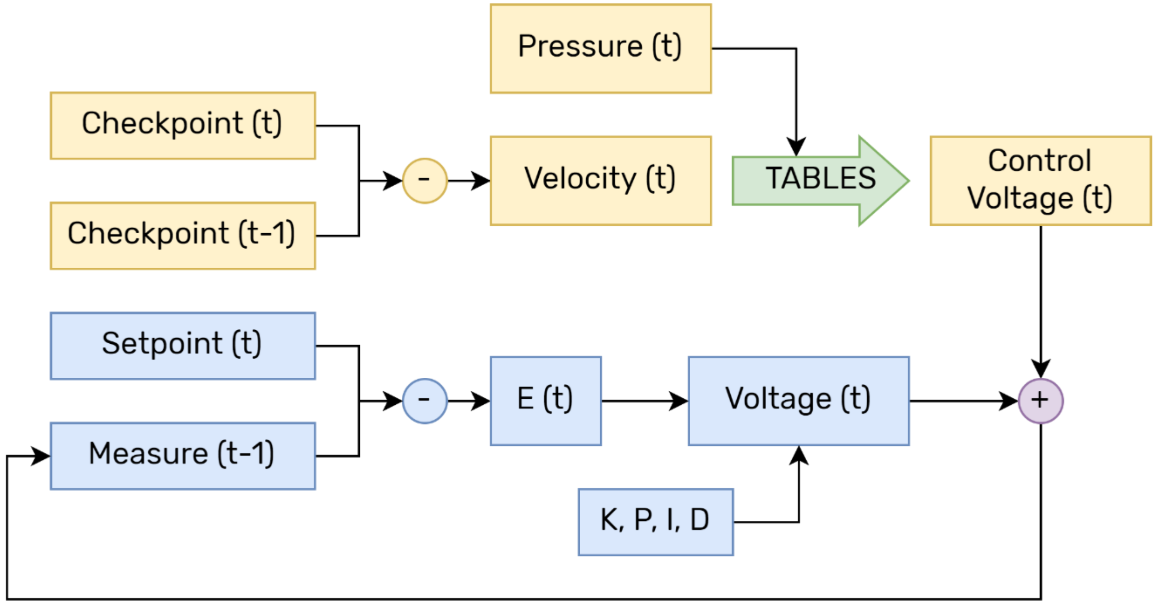
REGISTERED DELAY

CONTROL VOLTAGE

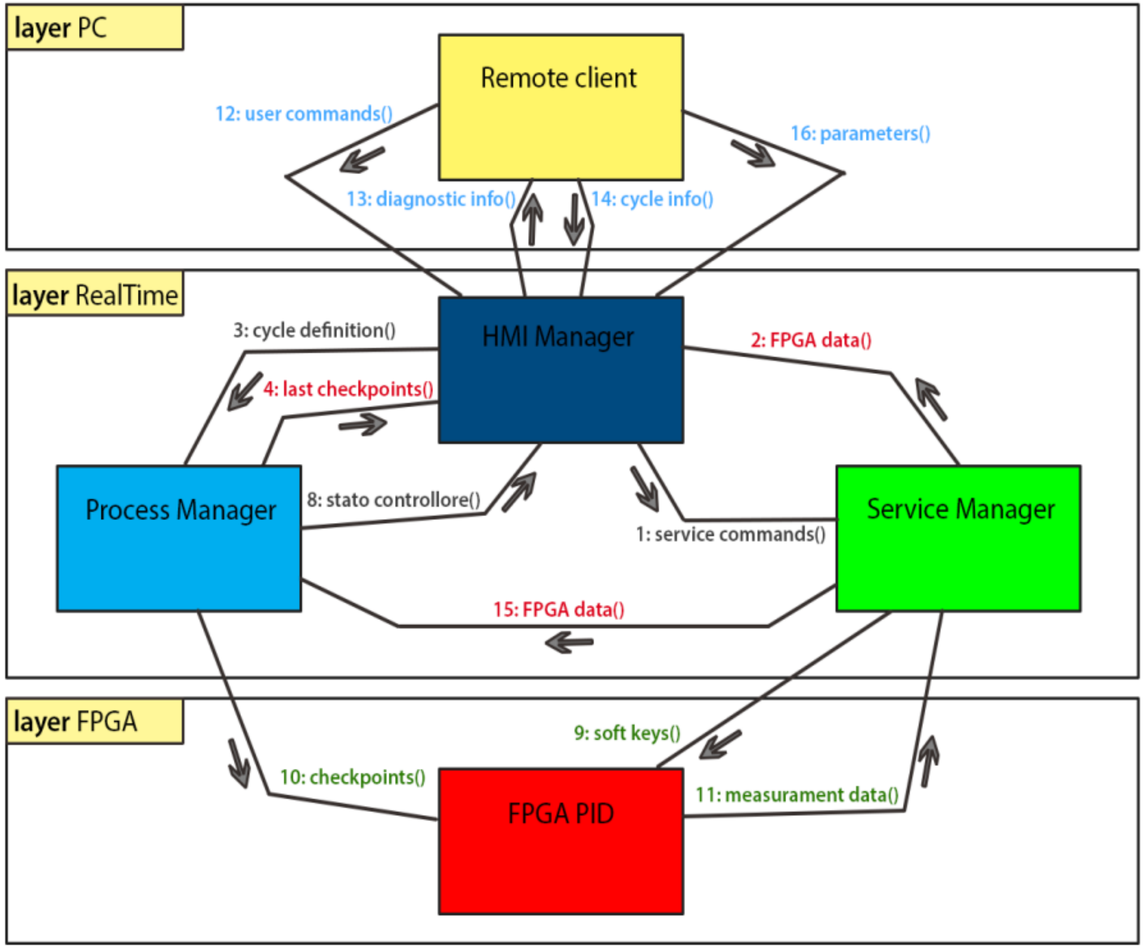
# Control logic
# Coordinated work cycle

- Between two successive checkpoints, the control follows the Proportional/Integral/Derivative (PID) logic by comparing the reference value (linear interpolation of the checkpoints) with the detected value

- Unlike the traditional PID, an element linked to the characteristics of the actuator and an element dependent on the checkpoints are introduced: it is constant during the action of the PID, but variable between one checkpoint and the next

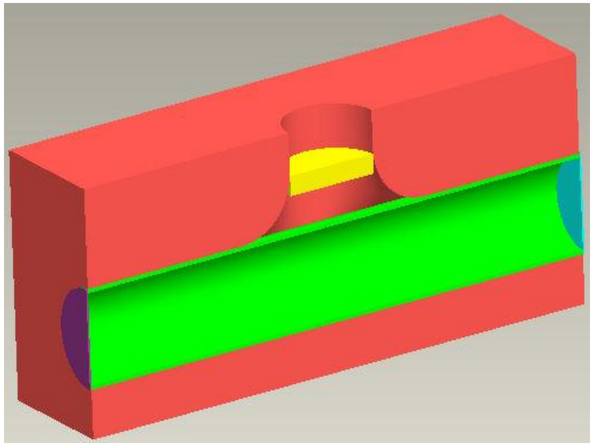


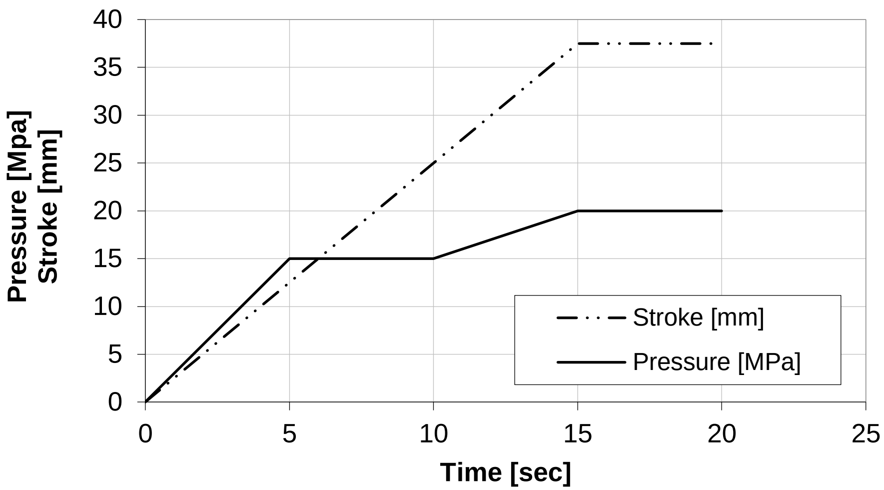
# Control Software structure

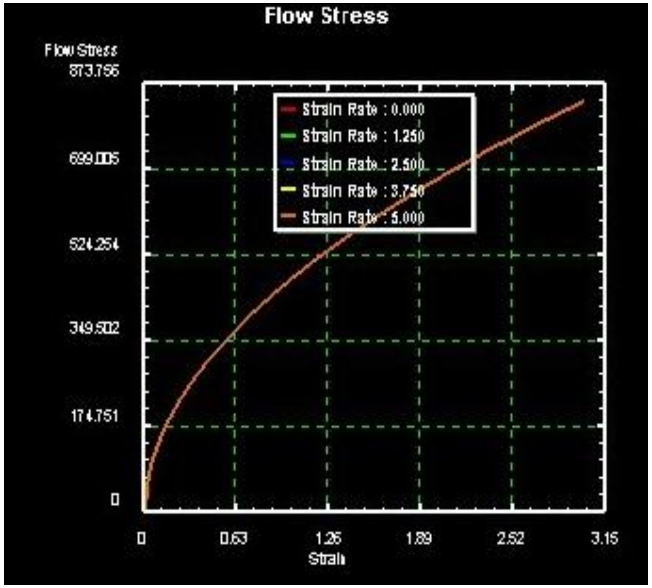


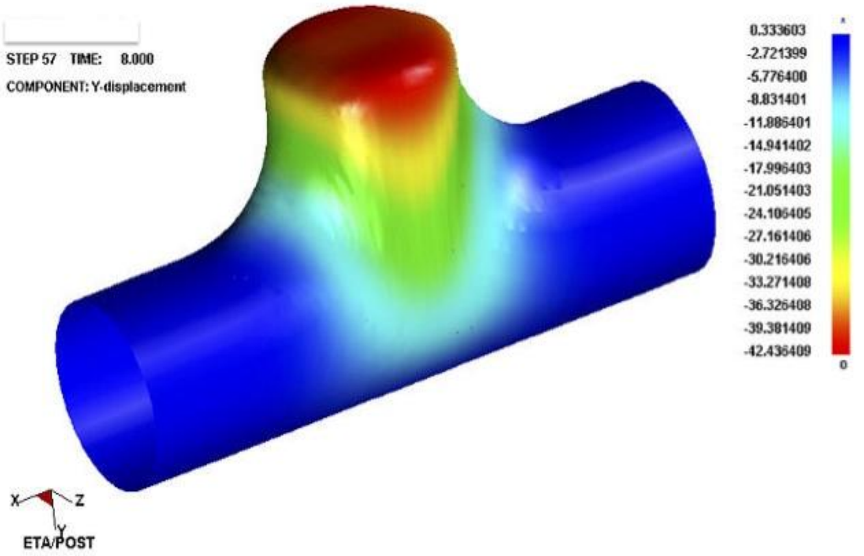

| | Cycle time |
|---|---|
| not real time | Not deterministic |
| real time | 25 ms |
| | 50 µs |

# FEM simulations for preliminary curve optimization



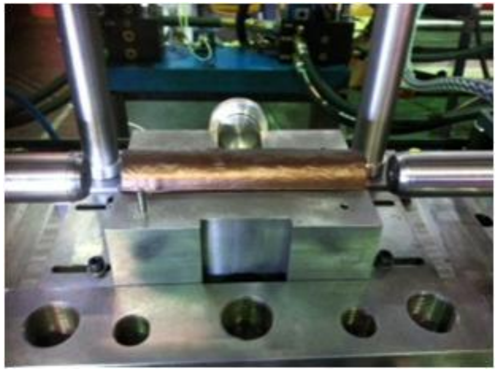


# Validation

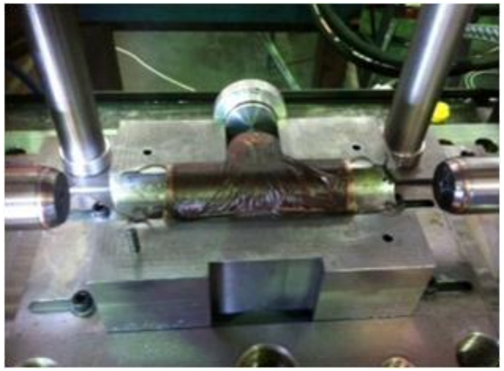
**Tube Positioning**



**Axial Actuators Approach**

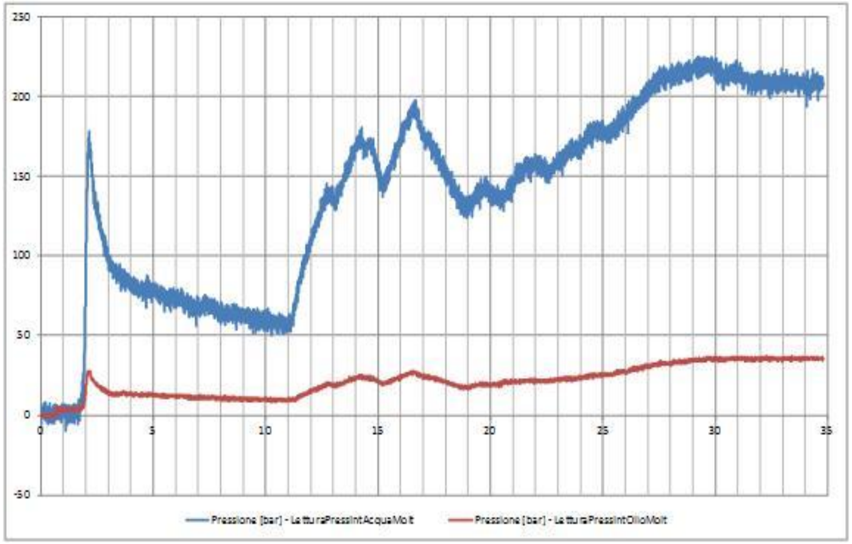
**Hydroforming**

**Finished part extraction**

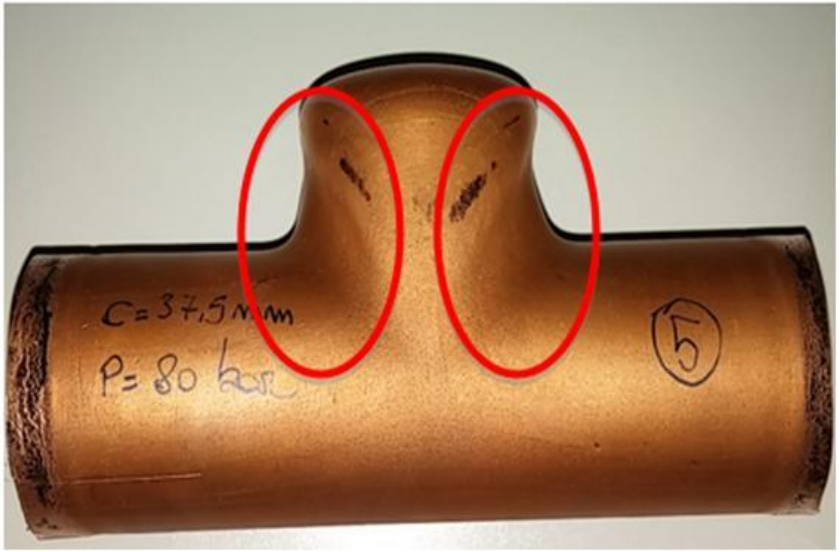


# Validation

Pressure curve




Defective part

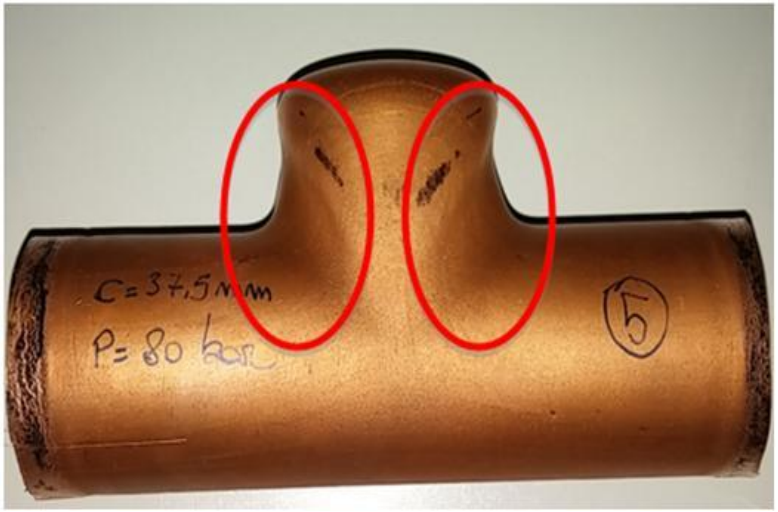


# Main defects that may occur

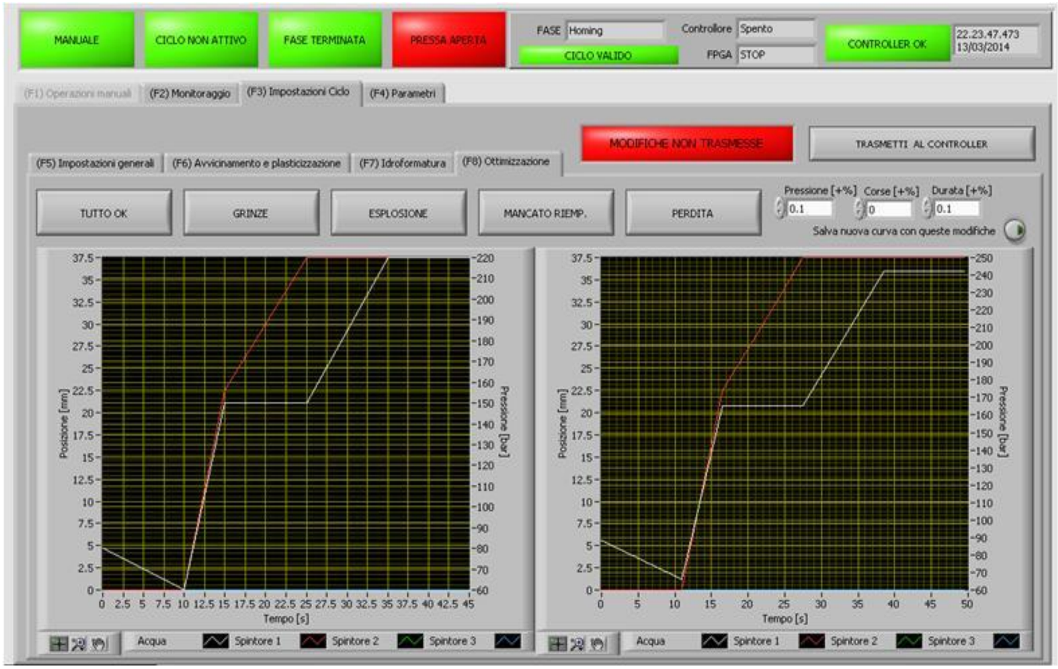
Breakage due to insufficient axial feeding


Wrinkling due to overfeeding

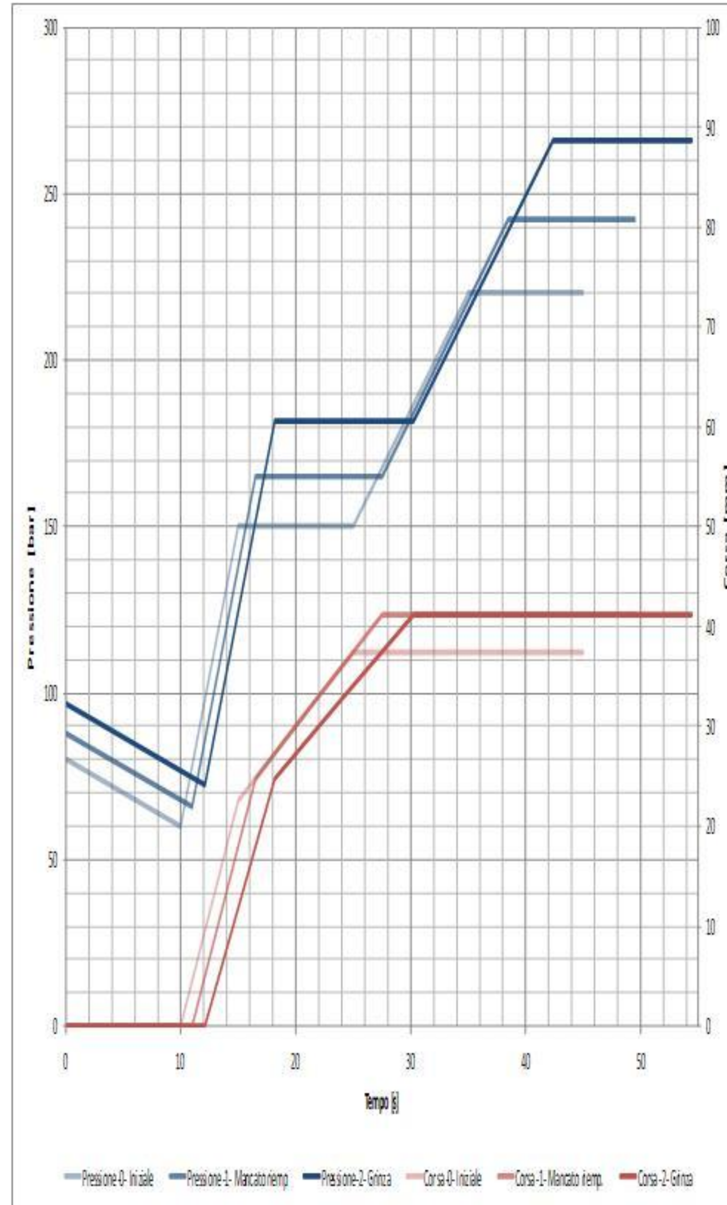

Insufficient filling due to insufficient pressure



# Optimizer

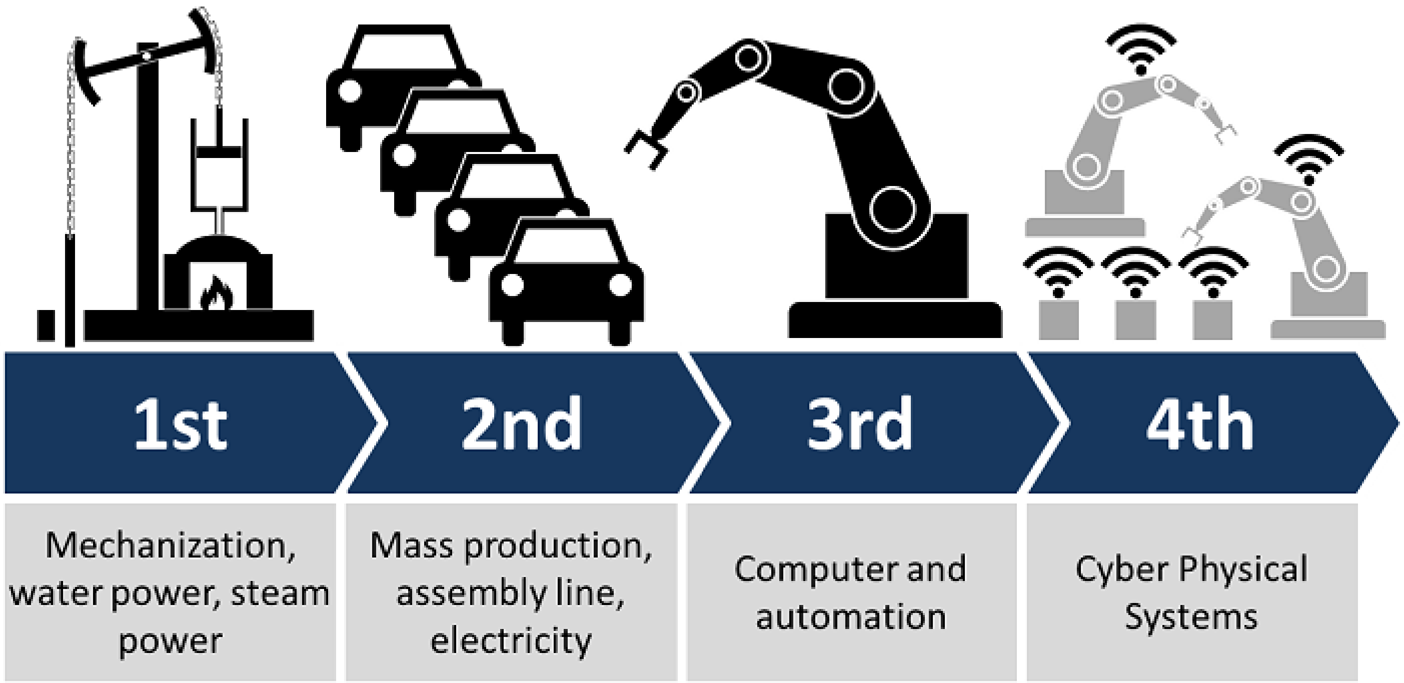



| Defect | Pressure | Stroke | Time |
|---|---|---|---|
| Wrinkles | +10% | = | +10% |
| Leakage | = | +10% | = |
| Bursting | -10% | = | = |
| Incomplete filling | +10% | +10% | +10% |



# The Industrial Revolutions

Industry 4.0
Internet of Things
Cluster Fabbrica Intelligente
Mass Customization



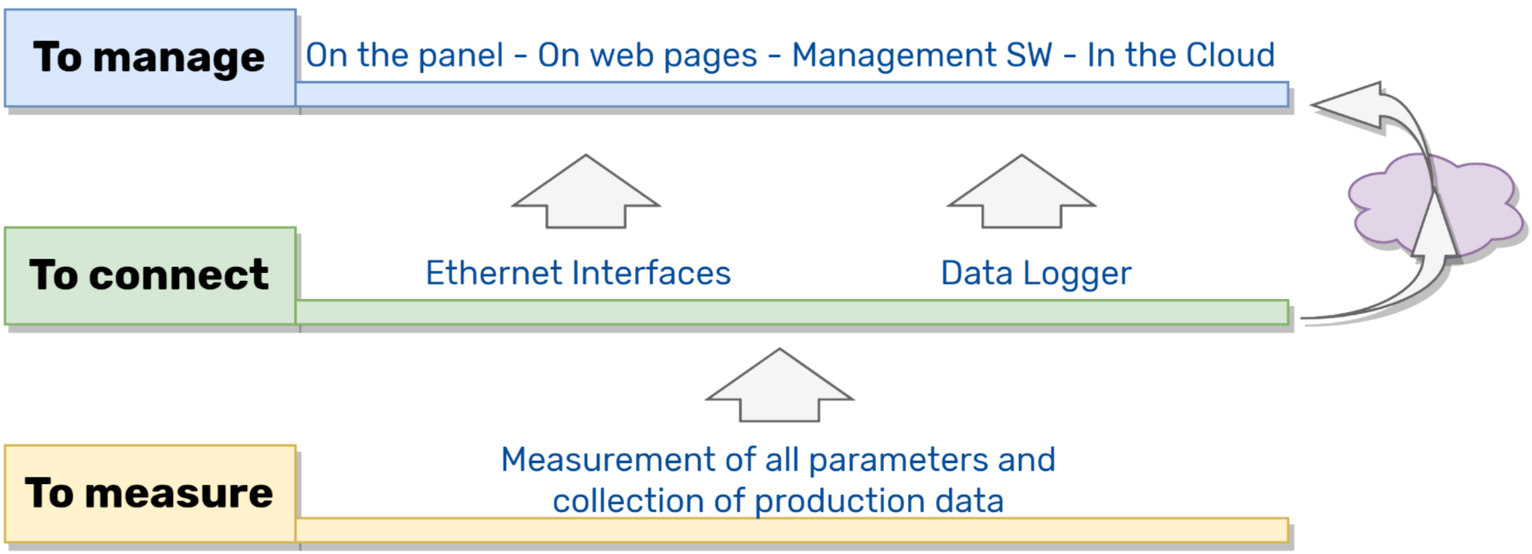
# What absolutely cannot be missing in I4.0

- Sharing of data and information:
  - all machines and equipment must be networked and must be able to communicate with each other to create not an intelligent machine but an intelligent production system capable of learning and correcting what it does by optimizing its operation

- This fourth industrial revolution is characterized by four constituent elements that change the production processes:
  - The exponential increase in the amount of data collected
  - The advent of new analysis models to improve production
  - New HMI (Human Machine Interface) systems that revolutionize human-machine interaction (touch-screen, augmented reality, ...)
  - Improvements in the transfer of digital instructions to the physical world

# The three levels structure of a data collection, analysis and management system

- **A measurement level**: measurement equipment with communication interface physically installed in the production system with which they interact and transmit information to subsequent levels
- **A connection level**: which allows mutual communication between the other two levels → wired systems, Wi-Fi or telephony
- **A level of data management** and analysis and the adoption of strategies aimed at improving efficiency through dedicated software

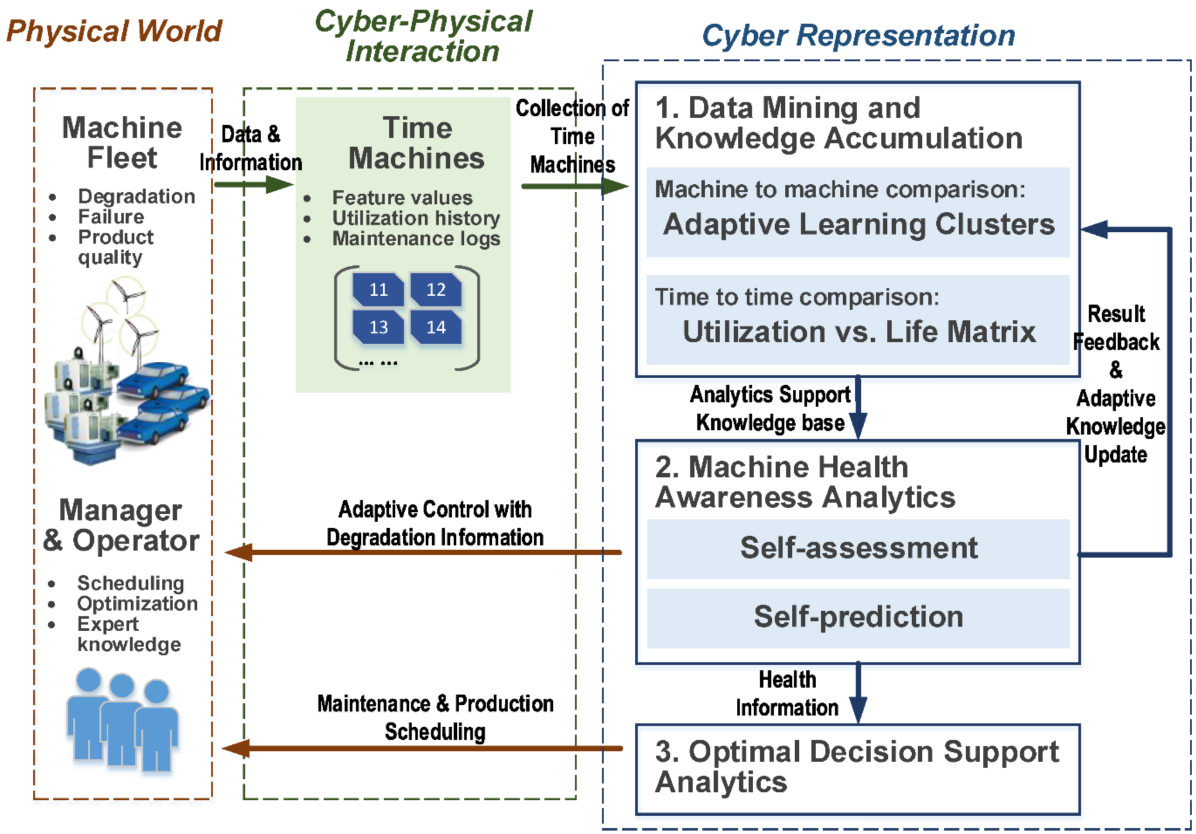


# The Internet of Things

- The IoT includes a **large variety of devices available** for many applications in the most varied configurations
- This enormous level of complexity brings with it **a number of possible weaknesses** that can be used to breach the system
  - Low Level: consists of the security problems related to hardware instrumentation
  - Medium Level: consists of the security problems related to the communication and transmission of information
  - High Level: consists of the security problems related to IoT management software
- This results in a **certain diffidence** in the use of the IoT:
  - for fear of its reliability (→ malfunctions due to complexity)
  - for fear of IT security (→ privacy and sensitive data)

- From this point of view, the development of platforms for the transmission and exchange of data based on **blockchain technology** is very promising

- Digital systems constantly collect data and measurements of physical systems by creating virtual models thanks to which they are able to make decisions relating to plant management in an autonomous and decentralized manner

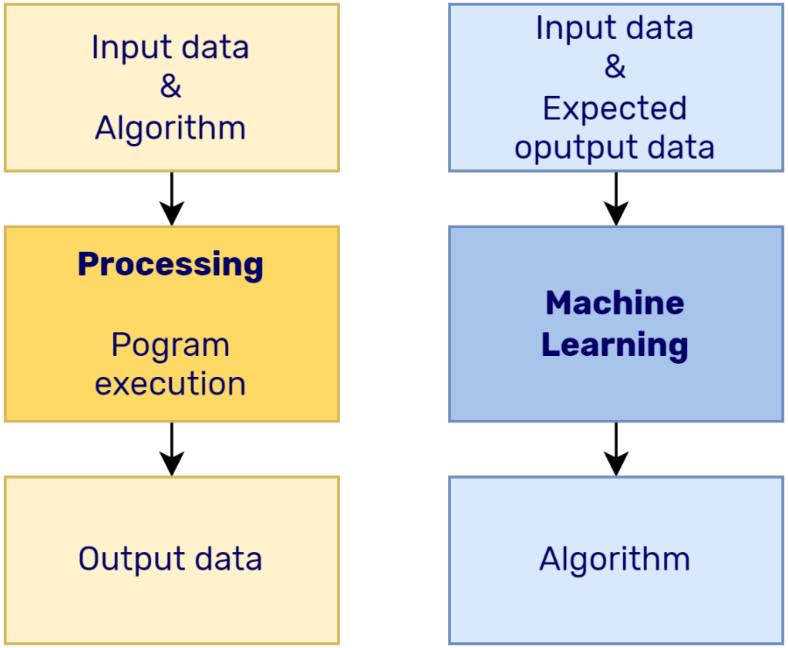



Hung-An Kao at alii, "A Cyber Physical Interface for Automation Systems—Methodology and Examples", Machines, 2015

- All this is possible thanks to **four key elements**:
  - Interoperability, thanks to which digital equipment is able to connect and communicate with each other independently
  - The creation of virtual models to simulate the real physical elements you are actually working on
  - Work in synergy between human and machine
  - Ability of cyber-physical systems to autonomously take many decisions requiring human beings to intervene only in exceptional cases

# The Machine Learning

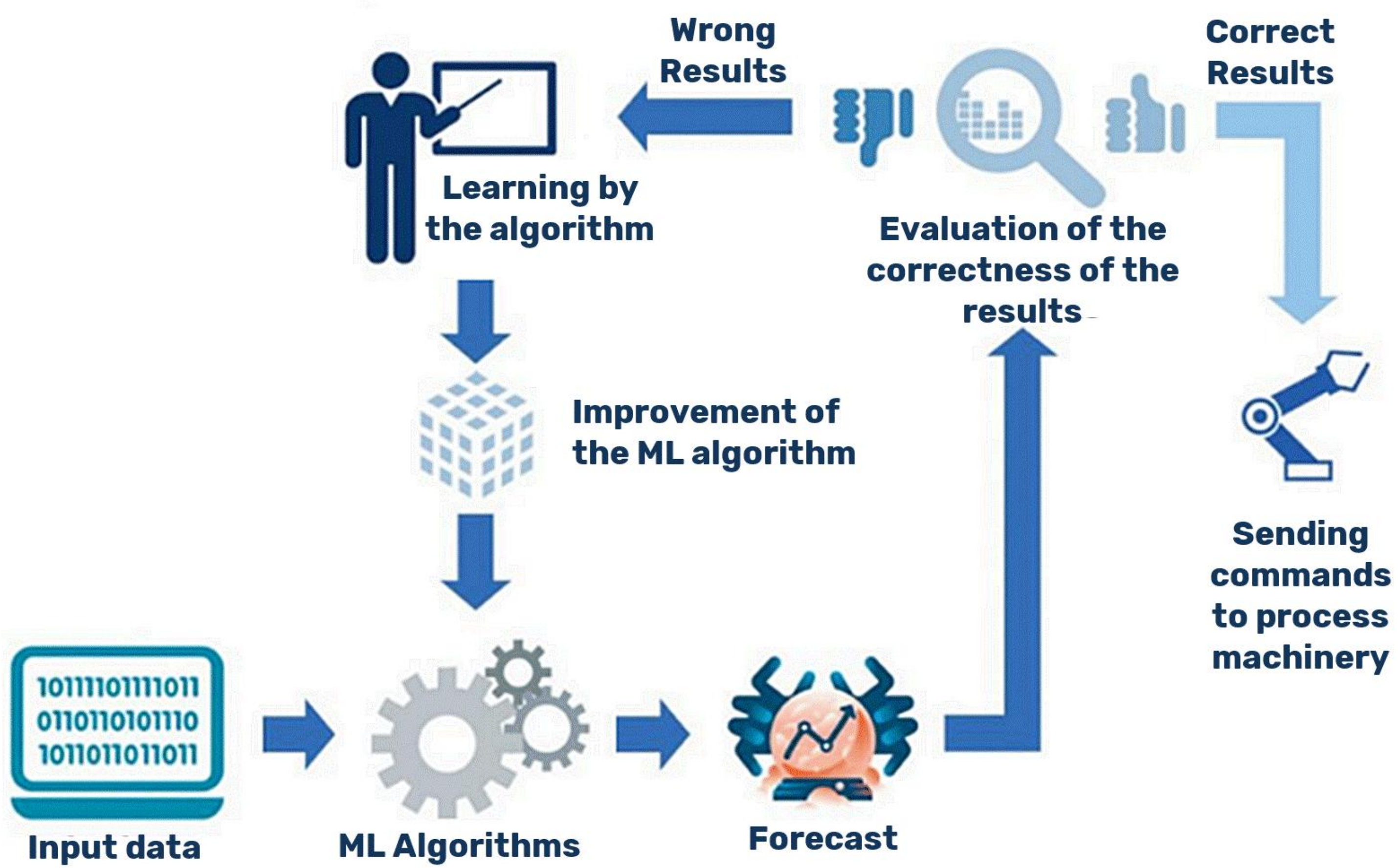
- It is a set of methods and tools developed in the field of AI to make a computer learn patterns without explicit traditional programming, improving the quality of the analysis performed
- It is used when the writing of an explicit algorithm is impossible or extremely inconvenient (for example an excessive number of complex rules to take into account)




Comparison between traditional program and ML

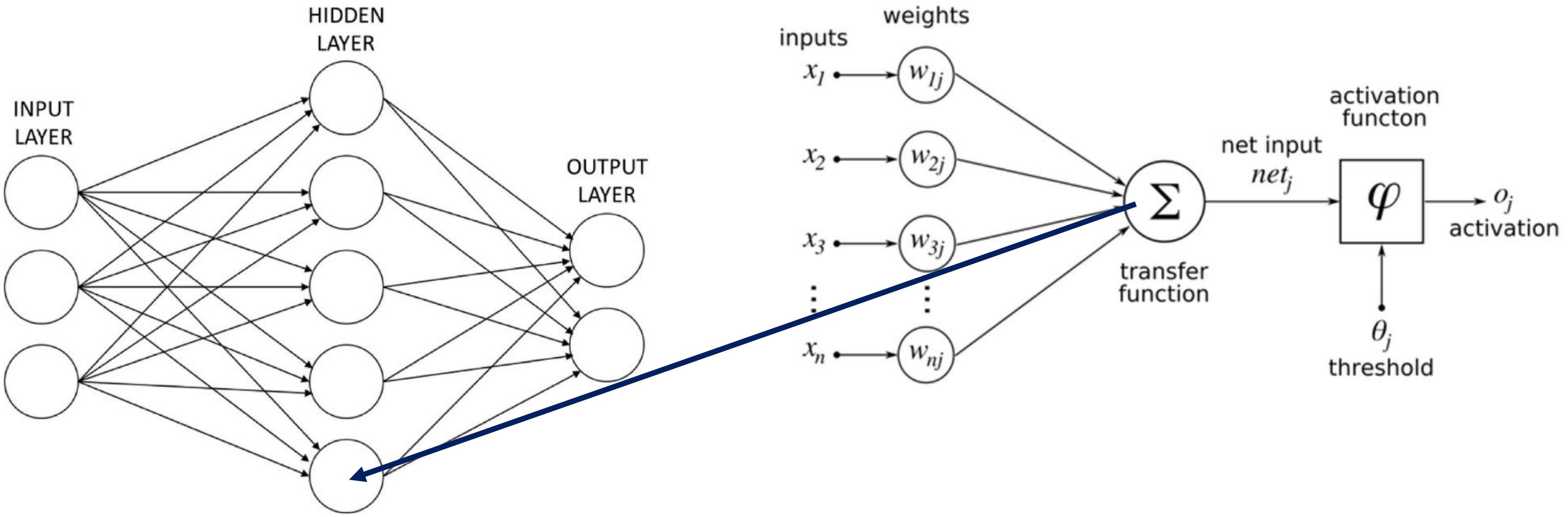
# The Machine Learning

Architecture of a system based on the ML



# Artificial Neural Network

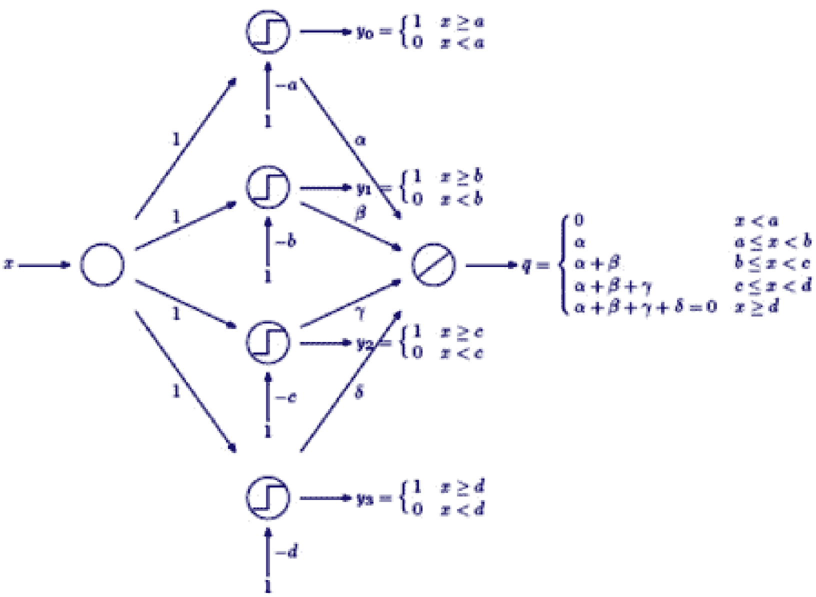
- They attempt to replicate the structure of **biological** neural networks
- The main unit is the **neuron** which communicates with other neurons through connections
- Neurons are organized in **layers**:
  - one of **Inputs** from which the data "enters"
  - one or more **Hidden**
  - one of the **Outputs** to which the data "comes out"

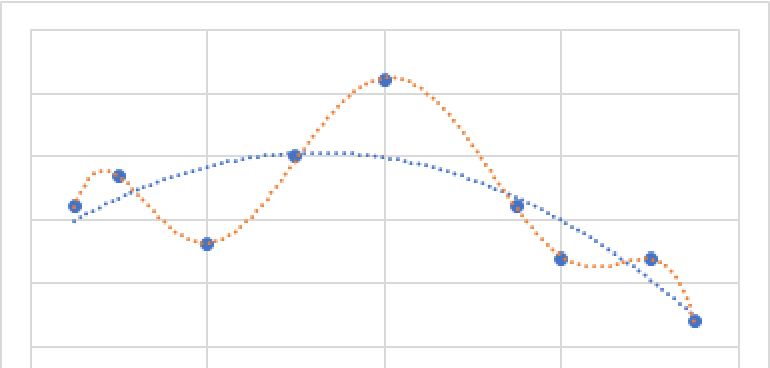


# Training activity

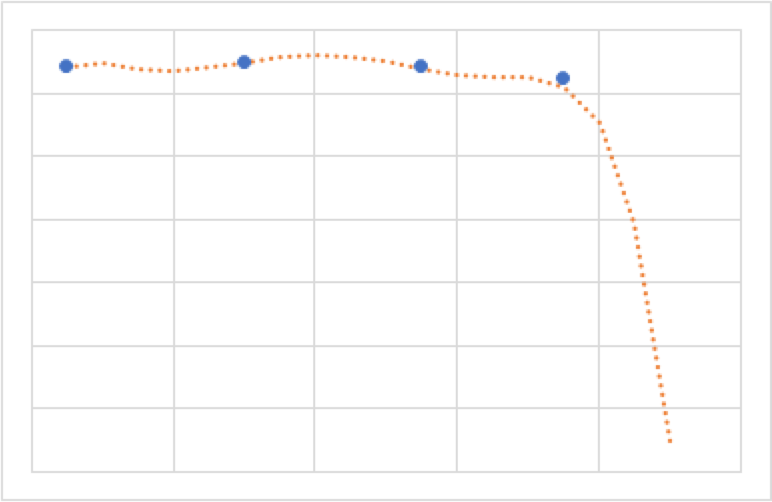
- Pattern **association**
- Pattern **recognition**
- **Approximation** of functions

- **Problems**
  - Overtraining or Overfitting
  - Extrapolation



The neural network is too powerful for the current problem (too many neurons and too little data).
It then does not "recognize" the underlying trend in the data, but learns the data by heart



# Training activity

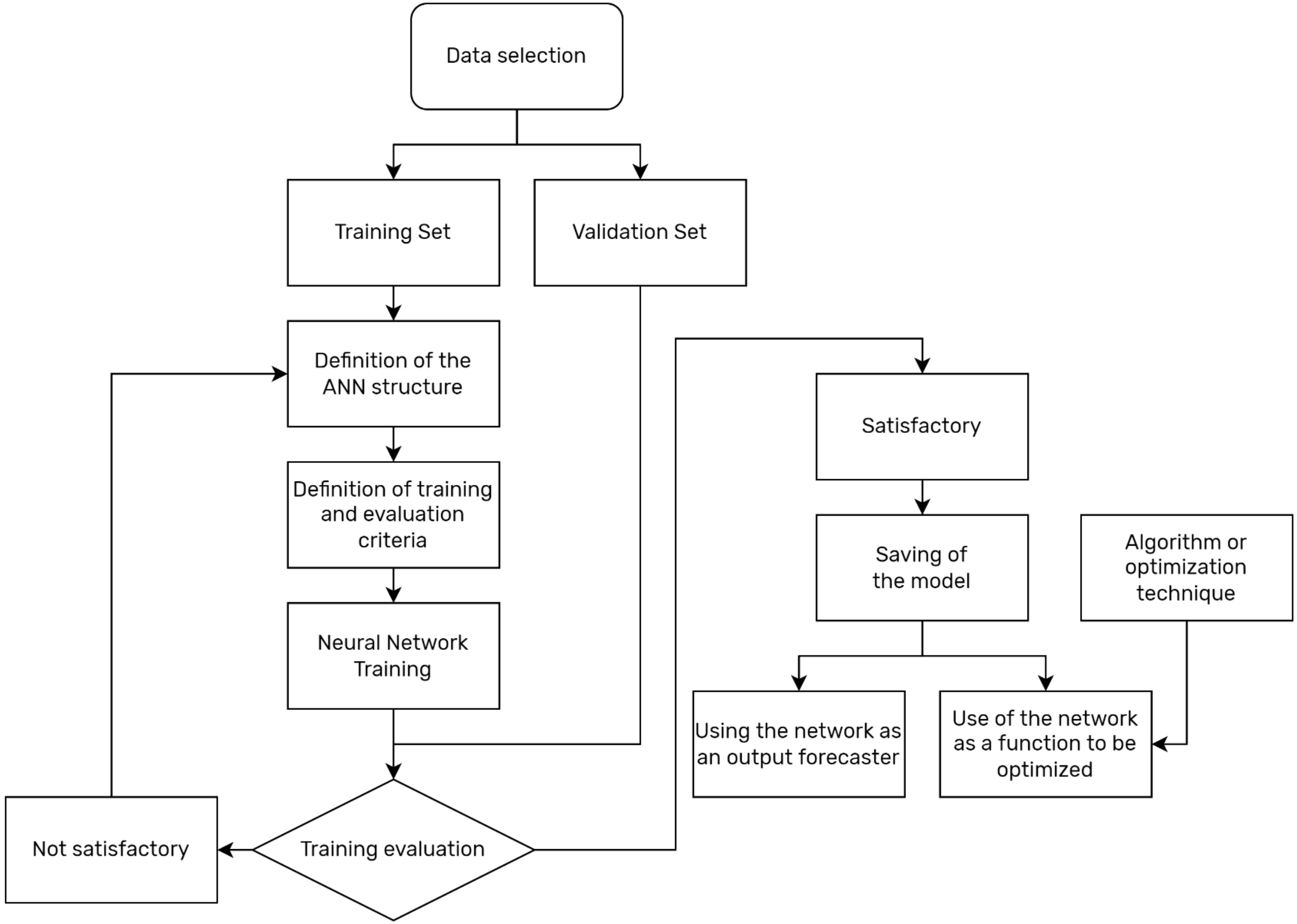
- **Problems**

Training set

What is this?

"A dog"

# Training activity



# An example: tool life analysis and forecasting

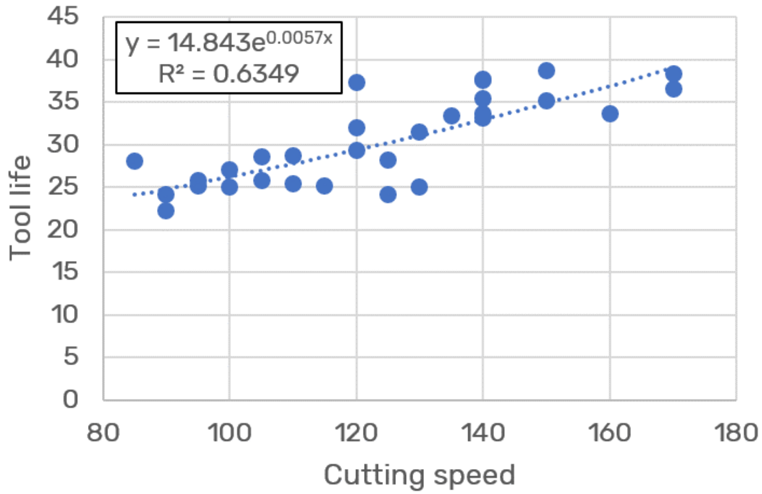
- Several tests of tool duration have been carried out varying the cutting speed $v_c$, the feed $f$ and the depth of cut $d$ giving the results reported in the table

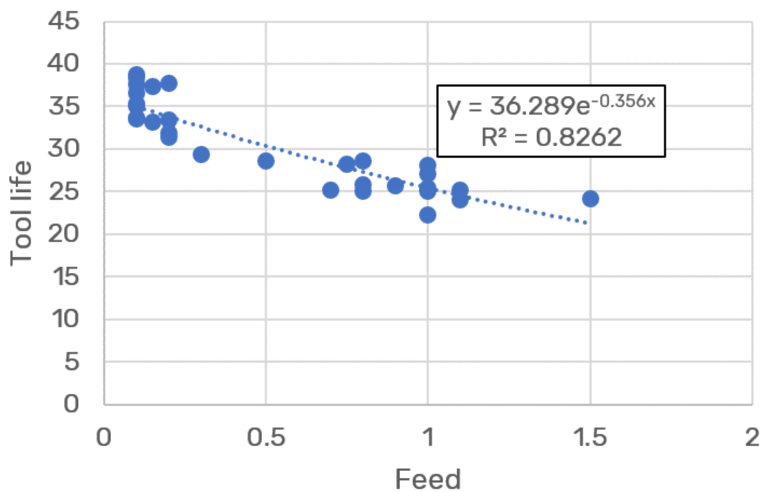
- The question is: are we able to forecast the tool life of a tool cutting with certain values of $v_c$, $f$ and $d$?

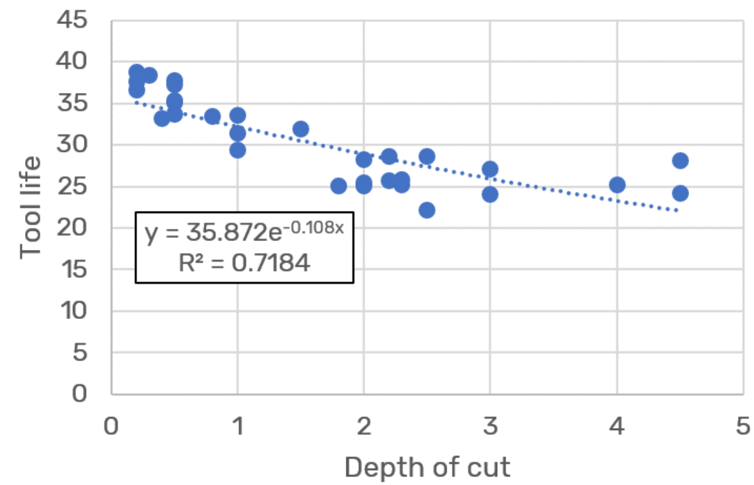
| $v_c$ | *f* | *d* | *Tool life* |
|---|---|---|---|
| 120 | 0.2 | 1.5 | 31.9255 |
| 140 | 0.1 | 1 | 33.55566 |
| 100 | 1 | 2 | 25.05031 |
| 120 | 0.15 | 0.5 | 37.28092 |
| 130 | 0.2 | 1 | 31.44172 |
| 120 | 0.3 | 1 | 29.332 |
| 140 | 0.1 | 0.5 | 35.36563 |
| 90 | 1 | 2.5 | 22.19987 |
| 150 | 0.1 | 0.5 | 35.10276 |
| 170 | 0.1 | 0.2 | 36.58954 |
| 170 | 0.1 | 0.3 | 38.30627 |
| 110 | 0.5 | 2.5 | 28.62618 |
| 110 | 1 | 2 | 25.4288 |
| 125 | 0.75 | 2 | 28.17959 |
| 130 | 0.8 | 1.8 | 25.03974 |
| 100 | 1 | 3 | 27.0452 |
| 85 | 1 | 4.5 | 28.05339 |
| 95 | 1.1 | 4 | 25.19024 |
| 105 | 0.8 | 2.2 | 28.61063 |
| 125 | 1.1 | 3 | 24.06943 |
| 105 | 0.9 | 2.2 | 25.71605 |
| 140 | 0.1 | 0.2 | 37.55328 |
| 150 | 0.1 | 0.2 | 38.70775 |
| 160 | 0.1 | 0.5 | 33.63382 |
| 135 | 0.2 | 0.8 | 33.42721 |
| 115 | 0.7 | 2.3 | 25.12755 |
| 95 | 0.8 | 2.3 | 25.78184 |
| 90 | 1.5 | 4.5 | 24.12797 |
| 140 | 0.2 | 0.5 | 37.68275 |
| 140 | 0.15 | 0.4 | 33.14212 |

# An example: tool life analysis and forecasting

- We can try to carry out a regression analysis of the sampled values, but it is evident that there is something strange since **the tool life increases as the cutting speed increases**
- On the contrary, the tool life decreases as feed and depth of cut increase



# An example: tool life analysis and forecasting

- We can try a non-linear regression model in Matlab according to this code

- *wdata*: are the $v_c$, *f* and *d* columns (i.e., the working conditions)
- *lives*: is the *Tool life* column (i.e., the experimental observations)
- *coeff0*: is the start point of the solution
- *ypred*: are the expected tool lives according to the identified function for the different working conditions
- *yci*: are the conf. interv. of the predictions

Workspace

| Name | Value |
|---|---|
| coeff0 | [1;1;1;1] |
| lives | 30x1 double |
| mdl | 1x1 NonLinearModel |
| wdata | 30x3 double |
| workcondition | 30x3 double |
| yci | 30x2 double |
| ypred | 30x1 double |

```
% -- Regression Analysis
coeff0=ones(4,1);
mdl=fitnlm(wdata,lives,@taylorlaw,coeff0)

% -- Analysis of the results
plotResiduals(mdl)
plotSlice(mdl)

% -- Prediction
% workcondition = [110, 0.5, 2.5];
workcondition=wdata;
[ypred yci] = predict(mdl,workcondition)

% -- Taylor law implementation
function life = taylorlaw(coeff,x)
C60 = coeff(1);
r = coeff(2);
m = coeff(3);
n = coeff(4);
vc = x(:,1);
f = x(:,2);
d = x(:,3);
life = (C60)./(vc.^r.*f.^m.*d.^n);
end
```

# An example: tool life analysis and forecasting

- The code output is the following →
These are the Taylor law coefficients

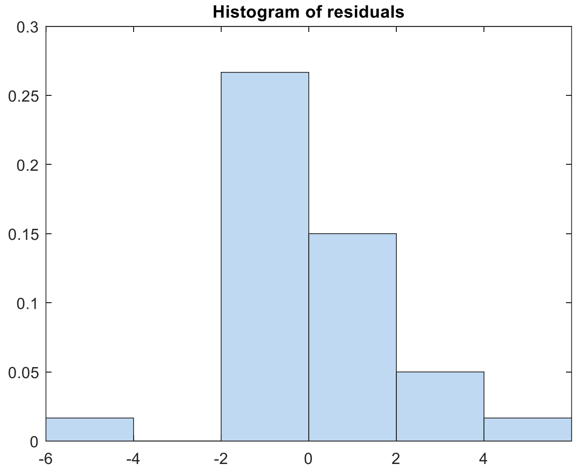
```
Estimated Coefficients:
             Estimate       SE        tStat       pValue  
             ________    ________    ______    __________

    b1         50.544      29.482    1.7144      0.098355
    b2        0.13197     0.12365    1.0673       0.29566
    b3        0.11602     0.02802    4.1404    0.00032392
    b4       0.068818    0.027544    2.4985      0.019122


Number of observations: 30, Error degrees of freedom: 26
Root Mean Squared Error: 1.78
R-Squared: 0.892,  Adjusted R-Squared 0.88
F-statistic vs. zero model: 2.23e+03, p-value = 1.46e-32
```

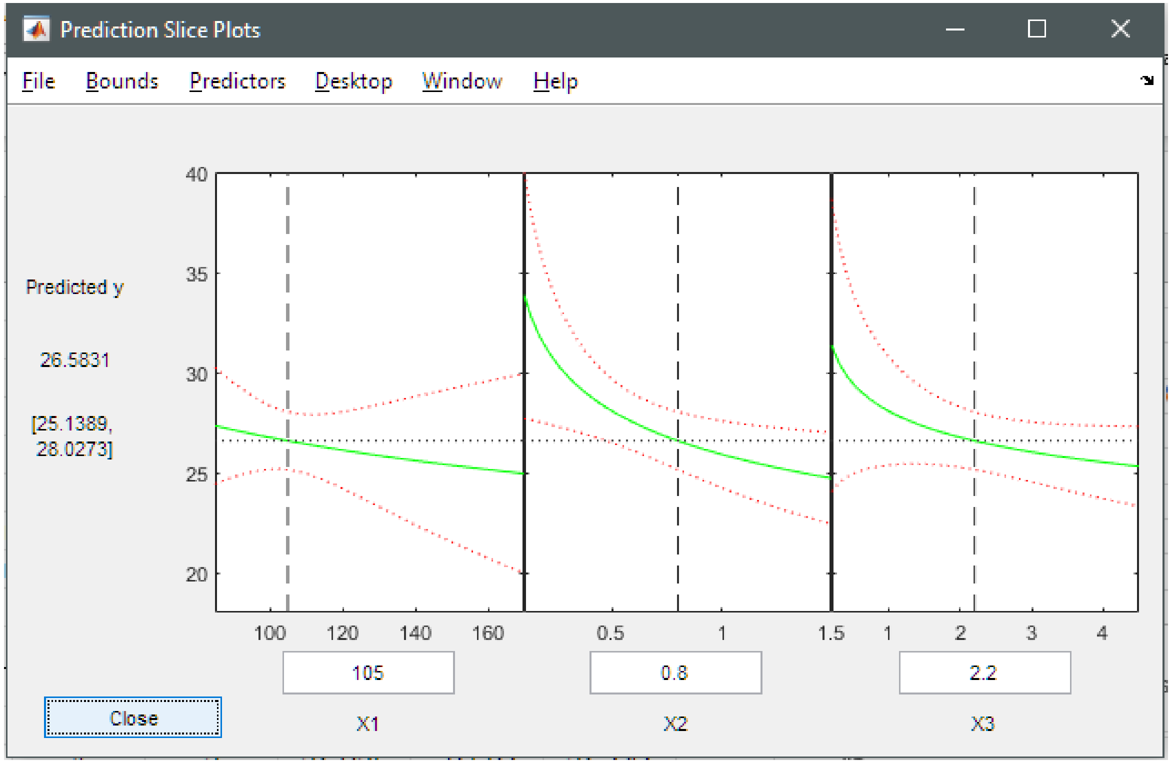
```
Tool life = 50.544/(vc^0.13197 * f^0.11602 * d^0.068818)
```

- The histogram of the residuals is →



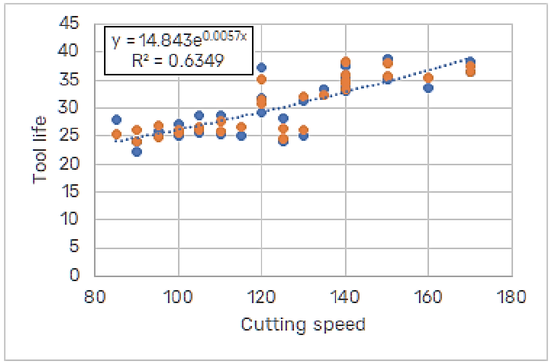
# An example: tool life analysis and forecasting

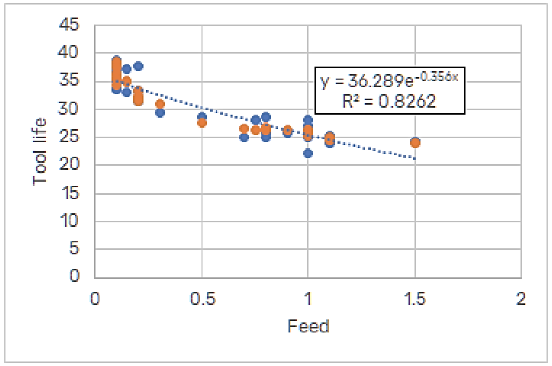
- Prediction slice plots →

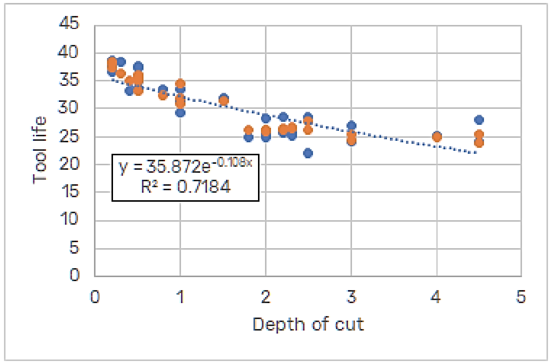


# An example: tool life analysis and forecasting

- Predictions



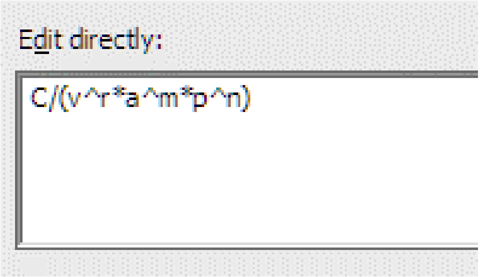




| $v_c$ | f | d | Tool life | Matlab Prediction |
|---|---|---|---|---|
| 120 | 0.2 | 1.5 | 31.9255 | 31.4954 |
| 140 | 0.1 | 1 | 33.55566 | 34.3918 |
| 100 | 1 | 2 | 25.05031 | 26.2427 |
| 120 | 0.15 | 0.5 | 37.28092 | 35.1218 |
| 130 | 0.2 | 1 | 31.44172 | 32.0463 |
| 120 | 0.3 | 1 | 29.332 | 30.8984 |
| 140 | 0.1 | 0.5 | 35.36563 | 36.0721 |
| 90 | 1 | 2.5 | 22.19987 | 26.2046 |
| 150 | 0.1 | 0.5 | 35.10276 | 35.7451 |
| 170 | 0.1 | 0.2 | 36.58954 | 37.448 |
| 170 | 0.1 | 0.3 | 38.30627 | 36.4175 |
| 110 | 0.5 | 2.5 | 28.62618 | 27.6567 |
| 110 | 1 | 2 | 25.4288 | 25.9146 |
| 125 | 0.75 | 2 | 28.17959 | 26.3459 |
| 130 | 0.8 | 1.8 | 25.03974 | 26.2037 |
| 100 | 1 | 3 | 27.0452 | 25.5205 |
| 85 | 1 | 4.5 | 28.05339 | 25.3563 |
| 95 | 1.1 | 4 | 25.19024 | 24.9132 |
| 105 | 0.8 | 2.2 | 28.61063 | 26.5831 |
| 125 | 1.1 | 3 | 24.06943 | 24.5074 |
| 105 | 0.9 | 2.2 | 25.71605 | 26.2223 |
| 140 | 0.1 | 0.2 | 37.55328 | 38.4199 |
| 150 | 0.1 | 0.2 | 38.70775 | 38.0717 |
| 160 | 0.1 | 0.5 | 33.63382 | 35.442 |
| 135 | 0.2 | 0.8 | 33.42721 | 32.3805 |
| 115 | 0.7 | 2.3 | 25.12755 | 26.5945 |
| 95 | 0.8 | 2.3 | 25.78184 | 26.8543 |
| 90 | 1.5 | 4.5 | 24.12797 | 24.0094 |
| 140 | 0.2 | 0.5 | 37.68275 | 33.2849 |
| 140 | 0.15 | 0.4 | 33.14212 | 34.9471 |

# An example: tool life analysis and forecasting

- Similarly, it is possible to use Minitab to conduct a non-linear regression analysis on the same observation imposing an equation of this type:




- The result is the following:

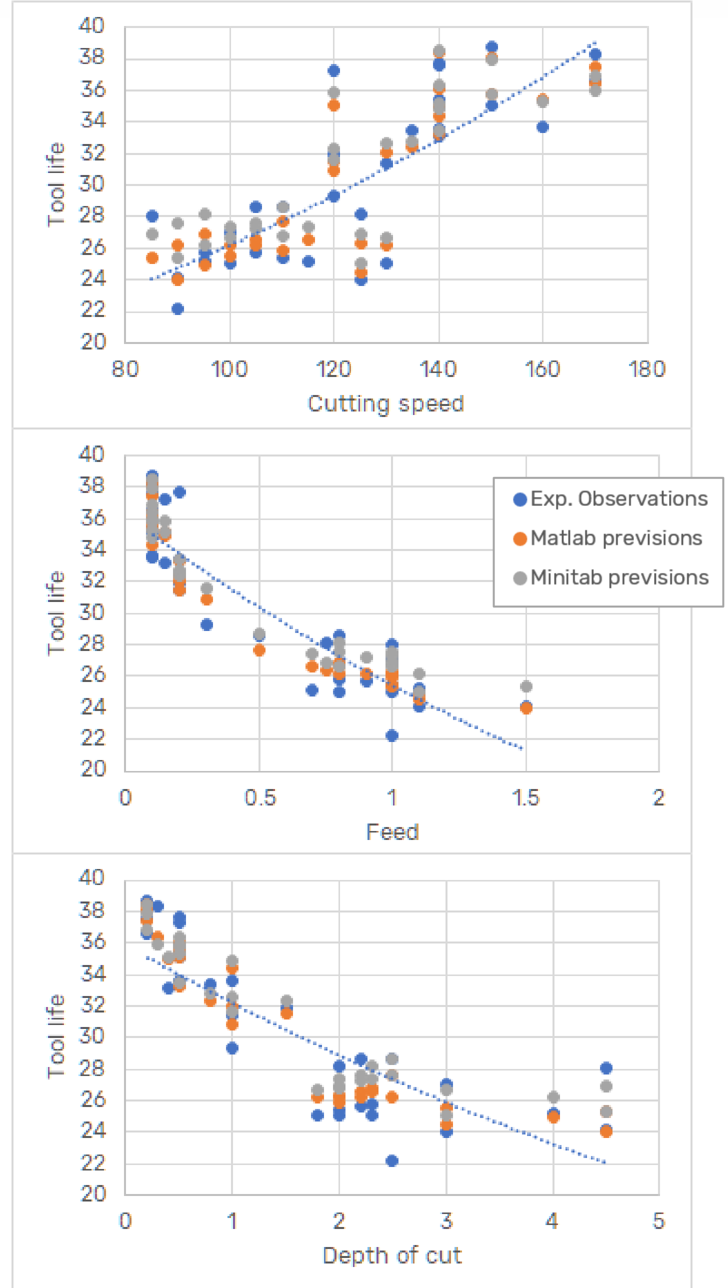
```
Tool life = 80.0494/(vc^0.223912 * f^0.119108 * d^0.0624083)
```

- Similar, but not equal to the one obtained in Matlab

# An example: tool life analysis and forecasting

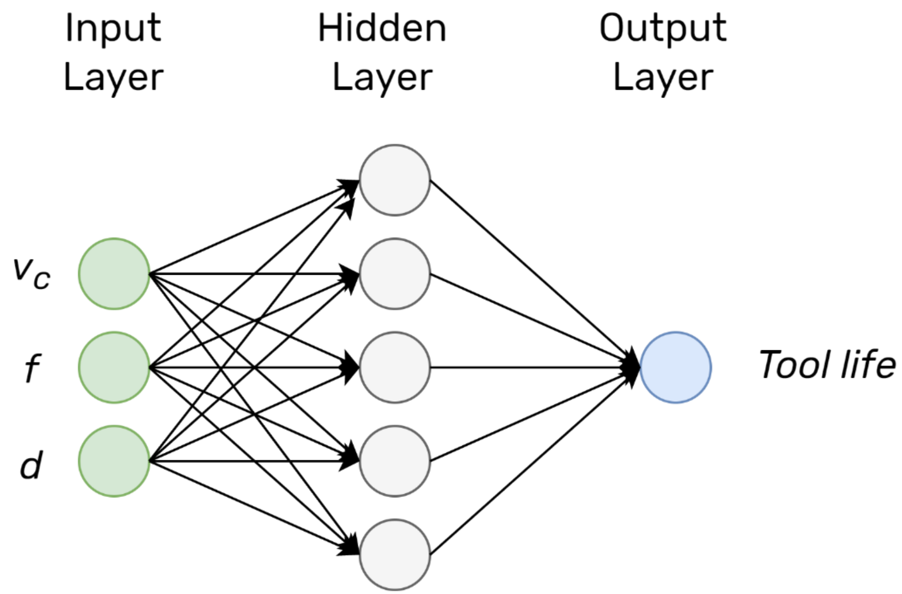
- Comparing the experimental observations and the previsions obtained in Matlab and in Minitab, we obtain →

- <u>Considerations</u>:
  - We knew the Taylor law, so it was easy to identify the several coefficients, but it is not always the case
  - The equation transforms a stochastic phenomenon in a deterministic law
  - Matlab furnishes also the Confidence Intervals, i.e. it can give an idea of the prevision variations



# An example: tool life analysis and forecasting

- In case the equation representing the phenomenon is not know, it is useful to use the ANN
- In this case we have a network with three input and one output neurons



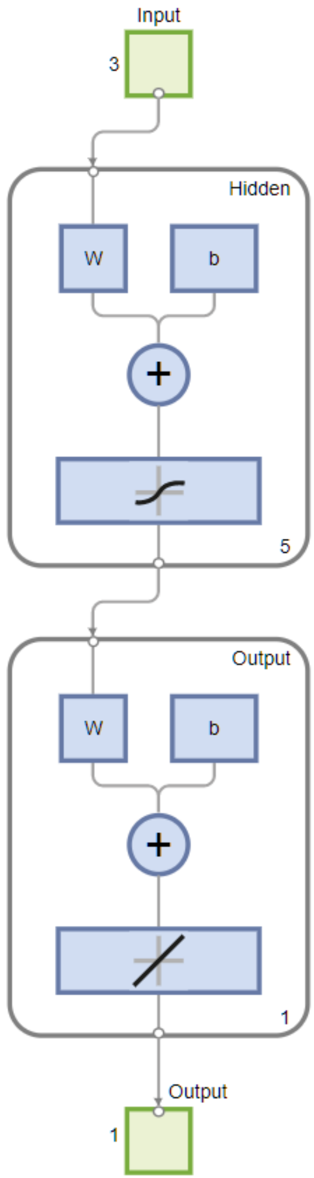

- The training set is made by the original table divided between the *wdata* and the *lives* used also for the regression analysis

# An example: tool life analysis and forecasting

- The Matlab code is the following:

Network scheme →

```
%-- Neural network
n_hidden_neurons = 5;
net = feedforwardnet(n_hidden_neurons);
net = train(net,transpose(wdata),transpose(lives));
prediction = net(transpose(wdata))';
```




- The *prediction* variable contains the previsions of the network for the *wdata* data

- Since every time the weights of the network are randomly generated, the training of the network is always different and, consequently, the previsions will be different

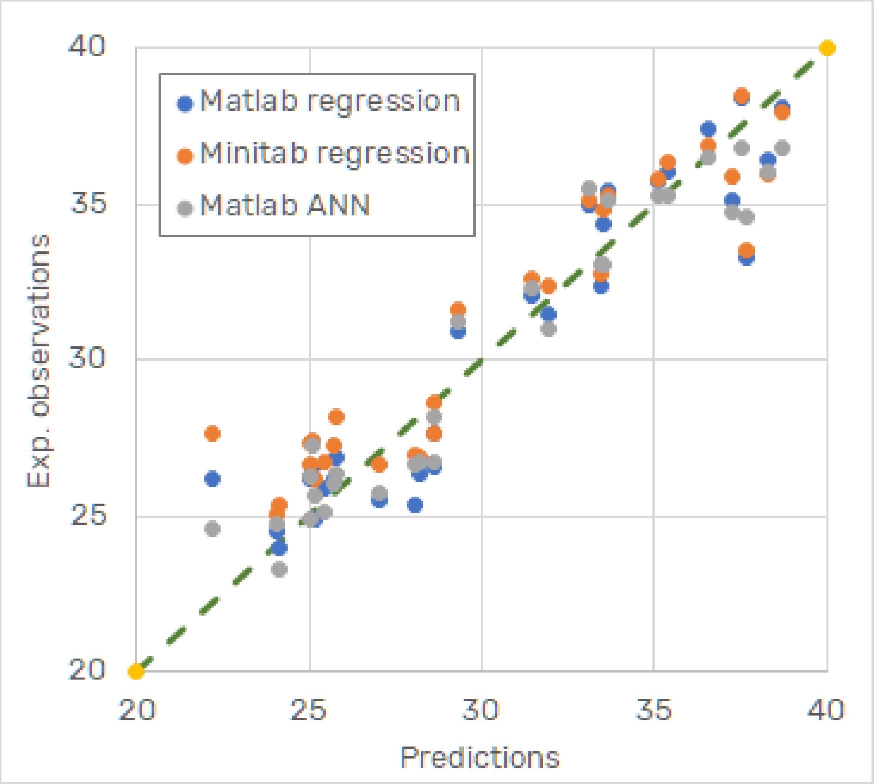
# An example: tool life analysis and forecasting

- It is also possible to teach more than one network (*n_model_max*) calculating the average values of the *prediction* of each of them according to the following code:

```
%-- Neural network
n_hidden_neurons = 5;
n_model_max = 10;
for n_model = 1:n_model_max
  net = feedforwardnet(n_hidden_neurons);
  net = train(net,transpose(wdata),transpose(lives));
  prediction = net(transpose(wdata))';
  ensamble(:,n_model) = prediction;
end
n_test_total = size(wdata);
%- average values calculation of all the predictions
% made by the n_model_max replicas of the trained networks
for n_test = 1:n_test_total(1)
  mean_output(n_test) = mean(ensamble(n_test,:));
end
```

# An example: tool life analysis and forecasting

- In this case, using an ANN, we don't know the regression equation, but we can query the network with the desired $v_c$, *f* and *d* obtaining the expected *Tool life*
- Please note that we have not tested the network with a dedicated set of experiments – in fact we have used the training set to test the network: this is not completely correct




- The graph represents the comparison between the predicted and the actual values
- The **RMSE values** are:
  - 1.66 for Matlab regression
  - 1.85 for Minitab regression
  - 1.43 for Matlab ANN

# An example: tool life analysis and forecasting

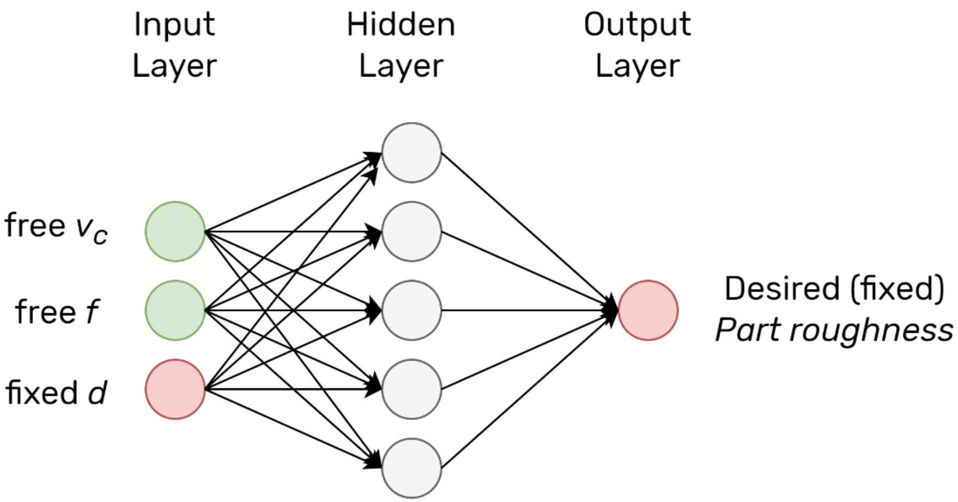
- **<u>Conclusions</u>**:
  - It is possible to improve the ANN ability by changing the number of the hidden neurons (be careful to the problem of overfitting) – there are several theories on how to determine the most correct number of hidden neurons
  - The ANN should be tested by using an appropriate set of experimental observations
  - The ANN can better its performance by increasing the number of observations used for the training set
  - The ANN can be refined by adding a new experimental observation to the training set every time a new value is available

- Please note that in any case, neither the non-linear regressions nor the ANN can give a precise forecast because **they are deterministic tools while reality has a stochastic nature** – the identification of the confidence interval can help in this sense

# How these tools can be used?

- The most immediate way of using these tools is for forecasting/predicting the output of a process
  - In this case we set the input values looking for the most probably output (i.e., good for image recognition)

- A more advanced use is that of researching which process parameters must be able to ensure a certain output (optimization)
- In this case we can have a combination of fixed and free input values and the challenge is to identify the most correct values of the free parameters able to assure a certain output value of the process
- Sometimes it is also necessary to define an objective function as combination of the process output



# Example of ANN + PSO application in EDM

- ANN + PSO

| **Input** |
| --- |
| Peak current *I* |
| Voltage *V* |
| Frequency *F* |
| Electrode diameter *Φ* |
| Workpiece material *WP* |
| Electrode material *El* |
| **Output** |
| Material Removal Rate *MRR* |
| Tool Wear Ratio *TWR* |
| Dimensional deviation *DD* |

We are looking for:

$$\min(f(I, V, F, \emptyset, WP, El)) = TWR + DD - MRR$$

→ $I, V, F, \emptyset, WP, El$ optimal

However, the function *f* is unknown

The ANN is trained with experimental data and it is used "backwards", i.e. not to predict the output, but by forcing the output and searching for the input values

# Example of ANN + PSO application in EDM

- Matlab code – we start from an already trained and saved network

```
load ('TrainedANN.mat');
nvars = net.inputs{1}.size;        % - variables number
lb = [0.0, 0.0, 0.0, 0.0, 0.0];    % - lower limits of input variables
ub = [1.0, 1.0, 1.0, 1.0 1.0];     % - upper limits of input variables
fun = @ObjectiveFunction;          % - definition of function and options
options = optimoptions('particleswarm','SwarmSize',100,'Display','iter');
optvalues = particleswarm(fun,nvars,lb,ub,options);  % - PSO algorithm call
Inputs = transpose(optvalues);     % - optimized ANN input (it is a vector)
Outputs = net(Inputs);             % - ANN output calculation (it is a vector)
TWR = Outputs(1);
...
objf = fun(optvalues);             % - optimal value calculation
% -- writing the results
disp ('Optimal Input ---');
ss = [' I = ',num2str(optvalues(1)),' - V = ',num2str(optvalues(2)), ...;
disp (ss);
...
```

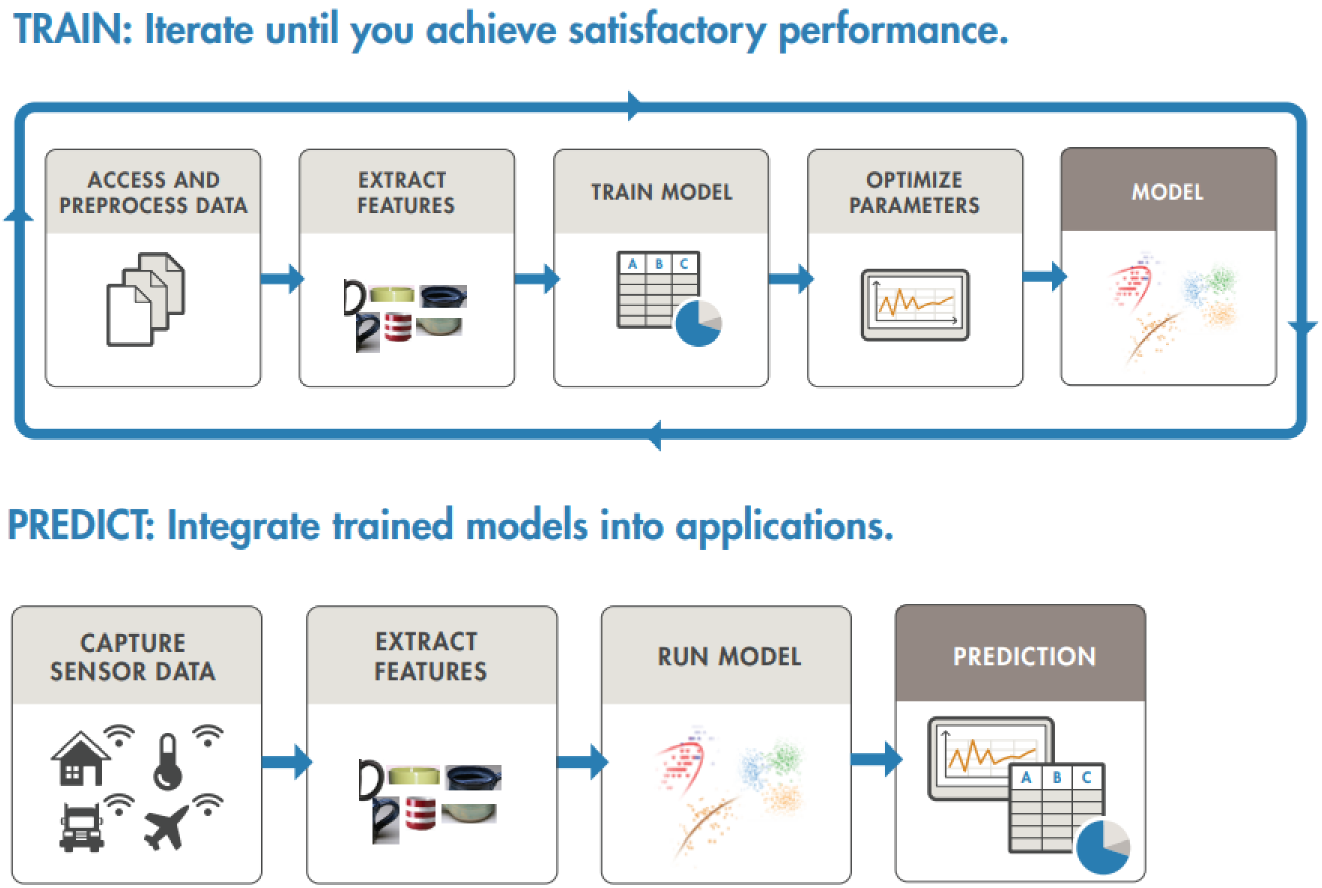
# Example of ANN + PSO application in EDM

- Matlab code continue

```
function objf = ObjectiveFunction(Inputs)   % - objective function definition
load ('TrainedANN.mat');
Inputs = transpose(Inputs);
Outputs = net(Inputs);
MRR_obj = 0.00193;         % -- valore desiderato del parametro MRR
TWR_obj = 0.29707;         % -- valore desiderato del parametro TWR
DD_obj =0.23288;           % -- valore desiderato del parametro DD
MRR = Outputs(1);
TWR = Outputs(2);
DD = Outputs(3);
% -- all the output are constrained
objf = abs(MRR-MRR_obj)+abs(TWR-TWR_obj)+abs(DD-DD_obj);
% -- alternative example: MRR constrained, TWR to be minimized, DD free
% objf = abs(MRR-MRR_obj)+TWR;
end
```

- Note that the PSO algorithm minimizes the *objf* function

# Differences between optimization and prediction




- Source: MATLAB "Machine learning workflow ebook"

# Comments

# What needs are there today in the manufacturing sector (but not only)

- Building resilient and agile value creation systems: to avoid short-term production interruptions such as personnel and machine failures or short-term changes in the order situation, machine builders urgently need modern planning tools
- With the help of mathematical models and artificial intelligence (AI), they can simulate countless scenarios in the shortest possible time and create an optimized alternative plan
- This allows companies to respond nimbly to outages and minimize their impact

# What needs are there today in the manufacturing sector (but not only)

- Develop a data strategy: The fuel for modern planning tools and other innovative software applications is data
- However, this can be used to add value to the business only with a data strategy
  - A data strategy helps to continually develop and deploy applications for using data, open new data sources, and make better decisions based on data
  - Prerequisites for this include the appointment of a manager, usually referred to as the Chief Data Officer, the development of internal data competence and a new decision-making culture in the company
  - After all, employees should trust the recommendations of their tools, and no longer just their instincts

# What needs are there today in the manufacturing sector (but not only)

- Focus on sustainable production: the efficient use of resources, the reduction of $CO_2$ emissions and the lowest possible environmental impact are now mandatory for mechanical engineering
- Not only because customers are increasingly appreciating climate-friendly products, but also because sustainable manufacturing offers significant cost-cutting potential
- With digital and forward-looking planning, machine builders avoid costly and environmentally harmful urgent deliveries, optimize stocks and thus reduce energy consumption and waste of raw materials
- At the same time, smart planning helps them make better use of the machines

# What needs are there today in the manufacturing sector (but not only)

- Create a single source of truth: For new tools to unfold their full power, businesses need digital data capture and interfaces for smooth data streams. In this way, they create a uniform database (sometimes referred to as a data lake) that all departments, employees and applications can access a so-called *single source of truth*
- This not only ensures that employees handle ever-changing binding jobs and order lists, but also reduces the need to transfer less data manually, thus minimizing errors
- It also helps the company to maintain transparency in all processes and to identify bottlenecks or critical pathways in planning at an early stage across all plants
- Schedule adjustments can therefore be made quickly and with relatively little effort, resulting in shorter lead times and more reliable planning information

# Effects of the increase in machine intelligence

- Performance increase:
  - increase in accuracy
  - time reduction (optimized tool paths)
  - cost reduction (less stress on tools = less wear)
  - reduction of energy consumption (lower environmental impact)
  - reduction of rework and waste
  - better surface quality (online monitoring of the surface appearance and learning characteristics)
  - greater safety for the operator, the piece and the machine
  - autonomous optimization of processing given the ego state and the ability to autonomously decide some processing parameters (for example the reduction of the chatter)

# Effects of the increase in machine intelligence

- Increase in self-diagnostic and self-repair capabilities:
  - ease in identifying the failure
  - support in identifying the causes of failure
  - reduction of machine recovery times
  - possibility of remote communication with the manufacturer
  - greater machine reliability (thanks to predictive maintenance)

# Effects of the increase in machine intelligence

- Ability for machines to work in decision-making autonomy
- We need to think about new professions both among designers, both builders and workers in the departments
  - Training is essential
  - These new technologies require new skills: those who do not adapt will run risks
  - Some realities may disappear because they will not have adapted to these new standards
- There is a risk of introducing innovations without understanding them and therefore without reaping the right benefits → **wrong investments**

# The 5th Industrial revolution

# 5$^{th}$ Industrial Revolution
# The new role of "humans"

- Natural evolution of industry 4.0:
  - If machines become intelligent, what role will humans play in the factory of the future?
- Industry paradigm 5.0:
  "*Man is placed at the center of modern, automated and intelligent industry*"

- Human-centric approach: technology to adapt the production process to the needs of workers, guarantee safety and well-being, ensure that new technologies do not interfere with the fundamental rights of workers

# 5$^{th}$ Industrial Revolution
# The new role of "humans"

- Technological evolution always in support of man
- The changes will not erase jobs, they will be simply recreated them in new contexts - is it a slogan?
- Modern industry is aimed at increasing prosperity (attention to environmental and social dimensions) - is it a slogan?
- New skills… not only digital but also transversal, linked to creative, flexible and open thinking that no artificial system can reproduce
- Man has the task of:
  - designing even more advanced, performing and sustainable systems
  - manage the **smart factory** and future industrial revolutions